Chapter

Limitations of Textile Recycling: The Reason behind the Development of Alternative Sustainable Fibers

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Abstract

The sharply increasing world population reveals the insufficiency of natural resources in meeting the needs of humanity, while creating a tendency to search for new resources. Textile products constitute one of the most basic needs of humanity and the consumption of textile products is also increasing due to the changing fashion sense, increasing population, and technology developments. Discovery of alternative or renewable energy sources, recycling of all kinds of materials, enhancing engineering methods and technologies used to make recycling effective, and trends like sustainable fashion that promote sustainability and take parts among the hot topics of this field. Recycling studies are also common in textile science. It is feasible to reduce the usage of natural fibers by utilization of recycled fibers. However, there are some limitations to textile recycling. These limitations led the development of new sustainable fibers and processes as alternatives to natural. In this context, most of the recycling and sustainability-based studies carried out in this field emphasized the indispensability of the subject, while neglecting a few points about limitations. Consequently, the limits of recycling in textiles and new fibers developed to overcome these limits are addressed in this chapter.

Keywords: textile recycling, textile wastes, limitations in textile recycling, textile eco-labels, sustainability certifications, sustainability

1. Introduction

Recycling is the process of converting materials from all kinds of waste to produce new products. Textile recycling implies the reuse and reprocessing of clothing scraps or any fibrous textile material [1]. All types of consumer or industry discarded textile goods are used as textile wastes for recovery. It is obvious that recycling, which has evolved into sustainability over time and its importance has been understood even in ancient times. It can be applied in many fields of the textiles as textile-to-textile (closed-loop) recycling or textile-to-nontextile (open-loop) recycling [2].

The demand for textiles and clothing is increasing day by day as a result of the increasing population, rising living standards, and the fast changing fashion trends [3–5]. Consequently, the amount of textile waste increases, and there are accumulations in landfills [4]. In addition to the consumption of high amounts of textile products, the packaging of these products also causes an increase in waste piles [6].

Textile and clothing waste causes environmental problems and deterioration of ecological balance. Therefore, the reclaim and disposal of waste clothing and textiles are important issues. Unfittingly and uncontrolled disposal of waste cause major problems [5]. The importance of recycling is considered in three subjects by Ref. 7 as economic, social, and environmental subjects [7]. Recycling of textile waste and diversifying the content of recycled raw materials could be a way to support the country's economy. The employment opportunities in the textile sector as in other sectors increase with well-run waste management. The recycling sector is an important supplier to many industries, and wastes are considered as cheap raw materials [8]. A wide variety of garment brand companies offer their products that contain recycled materials at certain rates, as a social responsibility issue in the market and to increase their prestige. It also adds profit to the company by paying less for recycled materials obtained from waste products.

Although there are several methods for the disposal of clothing waste, the most effective methods are recycling and reuse. Evaluation of waste clothing is very complex since clothes are made from different raw materials and may contain various accessories. Clothing may have many components such as labels, sewing threads, buttons, zippers, and interlining, and these components make the separation process difficult. Clothing recycling and textile recycling are two independent topics that are needed to be considered separately [5]. Textile wastes arise out of many production processes, such as fiber and filament manufacture, spinning, weaving, knitting, nonwoven, and clothing manufacturing [9]. In this context, textile wastes can be classified as pre-consumer and post-consumer wastes [10, 11]. Pre-consumer textile waste includes manufacturing waste from the processing of fibers, yarn, fabric, and nonwovens and clothing manufacturing [12]. Pre-consumer textile waste is generally seen as "clean waste" as it is released during the textile production process [13, 14].

When all these wastes are well managed, positive results emerge both in terms of providing economic gains via the recycling of materials and reducing the ecological damage to the world. Despite all advantages, there are recycling limits for all kinds of textile wastes. Not only for textile wastes but also for other solid wastes recyclability variates. Some types of wastes can be easily and well recycled, whereas some types cannot or can formidably be recycled [1]. These limits pave the way for the emergence of new recyclable fibers for the textile industry.

The purpose of this chapter is to present a systematic study for recycling of textiles mentioning the limits and alternative sustainable fibers. The content started with the history of recycling, continued with processes, standards, and certificates about textile recycling. Subsections of recyclable common textile fibers and new recyclable textile fibers are given in detail.

2. History of recycling

Recycling dates back to ancient times [15]. It is claimed that waste management and waste disposal processes date to BC in several references [16, 17]. Recycling is known as an efficient and effective solid waste management system [18]. In 4000 BC, silkworm wastes were used as protein source food in fish raising in China [19]. Scientifically, the foundations of recycling were laid in the 1980s [20].

When we consider textile recycling, it is known that it is as old as recycling in other fields. There are even references stating that it is one of the oldest fields, so textile recycling is called original recycling [21]. China hosted applications where recycled fibers from used clothing were obtained by hand carding and mixed with virgin fibers BC [14]. The textile recycling industry took its first steps in the thirteenth century [22]. In pre-modern societies, there were sustainability models based on the reuse and recycling of textiles [14]. For example, recycling has been done for years in India, both at the household and industrial level [23]. In the early and mid-1800s, reclaimed spin waste and rags were used for the manufacture of new products, and the invention of carbonization made it a unique technique to separate textile waste comprising of cellulose-based and wool fibers blend [22].

Environmental awareness concept had been newly introduced in the 1960s. The conscious interest of consumers and producers had just begun to turn to recycle at that time. Today, it is argued that this interest has evolved into sustainability [24].

Early academic studies conducted in the 1990s focused on presenting a model for the textile waste lifecycle [25]; detailing biological, physical, and chemical treatments of textile wastes [26]; determination of the number of sewn product manufacturers that support recycling in an American state [27]; the recyclability of post-consumer fibers, and market applications, while revealing the advantages of recycling [28]. After this decade, a positive acceleration was observed in the studies on both recycling and textile recycling. When "textile" and "recycling" terms are searched in a topic currently 1843 documents in WOS were encountered at all times. Moreover, 188,487 documents were encountered with the only term "recycling" at all times. The variation of the number of publications by years are given in **Figure 1** and in the first quarter of 2022, 41 documents were published about the textile recycling topic. As can be seen from the graph, the number of research on textile recycling has increased in parallel with the number of research on recycling over the years.

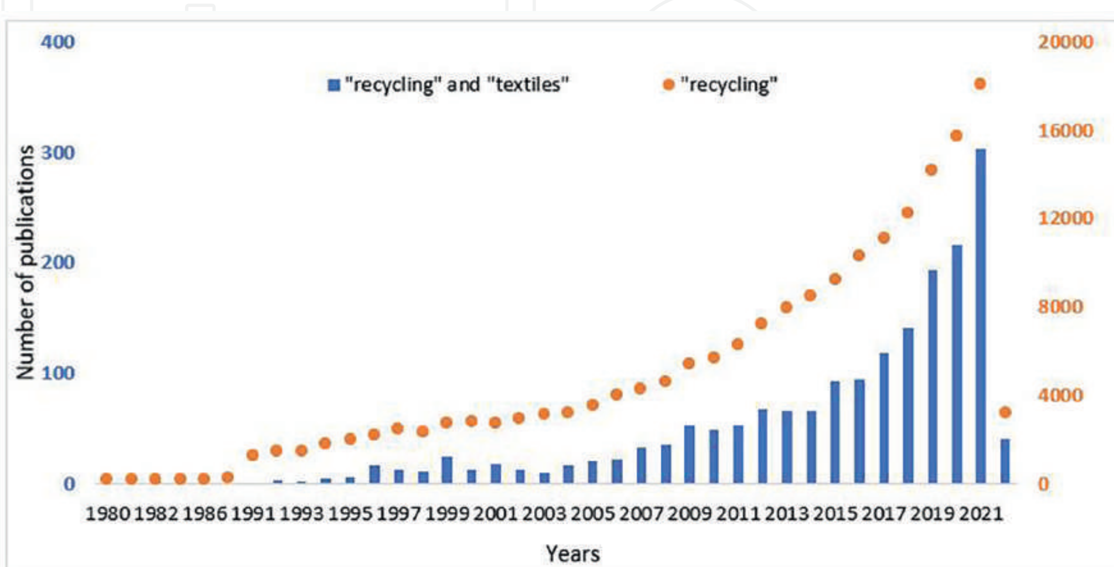

Figure 1.
The number of publications encountered with search terms "recycling" and "recycling and textiles" in WOS.

3. Processes in textile recycling

3.1 Recyclability of textile materials

Recycled fibers are used to make a variety of products. By producing yarns from recycled fibers, knitted or woven fabrics can be produced, or non-woven surfaces are obtained directly from these fibers. Recycled pre-consumer textile wastes are utilized in the construction, automotive, furniture, paper, and clothing industries. However, fibers obtained from pre-consumer textiles are used especially in coarse yarn production [29]. Many researchers studied about using pre-consumer waste and its conversion into a valuable product in the literature. Jamshaid et al. [30] span open-end rotor yarns from fibers in different blends reclaimed from yarn and fabric wastes. They evaluated the impact of various textile wastes on fiber and yarn quality. They underlined that the length and uniformity values of the fibers recycled from yarn wastes are better than those of the fibers recycled from fabric wastes. However, in terms of yarn manufacturing costs, it has been stated that yarns produced from recycled fabric/rag wastes are more economical than yarns produced from yarn wastes. The impact of cotton waste and various spinning conditions on rotor yarn quality was investigated by Halimi et al. [31]. The results showed that the quality of the rotor yarn is not affected by the addition of 25% waste in the first passage of the draw frame. Yilmaz et al. [32] produced yarns by blending the fiber wastes taken from the blow room, the carding and sucked in the draw frame, roving, and conventional ring spinning machines with the virgin cotton fibers at 5 different amounts varying from 5% to 40%. They emphasized that by designing machinery and process steps based on waste fiber type, it can be possible to produce yarns that are in comparable quality values and low cost.

The post-consumer textile wastes consist of clothing and home textiles that consumers no longer need for various reasons, such as damage, pulling on, or going out of fashion [14]. Contrary to pre-consumer wastes, post-consumer wastes are known as dirty and household waste [33]. Post-consumer wastes are evaluated with reuse and recycling techniques or incineration. The options to be applied to post-consumer waste vary according to many criteria such as the wear condition of the clothing, fiber content, and the technology of the recycling facilities [34]. The progress in recycling technology supports the sustainable disposal of waste clothing, and recycling is far more environmentally friendly and socially beneficial than incineration. In addition to this, technological advancements are required to produce upcycle products from waste clothing. Improvements in the collection and disposal of post-consumer textiles can be made with the application of environmental protection policies [5].

Post-consumer waste of sufficient quality is utilized as second-hand clothing by other consumers or sold to third-world countries. The volume of consumer waste is quite high, and clothes that cannot be worn again are shredded into fibers and used in new products, similar to pre-consumer wastes [6, 14]. The process of producing new clothing from post-consumer waste includes collecting waste, obtaining fiber from waste, and producing yarn by using a certain amount of blend in the yarn production stage [34].

When compared to original fibers, recycled fibers have different properties. The processes that the fibers are exposed to during the recycling process damage them and shorten their length. Fiber length is important factor in converting recycled fibers into yarn or producing nonwovens from these fibers, and the fibers must be long enough. Due to the short length of recycled fibers and the presence of non-fiber remnants such as fabric and yarn fragments, defining some quality parameters of

Figure 2.
Various recycling approaches.

these fibers is difficult. Fiber length, material break down degree, and fiber length distribution are three of the most widely analyzed properties of recycled fibers [35].

There are four different approaches to recycling (**Figure 2**) [36, 37]:

- Primary approach,
- Secondary approach,
- Tertiary approach, and
- Quaternary approach

Primary recycling is the most beneficial method, and in this approach, the product is recycled to its original form. This approach is also known as "original recycling." It is aimed at synthetic fibers such as PET (polyethylene terephthalate) and PA (polyamide) [37]. In this method, which can also be blended with the similar original raw material in order to increase the product quality, cleaned and pure scraps from waste are collected and recycled. In addition to the important advantages of this process such as being cheap and easy, it also has the disadvantage that the type of recyclable material is limited [38].

Secondary recycling is the process of converting waste into a product with different physical or chemical properties than the original [39]. Secondary recycling, which converts post-consumer wastes into raw materials, includes the collection and recycling process [40]. The content of textile waste, the degree of purity of the end product, availability, cost, and processing techniques are important factors for secondary recycling.

In tertiary recycling, known as feedstock recycling, wastes are separated into chemicals through pyrolysis, gasification, hydrolysis, and condensation [41]. Tertiary recycling, which is preferred for converting plastic wastes into chemicals, monomers, or fuels, utilizes clean and well-sorted pre-and post-consumer wastes [40].

Quaternary recycling is the use of heat produced by the incineration of fibrous solid wastes [42]. In summary, primary and secondary recycling usually involve the mechanical processes of industrial by-products and waste, while tertiary and quaternary recycling includes the pyrolysis and incineration of textile wastes for energy generation [41].

3.2 Recycling processes in textile

3.2.1 Physical processes in textile recycling

3.2.1.1 Mechanical process in textile recycling

Mechanical recycling is a low-cost and easy method [11], which is the preferred method for recycling a diverse variety of textile waste [43]. The recycling of post-consumer textile waste is generally carried out by mechanical recycling [42]. In the mechanical recycling technique, the fabric is broken down into fibers by cutting, shredding, carding, and other mechanical processes [44, 45]. Mechanical recycling machines gradually break the fabric into small pieces and make it fibrous, and these obtained fibers are reused in the production of yarn or nonwovens. In the mechanical recycling process, initially, wastes are sorted. Foreign components, such as metals and labels, are eliminated. After the fabric is cut into small pieces with rotary blades, it is separated into fibers by tearing [40].

Since garments are usually made from different raw materials, it is better to use pre-consumer waste instead of post-consumer waste in mechanical recycling. Fibers obtained by mechanical recycling from pre-consumer wastes such as denim scraps can be used to make higher-quality yarns. The length of the fibers recycled by the mechanical recycling process is short, despite the use of clean pre-consumer wastes [40]. The fiber length is shortened by the shredding/tearing process. The main reason for this is the friction between the fibers. Friction causes wear of fibers and melting of synthetic fibers. Lubricants are used to reduce friction between fibers during shredding and thus longer fiber lengths can be obtained [46]. In addition to the lubrication process, product quality is increased by blending original fibers with recycled fibers [45].

Recycled fiber properties such as length, fineness, and strength indicate the field the fibers can be evaluated in [47]. Good quality recycled fibers can be spun into fabrics, while lower quality fibers are used as decoration materials, construction materials [48], automotive components, insulation materials, and nonwovens [45, 47].

3.2.1.2 Thermal process in textile recycling

In thermal recycling, synthetic fibers are melted to be reshaped. The thermal recycling method is preferred for recycling synthetic fibers [48, 49]. Chips and pellets obtained by mechanical process from synthetic wastes are turned into fibers by melt extrusion [50].

3.2.2 Chemical recycling in textile

Chemical recycling, which is another method used in the recycling of textile waste, is the depolymerization of polymers or the process of dissolving polymers [2]. Polymers are converted or broken down into their original monomeric building blocks by chemical and biological methods [51].

Monomer and polymer recycling are the two forms of chemical recycling. The polymer chain is frequently degraded during polymer recycling. As a result, the quality of the recycled fiber decreases. In monomer recycling, original quality fibers are obtained. While monomer recycling is only used for synthetic fibers, chemical recycling is applicable to many textile fibers [49]. In addition to the chemical recycling of synthetic fibers, such as polyesters, polyamides, and polyolefins, in cotton and polyester blend products, the fibers can be chemically separated and then converted into new fibers [47].

3.2.3 Downcycling

Downcycling occurs when the quality and economic value [40] of a product obtained from recycling processes is lower than that of the original product [2, 50]. The use of recycled clothing and home textile wastes in agriculture and gardening

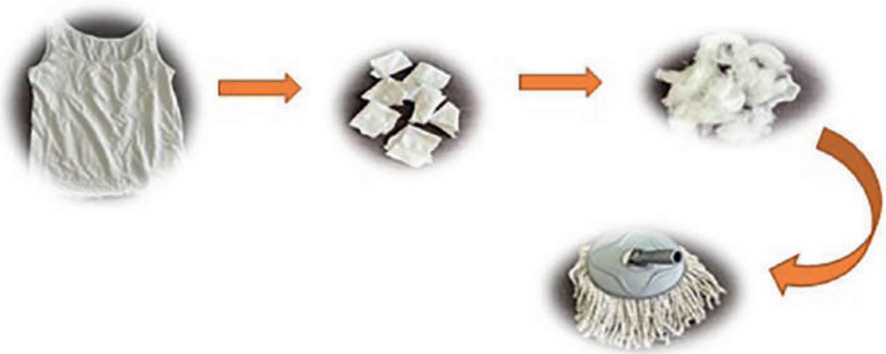

Figure 3.
Downcycling applications in textile.

products, decoration materials [48], insulation materials, low-quality blankets, and upholstery fabrics are the examples of downcycling (**Figure 3**) [2, 50].

3.2.4 Upcycling

When the quality of the recycled material is the same or higher than the original product, this process is called upcycling [2, 50]. Upcycling is a process in which existing resources are used and converted into more useful products. This environmental-friendly process is an important step for a zero-waste policy [52]. Within the scope of sustainability and circular economy, the production of raw materials such as cotton fibers and yarns from textile wastes with polymer and monomer recycling is an example of upcycling [2, 50].

3.2.5 Open-loop recycling in textile

Open-loop recycling is defined as the use of a product's raw material in a different production area. Secondary products obtained through open-loop recycling are generally destroyed after their lifetime [40]. The use of fibers obtained by recycling PET bottles in the textile industry (**Figure 4**) [40] and the usage of recycled textile fibers as insulation material in the construction industry are examples of open-loop recycling.

Figure 4.
Open-loop recycling.

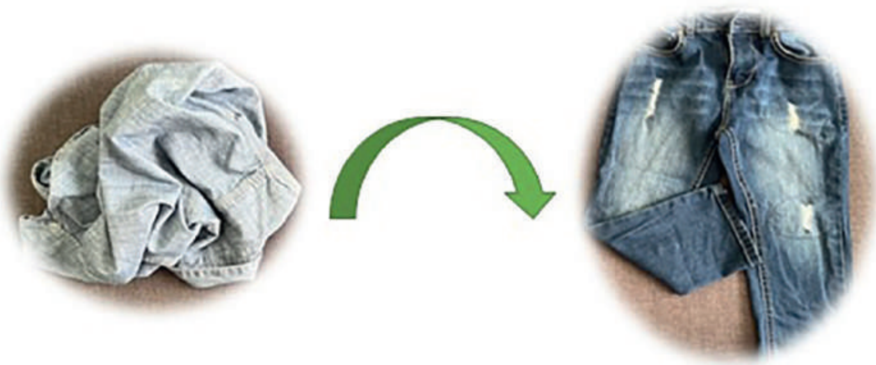

Figure 5.
Closed-loop recycling.

3.2.6 Closed-loop recycling in textile

The reuse of recycled textile waste in the textile industry is called closed-loop recycling [2]. The use of mechanically recycled pre-consumer or post-consumer textile waste in garment production is an example of a closed-loop recycling (**Figure 5**) [40].

4. Sustainable textile Fibers

4.1 Recyclable common textile fibers and limitations

The subject of recycling in textiles comes up with a lot of research based on the advantages created by the recycling process and with a limited number of studies based on recycling limits. In this subsection of the chapter, the limits of recycling in materials traditionally used in textiles are addressed.

Despite the approaches expressing that recycling is a process that only delays the conversion of waste to nature [53], several articles emphasized the importance of process development studies about the determination of recyclability limits [54]. Since it is impossible to apply a uniform recycling method for recycling all kinds of waste materials, different recycling techniques and their combinations have emerged over time [53]. For example, chemical recycling is raised in order to eliminate the limits in mechanical recycling [55]. As recycling can be classified as mechanical, chemical, thermal, and thermomechanical methods; each of them has numerous disadvantages in terms of the imperfections created on the recycled material. Considering these limits, alternatives purposed for the disposure of textile waste as anaerobic digestion, fermentation, composting, and acquisition of construction material [13].

An assessment can be made on the basis of fiber source for recycling limits. Based on the disadvantages, such as shortening or shredding the fibers created the fibers by each recycling cycle, it is stated in the literature that an average of 8 recycling cycles for synthetic fibers and an average of 5 cycles for natural fibers can be actualized [56, 57]. While the recyclability limits are more evident in natural fibers, the same rule is not valid for the fibers formed from thermoplastic polymers. This is the main reason why thermoplastic polymer-based textile waste is the most recycled waste [58].

To increase the quality of the recycled end product in cotton mechanical recycling, there is an obligation to use virgin fibers in addition to recycled fibers at a predetermined ratio. This can be attributed to the decrease in strength according to the recycling cycles as each cycle results in a lower degree of polymerization [59]. The upper usage limit of 30% for recycled cotton in fabrics is specified due to the shortened fibers. The amounts higher than this value causes decreases in fabric quality and performance [60]. Another study in the literature supported this result [61]. Since the fiber breakages are created in the mechanical recycling of cotton [59, 62], low-performance fabrics may be obtained not suitable for professional wear such as workwear, personal protective equipment, career wear, and uniforms [63].

Recycling is classified as primary and secondary recycling in several references. Secondary recycling can be handled as mechanical recycling and the limits mentioned above are also valid for this type of recycling. On the other hand, in primary recycling, the features of waste such as being from a single source and being pure are indisputable, while the low cycle number for each material and even the non-recyclability of some materials constitute these limits [64].

An important factor limiting the chemical recycling process of cotton is the use of harmful chemicals in the industry. While trying to minimize the damage to nature with waste disposal, the use of harmful chemicals which refers to the duality in this phenomenon creates greater harm to both nature and the consumer [59]. Moreover, the need for the separation of textile waste according to color and/or product type is inconvenient. One of the problems encountered in cotton recycling is that most of the cotton products are dyed ones and it is difficult to work with mixed-colored wastes [63]. Besides, there are studies proving that cotton fibers recycled from colored fabrics tended to possess lower quality values [65]. Thus, the demand for more environmentally friendly approaches continues [59].

Wool is a natural fiber that can only be mechanically recycled. The staple length of wool gets shorter with recycling, and it is used in blend ratios with virgin wool up to 70 recycled/30 virgin. The limited market of recycled wool is also a huge obstacle to the recycling of this fiber [63].

Nylon is a polymer with a wide variety of types that is stated as an infinitely recyclable polymer [66]. It is difficult to recycle nylon with mechanical recycling in the industry. In addition, the low number of nylon suppliers makes recycled nylon fibers more expensive [63]. Vidakis et al. studied the effects of multiple recycling cycles of PA12 on its properties. There was a decrease in mechanical properties above 5 recycling cycles. This weakening in mechanical properties is explained by the decrease in crystallinity and the beginning of degradation [67]. When the thermal recycling of polyamide 6 is evaluated, it was seen that a drying process is suggested before melting. It is revealed that the drying process prevents hydrolytic chain scission in wet materials and the intrinsic properties of PA6 polymer are remained [68].

Various studies were conducted in the literature in the last two decades for the determination of recycling cycle limits of polymers. PET which is a thermoplastic polymer widely used in the textile sector one of the polymers tested. Högg performed four recycling cycles on PET and characterized the basic polymer properties. He revealed that there was a considerable decrease in Young's modulus according to the decrease in intrinsic viscosity [69].

The polyolefin fibers react with oxygen in remelting cycles. High temperature or UV light applied in remelting cycles result in molecular weight loss. The dissolution/reprecipitation process for the recycling of high-density polyethylene (HDPE) has been suggested to overcome this limit by Poulakis and Papaspyrides. It is remarked that both the polymer and the solvent has been recovered efficiently. According to this process applied as two recycling cycles to HDPE, no changes in molecular weight, distribution of grain sizes, crystallinity, and mechanical properties were observed [70]. The same researchers applied this technique to virgin PET in pellet form and PET in blow-molded bottle form in two cycles. It was observed that the properties of recycled PET did not change [71].

The effects of seven recycling cycles on PLA (polylactic acid) polymer which is also a polyester was evaluated by Pillin et al. They observed a notable decrease in the molecular weight of the polymer. They attributed the changes in stress and strain at break, modulus, and hardness via recycling cycles to the decrease in molecular weight [72]. Another group studied eight recycling cycles of PLA and concluded that there were no changes in the mechanical properties of the polymer due to the successive cycles [73].

PAN (polyacrylonitrile) is another polymer commonly used in the production of textile products as an alternative to wool. The most critical factors limiting the recycling of PAN are the easy accessibility of perfect virgin PAN and the harsh processing conditions. From this point of view, economic conditions come into play in the recycling of PAN. The high temperature applied during recycling is also shown as a disadvantage for acrylic, which is a polymer inclines to open-loop recycling [74].

Textile wastes consisting of blends of various fibers complicate the recycling process and sometimes even make it impossible. These fibers need to be separated, which should be done by expert workers to avoid problems with the recycled final product. In addition, when it is impossible to recycle these wastes, they reach their end-of-life by utilization in energy recycling [75].

From a different point of view, there are basically two main factors limiting the recycling of textile fibers. The first one is the technological limits of recycled fibers and their inability to be used within virgin fiber, yarn, or fabric production methods. The second is that the expected product quality value cannot be reached by using these recycled fibers [76].

There are two types of sustainable fashion drivers in a sustainable fashion as production and consumption drivers. Material, human and intellectual resources form the production drivers and purchasing decisions, usage, and post usage form the latter. While technical limits are considered in the first derivatives, unawareness of consumption causes a considerable increase in waste [77]. The fact that recycled materials are generally suitable for downcycling emphasizes an important point that should be evaluated economically. Another economic point is the low consumer demand for recycled products. The reason behind the low market demand is the use of dangerous chemicals in recycled products. In addition, waste sorting is a big problem and if it is not done properly, it negatively affects the recycling process from the beginning. Finally, the relevant standards are still in their infancy. All of these may be listed as examples of the limits of recycling [78].

4.2 Branded sustainable textile fibers

Cotton and polyester are the most recycled fibers as referred before. Cotton is the most used type of natural fiber in the textile and clothing industry global consumption is reported as 26.16 million tons and the production rate is 26.43 million tons by the year 2021. When we evaluate cotton cultivation in terms of environmental aspects, it requires a large quantity usage of land occupation, water, and also pesticides. Due to pesticides, it pollutes clean water resources. In the textile production process, cotton dyeing needs a high amount of energy consumption, water, steam, and chemicals, such as bleaching agents, soap, softeners, and salts for obtaining the desired color [55, 79, 80]. Polyester is a non-biodegradable fiber in the environment. Its production process is very similar to polyamide. But polyester is extensively recycled especially as plastic bottles made of polyethylene terephthalate to reduce the landfills. Polyamide is used especially in carpets as referred before. But its recycling process is difficult because of the used dyes and chemicals added to its polymer solution [10].

Besides these types of common fibers, there have also been come out brands with the increasing recycling trend. Renewcell® technology is the upcoming brand from Sweden since 2017. For this process, used garments and textile production waste with high cellulosic content such as viscose, lyocell, modal, acetate, and other types of regenerated fibers (also called man-made cellulosic fibers) are used. Their accessories, such as buttons, zips are removed from the textile material, then it is turned into a slurry. Contaminants and non-cellulosic contents are sorted out from this slurry. This blend, brand named as Circulose® that is consisted of dissolved pulp from 100% recycled textiles dried and packaged as bales for being involved in the textile production process [81, 82].

Repreve® is known as the r-PET staple and filament yarns which are made from post-consumer water bottles and pre-consumer waste, and their fibers are used in many types of industrial product categories. Accessories, apparel, automotive, bedding, flooring, footwear, furnishings, medical accessories, military, outdoor, socks, and hosiery are some of them. As they stated they eliminated the processes; crude oil wellhead, crude oil refinery, Naptha, Xylenes, Paraxylene, TA (Terephthalic Acid) & MEG (Mono Ethylene Glycol). They have chip production (polymerization), extrusion, and texturing for Repreve® polyester filament yarns and feed stock preparation (polymerization), extrusion, and staple processing for Repreve® staple polyester fibers [83, 84]. Moreover, there is a recycled Nylon brand that is Repreve® Nylon 6 fibers. In production, they have also eliminated the processes; crude oil wellhead, crude oil refinery, benzene, cyclohexane, HMD (Hexamethylenediamine), adipic acid, and nylon salt. They have only chip production (polymerization), extrusion, and texturing processes [85].

Trevira® Sinfineco is the brand used for textiles that contain sustainable Trevira® products. They worked together with Thailand-based parent company Indorama whose manufactures recycled chips from PET bottles. They have certificates for recycled chips, fibers, and filaments from GRS (Global Recycled Standard) and RCS-NL (Recycled Claim Standard). Their products are mainly used in the automotive and apparel sectors. Trevira® Sinfineco PLA fibers and filaments are produced from plant sugars (sugar beet, sugar cane, and maize). So, they are recyclable and 100% biodegradable (industrially compostable) fiber materials. The plant sugar is subjected to the fermentation process and it is transformed into lactic acid. Besides their advantageous properties such as UV stability, fastness to light resistance, good wicking properties, it has less environmental impacts. 70% less CO_2 is emitted and 42% less energy is consumed in the raw material production process. They have ISEGA certification for PLA fiber types used in hot water filtration applications (tea and coffee filters) and packaging materials contacting with food [86].

rPET companies supply post-consumer materials in different ways. One of these interesting materials is Bionic®, which collects its source from the coastline of the oceans and waterways to produce rPET PES. Besides environmental benefits, they also get community support both for collecting and cleaning, building up waste management systems including sorting by material and color, compacting, grinding, and warehousing. Besides, they teach the system wherever their collecting point is. Then, they send them for pelletizing. Finally, the recycling process goes in the traditional way. They have three kinds of yarns; FLX® from marine plastics, DPX® from recycled plastics, and natural or synthetic fibers for gaining softer texture, HLX® from 3 layers; core, recovered with rPET and natural fibers in the outer sheath [87].

As technological sustainability process Lenzing™ introduced Refibra™ Technology which is called as reborn Tencel® Fiber Technology and they addressed that it is one of the circular economy solutions. It is a closed-loop technology in which cotton scraps and wood are used for pulping processes. For cotton scraps, they use a special and patented method for transforming colored cotton rags into the lyocell grade pulp by dye removal process and degree of polymerization adjustment. Recycling and upgrading of cotton scraps to new virgin lyocell fibers are free from water and solvent usage. It is certified according to Recycled Claim Standard (RCS) and Global Recycle Standard (GRS) [88, 89]. Lenzing™ EcoVero™ fibers are sustainable viscose fibers that are produced by the use of certified and controlled sustainable wood sources, ecological production process, and supply chain transparency as stated. It has 50% lower emissions and water impact than generic viscose. Lenzing™ EcoVero™ fibers are certified with the EU Ecolabel. It means that the production method has a lower impact on the environment compared with other products in the market [90]. Livaeco by Birla Cellulose™ is eco-enhanced viscose manufactured using a closed-loop process. As they declared, they make a series of changes in the process to be more environmental-friendly. They used a molecular tracer so that they can follow the product from fiber stage to garment form and they can verify the product easily. They emphasize that their source is from certified sustainable forests, they consumed lower water compared with other types of natural fibers, lower greenhouse gas emissions and biodegrades in 6 weeks. They stated that cost of Livaeco™ is 4–5% higher than the conventional type of their fibers produced [91]. Livaeco™ has the FSC® C135325 certificate that refers wood is sourced from the forests following the principles of Sustainable Forestry Management provided environmental, social and economic benefits. They also have various certificates, tools, and documents about sustainability for different processes. They have Forest Stewardship Council (FSC®) certificate for obtaining wood, pulping, fiber production processes regularly; Rainforest Alliance certificate in pulping process; Higg Index, Thinkstep in fiber production step; Tracer tool (fiber, yarn, fabric, garment), OEKO-TEX 100, Sustainable Textile Solution for their Livaeco™ viscose fiber, BLOCKCHAIN for Fiber 2 Retail Process. Besides these certificates, they achieved Dark Green Shirt, Ranking in Canopy's Hot Button Report in 2020 [92]. Kelheim Fibers have also CELLIANT Viscose which is introduced as the first in-fiber sustainable viscose infrared (IR) solution that is an alternative to synthetic fibers. They use natural minerals and embedded them into plant-based fibers. It is certified by FSC® or PEFC™ about raw material used. They are also awarded with a dark green/green shirt in Canopy's 2021 Hot Button Report, which is a sustainability indicator for viscose fiber producers [93].

When polyamide is considered, one of the brand marks is Econyl® by Aquafil S.P.A. It has two types of nylon textile filament yarns; ECONYL® FDY yarns on beam and ECONYL® texturized yarns on cones that are both types of yarns produced via using 100% recycled post-consumer and post-industrial recycled content. They use fishnets, carpets, oligomers (generated by polymer industries), and other types of PA6 materials as wasted content. In ECONYL® plant operation processes has two steps as depolymerization step (where the specific mix of waste is transformed back into secondary raw material-caprolactam) and the purification step of caprolactam [94].

Fulgar is another company that has various types of sustainable fibers with the brand names; Q-NOVA®, Q-CYCLE®, EVO®, AMNI SOUL ECO®. Q-NOVA® PA 6.6. yarn has an eco-friendly process called as MCS (Spinning Continuous Melting). MCS is a mechanical regeneration system that does not involve using chemical materials which would lessen the sustainability of the end product. More than half of it is produced by pre-consumption waste. This waste is remolded using a mechanical regeneration process, then after, it is turned into a form of a polymer. Its prominent features are stated as lightness, breathability, having bright colors. It has certificates as The Global Recycled Standard (GRS), EU ECOLABEL, Higg index [95]. Q-CYCLE® yarn is their new eco-sustainable PA 6.6 yarn produced with their interaction with BASF's ChemCycling™ recycling project. They use post-consumer recycled contents like plastic wastes (used tires) that is not possible to be mechanically recycled. Its certifications are under the evaluation process [96]. EVO® is the other trademark of Fulgar that is a bio-based origin polyamide that its polymerization is partially or completely sourced from castor oil (from castor seeds) [97]. AMNI SOUL ECO® has enhanced PA 6.6 formula, developed by Rhodia-Solvay group, which enables garments to be a biodegradable feature when left in landfills [98].

Considering the polyurethane known as elastane in the market, COREVA™ can be mentioned. It is a plant-based yarn obtained from natural rubber for replacing synthetic, petrol-based yarns and is patented by Candiani Denim. Organic cotton is wrapped around a natural rubber core, so they produce plastic-free yarn by replacing conventional synthetic and petrol-based elastomers. As they declared, Candiani has created an innovative, biodegradable stretch denim fabric but still, it has the features such as elasticity, physical qualities, and durability that are important factors for producing jeans [99].

4.3 Sustainability certifications for textiles and textile eco-labels

Environmental issues are trending topic and their importance increase gradually. There are some international treaties to regulate the behavior of the countries to reduce greenhouse gases and protect the ozone layer. Kyoto Protocol and Montreal Protocol are exemplary treaties for the sign of industrialized countries, describing the precautions that they should take [55]. The carbon footprint is the amount of the greenhouse gases released from fossil fuels used for electricity, heating, and transportation purposes. Textile and clothing sectors are the leading sectors that have high carbon footprint generation and greenhouse gases emissions [37]. Energy is the other critical case for the textile industry. The consumed energy according to textile processes can be given as 34% for spinning, 23% for weaving, 38% for chemical process, and 5% for various purposes [100].

All the efforts for sustainability including getting certifications, discovering new sustainable processes, producing new sustainable fibers, getting textile ecolabels, United Nations' The Sustainable Development Goals (UNSDGs) are playing a major role. United Nations' 17 goals can be listed regularly as; no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry, innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace, justice and strong institutions, partnerships for the goals. There are various studies about the relationship between UNSDGs and fashion brands, certifications, and new type of sustainable fibers [101, 102].

In the past, products are disposed of after the end-of-life or disuse of the products. But today, solutions and precautions for sustaining the environmental cycle are steadily taken. ISO 14040:2006 (Environmental Management-Life Cycle Assessment-Principles and Framework) is the valid standard to evaluate the sustainability of the product cycle [103, 104]. Life cycle assessment (LCA) is a methodology that is determined by the ISO 14040 and ISO 14044 [80]. It merges the environmental impacts of the studied product or service through the value chain [104]. It is possible to determine the potential environmental benefits of various systems of textile reuse and recycling processes within the methods of LCA [50]. LCA does not contain design and development stages because it is considered that design of the product has not environmental impact. But the design of the product can be affected by the other life cycle stages such as emissions to air, water, and land at each stage of manufacture, use, and disposal of the product [105].

There are various textile sustainability standards and certifications. EU Ecolabel supports Europe strategy for zero pollution and circular economy targets by minimizing products' harmful impact on the environment. Products labeled with EU Ecolabel make a reduction in water consumption, make less pollution in the air, restrict the use of hazardous chemicals, and minimize the waste [106, 107]. Better Cotton Initiative (BCI) is claimed itself as the world's leading sustainability initiative for cotton. Their mission is to help cotton communities survive and thrive while protecting and restoring the environment. They have selected five impact areas consisted of climate change mitigation, soil health, pesticide use, smallholder livelihoods, and women's empowerment [108, 109]. In BCI's Better Cotton Assurance Model, they have a roadmap for Better Cotton Farmers and farmer groups to move from baseline performance to meeting the key indicators of the Better Cotton Principles and Criteria and ultimately achieving long-term improvement goals. The model has four overarching goals. The first one is giving license to sell their cotton as Better Cotton if they can meet the standards and criteria to license for selling their cotton as Better Cotton. The second one is improvement in the framework for making sustainable practices. The third one is the development in the improvement of connection between producers and partners. The last one is measuring the sustainability performance of the farmers [109, 110].

Besides OEKO-TEX Standard 100, OEKO-TEX has series of Sustainability Standards comprising of Oeko-Tex Sustainable Textile Production (STeP), Made in Green by OEKO-TEX®, ECO PASSPORT by OEKO-TEX®, OEKO-TEX® DETOX TO ZERO. ECO PASSPORT by OEKO-TEX® is used for chemical products (textile and leather chemicals, colorants, and auxiliary agents) that are used in the textile, leather, and clothing industry. Oeko-Tex Sustainable Textile & Leather Production (STeP) is the standard for modules, such as chemical management, environmental performance, environmental management, social responsibility, quality management, health, and safety in production chain. To get Made in Green by OEKO-TEX® certificate, some criteria (some OEKO-TEX® certificates) should be taken due to finished products that consumers can buy at retailers or semi-finished products sold to companies within the supply chain. This certificate means that textile or leather products' materials are tested for harmful substances, produced as environmentally, safe, and socially responsible workplaces are supplied [111].

GOTS is also one of the textile processing standard for organic fibers, also both for ecological and social criteria. It comprises the whole textile supply chain starting with harvesting of the raw materials till packing and labeling. It is important to use dyes and chemicals that have a low impact on environment and even it has water norms in production, besides this, it also considers fiber requirements, environmental criteria, social criteria, and traceability. GOTS have various production criteria limits. For example, additional fiber limits for natural fibers both for vegetable and animal fibers (linen, hemp, wool, silk, mohair, etc.) is up to 30%; for sustainable regenerated fibers is (Lyocell® & protein based fibers: from organic, FSC(Forest Stewardship Council™)/Programme for the Endorsement of Forest Certification (PEFC) certified recycled raw materials is up to 30%; for Recycled Claim Standard (RCS from Textile Exchange), Global Recycle Standard (GRS from Textile Exchange), Recycled Content Standard (from SCS) certified synthetic fibers (polyester, polyamide, polypropylene, and polyurethane) is up to 30%. There are also restricted fibers in blends like conventional cotton, virgin polyester, conventional angora hair, acrylic, asbestos, and carbon, silver. They have also an obligation for using virgin synthetic and regenerated fibers like viscose, modal, polyamide, elastane, and polypropylene in fiber blends as the maximum ratio is 10%. They have given some more examples like it is permitted to use 70% organic cotton, 30% lyocell from the organic plantation; but, it is not permitted to use 70% organic cotton, 30% lyocell from conventional wood [112, 113].

BlueSign® is one of the sustainability standards that offer a system with solutions for industry and brands for increasing their sustainability performance. They have various criteria such as chemical products for end-consumer use, surface treatment of metals, and plastics/non-textile substrates, fiber manufacturing, textile manufacturers, down and feathers processing, flame retardants, nanoscale materials/structures [114]. They have also a restricted substances list (RSL). In fiber manufacturing for production sites, it is stated that 99% solvent recovery (lyocell, acetate, etc.) rate should be aimed at dry spinning or wet spinning. They encourage their partners to develop fibers that meet their requirements for supporting a circular economy and to give ahead manufacturers to produce and use of recyclable and recycled fibers for circular textile production. It is obligatory for fiber manufacturing sites to pass the chemical assessment that they use Alkylphenol ethoxylates (APEO), free agents, in all preparation and sizing agents used. It is possible to give more examples for other type of fibers. In polyester fiber production, they have limited values of volatile organic compounds (VOCs) not only for year, but also limited emission factors per PET chips (one kg) and filament fiber (one kg). It is also important to have wood policy for cellulosic regenerated fibers, such as viscose, lyocell, and acetate. In production, 25% of sourced pulp fibers/pulp should be used from the wood certified by independent third-party certification with the label of the Forest Stewardship Council (FSC®). Besides this, independent third-party risk assessments, audits and on-site visits should be taken with positive results by audits (preferably a CanopyStyle Audit with at least bronze status) or independent third-party certification of sustainable forest management programs (e.g. Rainforest Alliance) [115].

The Higg Index is used as a tool for the standardization of sustainability measurement. It is comprised of five tools; the Higg Facility Environmental Module (FEM), Higg Facility Social & Labor Module (FSLM), Higg Brand & Retail Module (BRM), Higg Materials Sustainability Index (MSI), and Higg Product Module (PM). They evaluate the social and environmental performance of the value chain together with the environmental impacts of products. It gives an opportunity to consumers using the Higg Index to inform their individual sustainability strategies in crosswise topics, such as water use, carbon emissions, labor conditions, consumer goods brands, retailers, manufacturers, and governments [116].

The Recycled Claim Standard (RCS) and Global Recycled Standard (GRS) are stated as international and voluntary standards. They set requirements for third-party certification about recycled input and chain of custody. Their aim is to raise the usage ratios of recycled materials. The GRS contains also social and environmental processing requirements and chemical restrictions as additional criteria compared with RCS [117]. For RCS, labeling can be applied to all products containing at least 5% recycled material for textiles. It also enhances the traceability of recycled raw materials, transparent communication, clear labeling, and stakeholder engagement [118]. The GRS label assured that there are high percentages of recycled contents in products, the harmful impact is reduced both for people and the environment, traceability and stakeholder engagement are supplied [119].

Cradle to Cradle Certified® is another global standardization for safe, circular, and responsibly made products. It evaluates the safety, circularity, and responsibility of materials and products in five categories of sustainability performance such as material health, product circularity, clean air & climate protection, water and soil stewardship, and social fairness [120].

Forest Stewardship Council® (FSC) forest management certification endorsed that the management of forests is made by taking care of biological diversity and benefits the lives of local people and workers. There are 10 principles for forest operation for receiving FSC forest management certification. These principles include a broad range of issues, from maintaining high conservation values to community relations and workers' rights, as well as monitoring the environmental and social impacts of forest management [121].

There are also some other sustainability standards like Cotton Made in Africa, Organic Content Standard (OCS), Soil Association Organic Standard, Responsible Down Standard (RDS), Responsible Wool Standard (RWS) [122–126].

5. Conclusions

Recycling has shown continuity since ancient times as a technique that people comprehended its importance towards the purpose of living with scarce resources and applied it even if not in a scientific sense. Recycling has reached scientific meaning throughout history, and then the subject has evolved towards sustainability. Textile recycling has a great place within the scope of this subject, which has been on the agenda for a long time and will also continue to be, with the advantages it creates in both environmental and economic terms. Human beings fall into textile products from the moment that they are born, they need these textile products throughout their lives (even when they die in some cultures—due to the rituals of burial with various fabrics). The indispensability of textile has always kept it at the forefront in various areas for years.

Engineering-based scientific research always aims to increase the quality of life and make the world habitable for a longer period. In this context, these purposes are embodied as the main objectives in the studies on recycling and sustainability. As the decrease in natural resources, population growth, changes in fashion causing excessive consumption of resources, and technological developments continue, the interest in recycling and sustainability will increase acceleratingly. As emphasized herein, recycling in textiles, recycling limits in textile wastes, and the search for sustainable new textile resources will continue to be hot topics of the area. In conclusion, approaches on more effective utilization of traditional fibers, the discovery, commercialization, and popularization of new sustainable fibers, and the representation of new models for the management of textile waste will be the focus of researchers for years.

Conflict of interest

The authors declare no conflict of interest.

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Chapter

Numerical Investigation of Braided Structure Potential as a Cast for Femur Shaft Fracture

Jerry Ochola and Michele Conti

Abstract

Femur fractures are repaired using orthopedic implants involving external and internal fixators. Meanwhile, tubular braided structures have not been considered for bone-shaft fracture repair, despite their potential in use as orthopedic casts. This study investigates potential of using bi-axial braided structures as casts for femur diaphysis fracture under bending loads. The braided structure model was developed using a python script while a hollow femur bone shaft was created in a 3D interface using FE Analysis methods in ABAQUS (v17) from a femur bone model rendered using MIMICS from femur bone CT scan. Numerical methods were used to investigate the change in bone shape eccentricity due to bending loads in-terms of load carrying capacity, bone curvature, bending resistance and stresses in the bone shaft. The results portrayed influence of the braided structure in ensuring the stresses due to the bending load are distributed evenly on the femur shaft surface.

Keywords: femur, braid, biaxial, python, crack, diaphysis, FEM

1. Introduction

Human Femur bone is a natural composite material consisting of a cellular component and an extra cellular component. It consists of the cortical bone and the trabecular bone [1]. The femur bone's cortical bone is the primary load carrying material. This is attributed to the presence of osteon density and fraction of osteonal structures within the cortical bone layer of the femur structure [2]. It has also been shown that tissue strength in the cortical region is superior compared to other sections of the femur bone [3]. In the course of femur use during motion the cortical bone is loaded mostly by bending moments, resulting in a high percentage of tensile strain. Even though cortical shell and the trabecular matrix contribute substantially to the strength of the peripheral skeleton [4], the cortical bone has also been attributed with supporting most of the loads on the human skeleton. The toughness of femur bone also known as energy to failure, which is the bones property associated to its capability to absorb energy during failure has been linked to the risk of fracture in the bones. Nevertheless, even though the bone structure is susceptible to rupture, there is evidence that the living tissue material within its micro-structure is capable of self-repair [5]. This special property can be exploited during repair of femur bones.

Conventionally, fracture in femur's cortical bone has been done using metal plates [6]. This repair technique using plates is normally associated with stress shielding that may lead to resorption and osteoporosis [7] due to insufficient physiological loading on the bone [8]. which eventually can cause bone refractures when the plate is removed especially in fracture in diaphyseal region [9].

An attempt of replacing the conventional bone repair techniques have been done by using braided [8, 9] and knitted [10] composite casts to repair bone fractures. The results from the use of the braided structures were associated with reduction in stress concentrations in the fractured ends of the bone than a plate. It was also reported that The tubular cast has been shown to be a promising fixation method for healing broken bones [8]. This could be linked to the fact that braided structures used as bone casts have demonstrated better ability for distributing stress [11].

The use of Finite Element (FE) modeling has been effective in the analysis of bone mechanics [12]. Further, FE approaches have been used in predicting modes of bone failure under stance and fall configurations [13] and also in the analysis of the composite reinforcement of femur bone using composite casts [8].

In this paper, we propose a braided structure with enough rigidity to reinforce the bone at fracture site. The braided structure potentially offers support and enough stiffness to the bone around the site of fracture. This study applies numerical and analytical techniques to demonstrate feasibility of using tubular braided structures in reinforcing fractured femur bones under single stance conditions.

2. Design of braided reinforcement structure

The reinforcement consists of a braided structure and fixators at both ends of the structure. The design of the braided structure was done by modeling a circular coordinate of a helical path in a three-dimensional space in both clockwise and counter-clockwise directions. The general coordinates of the helical yarn path in the clockwise and anticlockwise direction as (**Figure 1**):

Clockwise direction:

$$X_i = [r_o + r(\theta)] \cos[-\theta - (i-1)\beta], \quad i = 1, 2, \cdots n \tag{1}$$

$$Y_i = [r_o + r(\theta)] \sin[-\theta - (i-1)\beta], \quad i = 1, 2, \cdots n \tag{2}$$

$$Z_i = r_o \tan\alpha\theta, \quad i = 1, 2, \cdots n \tag{3}$$

where:

$$r_o = \frac{2p\cos\propto}{\beta} \tag{4}$$

$$r(\theta) = \frac{a}{2} \sin\left(\frac{2\pi}{\beta}\theta + \frac{3\pi}{2}\right) \tag{5}$$

Anti-clockwise direction:

$$X_i = [r_o + r(\theta)] \cos[\theta + (i-1)\beta], \quad i = 1, 2, \cdots n \tag{6}$$

$$Y_i = [r_o + r(\theta)] \sin[\theta + (i-1)\beta], \quad i = 1, 2, \cdots n \tag{7}$$

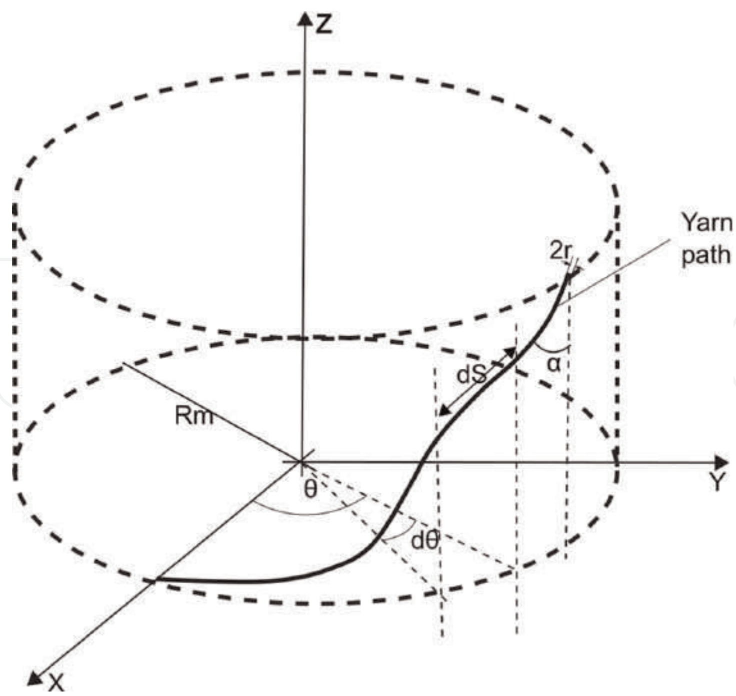

Figure 1.
Illustration of the geometry of the yarn path on a tubular braided structure.

$$Z_i = r_o \tan\alpha\theta, \quad i = 1, 2, \cdots n \tag{8}$$

In which the values of r_o are the same as Eq. (4) and $r(\theta)$ can be evaluated as: where:

$$r_o = \frac{2p\cos\propto}{\beta} \tag{9}$$

$$r(\theta) = \frac{a}{2}\sin\left(\frac{2\pi}{\beta}\theta + \frac{\pi}{2}\right) \tag{10}$$

The generic designs of braided fabrics can be modeled by formulating the coordinates for the yarn path by imputing the values of the parameters r_o and $r(\theta)$ into Eqs. (6)–(8) to (9)–(11). In the case of a diamond braided fabric, the parameters can be evaluated as follows:

Clockwise direction:

$$r_o = \frac{(2p + p')\cos\propto}{\beta} \tag{11}$$

$$r(\theta) = \begin{cases} \dfrac{-a}{2} & 0 < \theta < \dfrac{k_1\beta}{2}, \\ \dfrac{a}{2\sin\left(\dfrac{2\pi}{\beta}\theta + \dfrac{3\pi}{2}\right)} & \dfrac{k_1\beta}{2} < \theta < \dfrac{(k_1+1)\beta}{2}, \\ \dfrac{-a}{2} & 0 < \theta < \dfrac{k_1\beta}{2}, \\ \dfrac{a}{2\sin\left(\dfrac{2\pi}{\beta}\theta + \dfrac{3\pi}{2}\right)} & \dfrac{k_1\beta}{2} < \theta < \dfrac{(k_1+1)\beta}{2}, \end{cases} \tag{12}$$

Anti-clockwise direction:
the value for r_o can be evaluated using Eq. (11), then,

$$r(\theta) = \begin{cases} \dfrac{-a}{2} & 0 < \theta < \dfrac{k_1\beta}{2}, \\ \dfrac{a}{2\sin\left(\dfrac{2\pi}{\beta}\theta + \dfrac{3\pi}{2}\right)} & \dfrac{k_1\beta}{2} < \theta < \dfrac{(k_1+1)\beta}{2}, \\ \dfrac{-a}{2} & 0 < \theta < \dfrac{k_1\beta}{2}, \\ \dfrac{a}{2\sin\left(\dfrac{2\pi}{\beta}\theta + \dfrac{3\pi}{2}\right)} & \dfrac{k_1\beta}{2} < \theta < \dfrac{(k_1+1)\beta}{2}, \end{cases} \tag{13}$$

3. Materials and methods

The study involves 3D CAD developed human femur bone. Quasi-Static structural analysis was carried out using ABAQUS17 to determine the load, stress, and deformation criterion of the bone with fracture before, during and after repair with a braided structure. The model of the braided structure was developed using a python script using the parameters illustrated in **Figure 2**.

A force of 800 N was applied to induce bone displacement to simulate two configurations of single stance conditions of a human femur: (SC1, θ = 120 and SC2, θ = 90) as shown in **Figure 3**.

The profile of the femur mid-shaft was isolated inform of a surface using the commercial software paraview and then the center-line of the shaft surface traced in VMTK after-which a MATLAB algorithm was used to develop a crimper model for deploying the circular braided structure onto the oblique cut-femur bone as shown in **Figure 4** in ABAQUS CAE.

The 3D model of the braided structure was developed using a python script, an input file generated and imported into ABAQUS17. The assembly of the bone and braided structure and quasi-static structural analysis was carried out in ABAQUS17. The material properties assigned for the cortical bone are as shown in **Table 1**. The

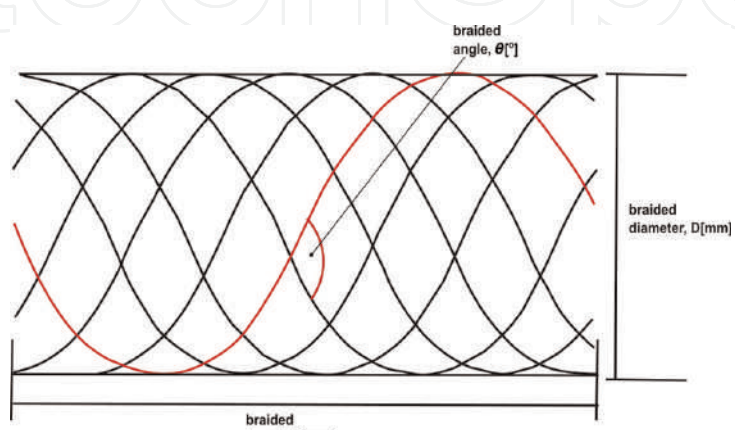

Figure 2.
Illustration of the geometry of braided structure.

Figure 3.
Models of the femur bone structure showing: (a) single stance configuration (SC1 θ = 120); (b) position of the femur fracture at the bone shaft; and (c) ingle stance configuration (SC2 θ = 90).

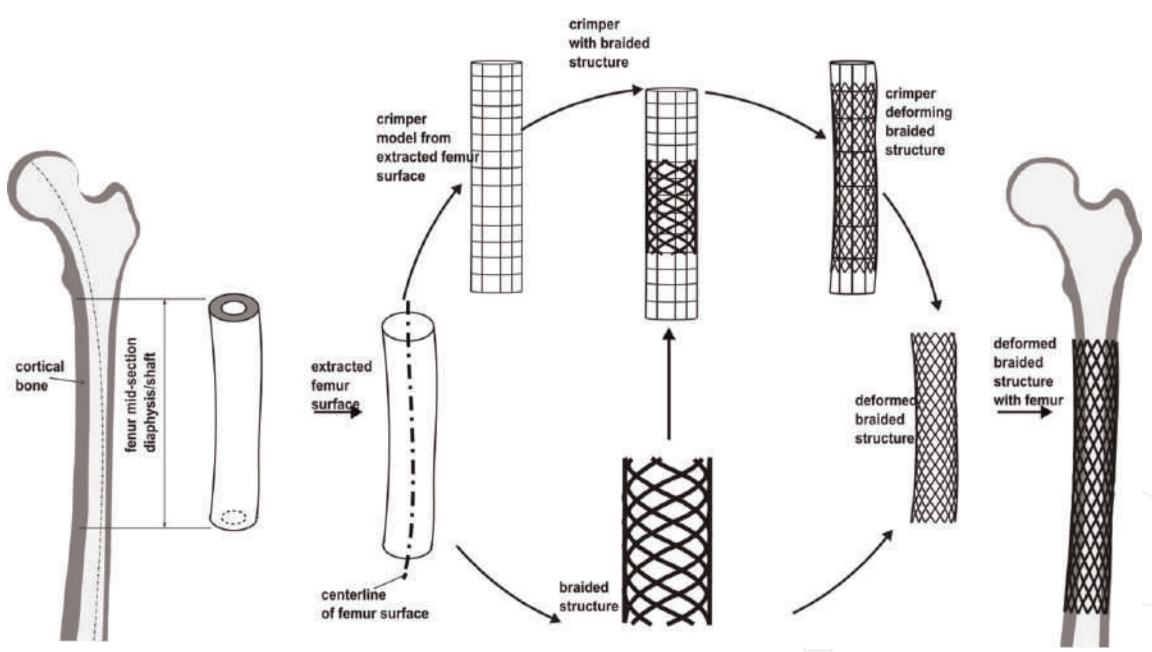

Figure 4.
Illustration of the numerical models for deployment of the braided structure onto the cut-femur model.

femur bone was modeled as a linear elastic material to reduce computation time and complexity of the analysis [15].

Quasi-Static structural analysis was carried out for both the models of the single stance configurations (SC1, θ = 120 and SC2, θ = 90). The lower end of the femur bone was fixed to mimic the normal human stance condition in all the analysis. Force applied was 800 N and was applied on femoral head at 120 and 90. The total load in the femur von Misses stress and total deformation in Z axis were evaluated for an intact femur, then for a fracture femur and eventually for a reinforced femur.

SI units	Material properties
Young's modulus	17 GPa
Density	2 gcm^{-3}
Poisson's ratio	0.30
Tensile strength	130 MPa

Table 1.
Material properties of cortical bone [14].

4. Validation

The Finite Element (FE) models adopted in this study were validated using data from previous research [16] as shown in **Figure 5**. The data shows close correlation between our model data and experimental data of femur bone analysis. The data was then used in the analysis of fall and stance configuration for the femur bone used in this study.

5. Results and discussions

The results from the numerical simulation of a single stance configurations (SC1 and SC2) for a human intact femur bone were plotted as shown in **Figure 6a** for load against displacement. It was established from the results that in an intact femur the load due to SC1 will be more than that in a SC2 type of stance configuration. The results further show that the intact bone during SC1 stance could withstand more stress than in the SC2 stance as shown in **Figure 6b**.

A fracture was then introduced to the intact femur. The force of 800 N was then applied to simulate a single stance configuration. The results of numerical simulation were plotted as shown in **Figure 7a** for load against displacement. It was established from the results that in a fractured femur the load due to SC1 stance will be more than that in an SC2 configuration. The results further show that the fractured bone during SC1 stance could withstand more stress than in the SC2 configuration as shown in **Figure 7b**.

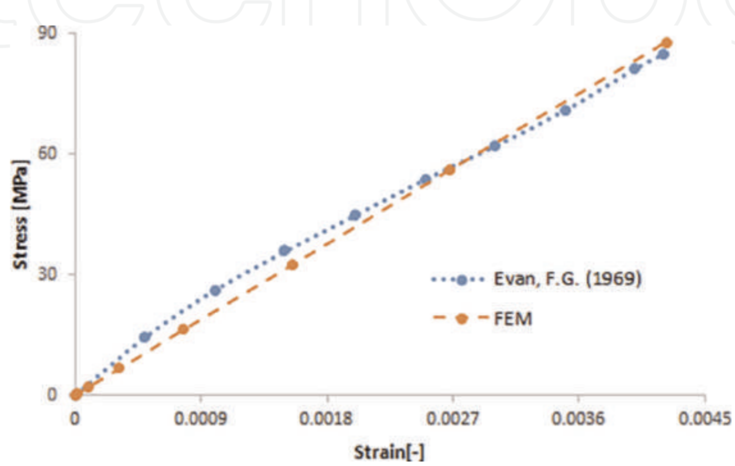

Figure 5.
Validation results for 3D femur model.

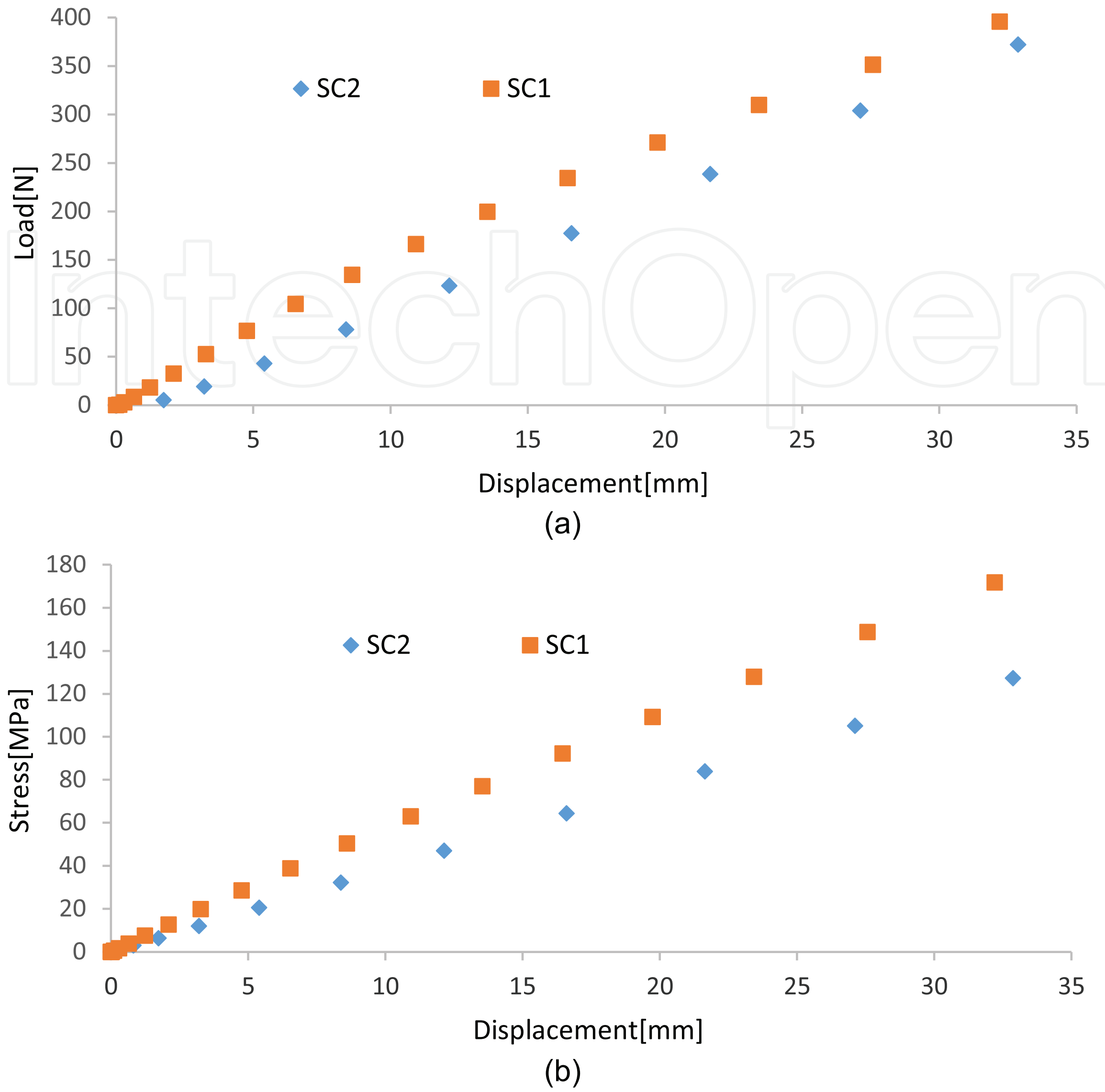

Figure 6.
(a) The illustration of load against displacement for human femur fall and single stance configuration for an intact bone structure; and (b) the illustration of stress against displacement for human femur fall and single stance configuration for an intact bone structure.

The model of the fractured femur was then reinforced using a tubular braided structure. To simulate fixators on the braided structures tie-constraints in ABAQUS were introduced at the ends of the the braided structure. An 800 N was then applied to simulate a single stance and fall configurations. The results of numerical simulation were plotted as shown in **Figure 8a** for load against displacement. It was established from the results that in the reinforced femur the load due to SC1 stance was more than that in an SC2 configuration. The results further show that the reinforced bone during SC1 could withstand more stress than in the SC2 configuration as shown in **Figure 8b**.

The deformation of the femur bone was analyzed for the SC1 conditions because it had higher mechanical properties than the SC2 stance as shown in the results. The deformation results established as shown in **Figure 9** that in an intact femur there was an increase in bone deformation with yielding stress. This was illustrated by the contour plots for the von Misses stress on the surface of the femur bone.

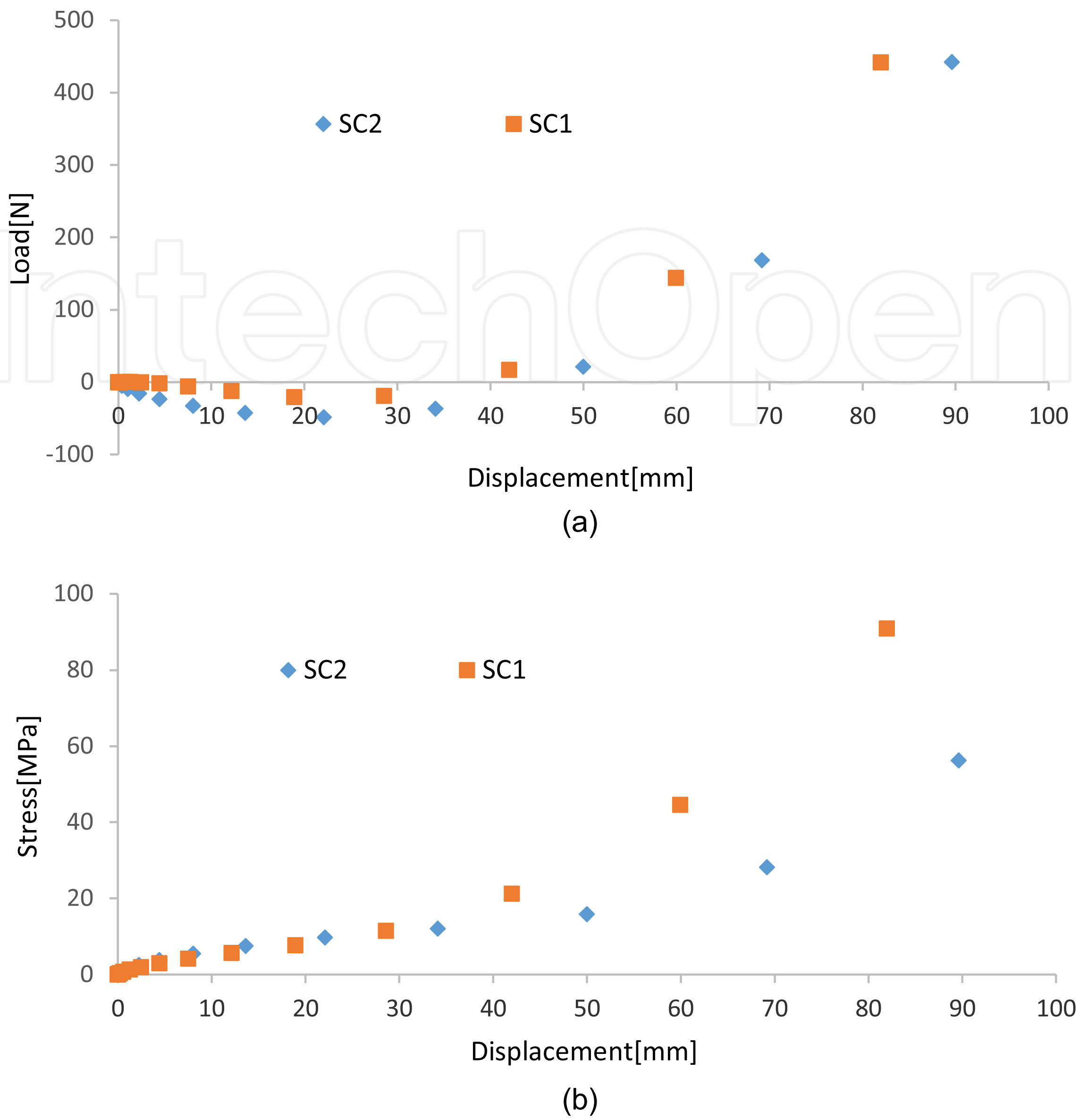

Figure 7.
(a) The illustration of load against displacement for human femur fall and single stance configuration for a fractured bone structure; and (b) the illustration of stress against displacement for human femur fall and single stance configuration for a fractured bone structure.

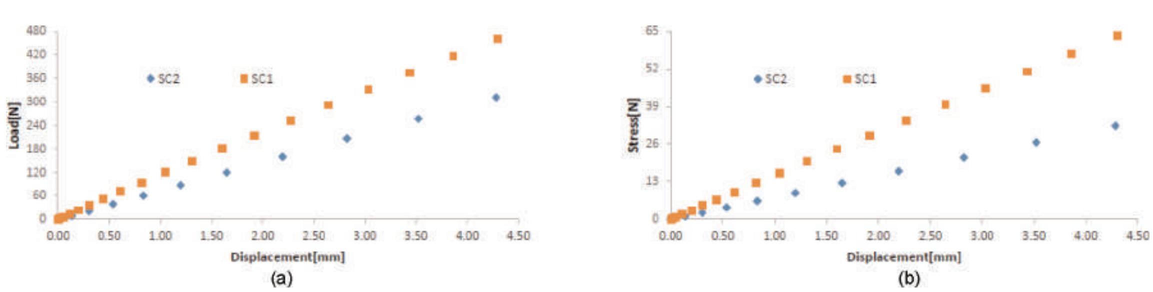

Figure 8.
(a) The illustration of load against displacement for human femur fall and single stance configuration for a braid-reinforced femur bone structure; and (b) the illustration of stress against displacement for human femur fall and single stance configuration for a braid-reinforced femur bone structure.

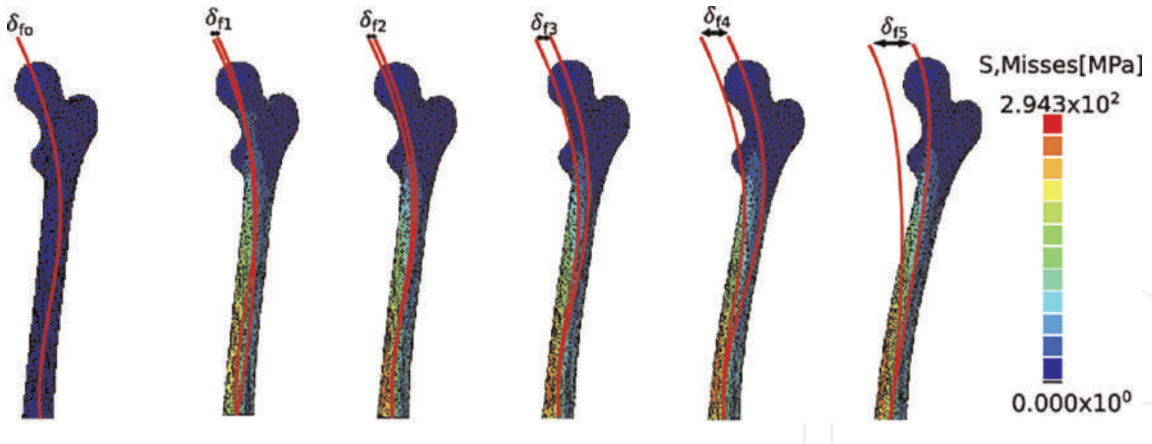

Figure 9.
Contour plots for the deformation of the model of the intact femur bone under stance configuration.

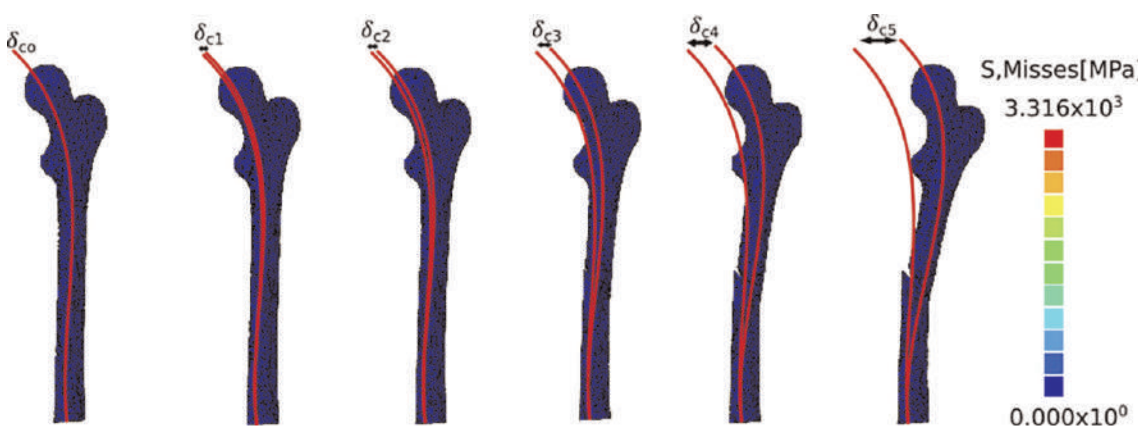

Figure 10.
Contour plots for the deformation of the model of the fractured femur bone under stance configuration.

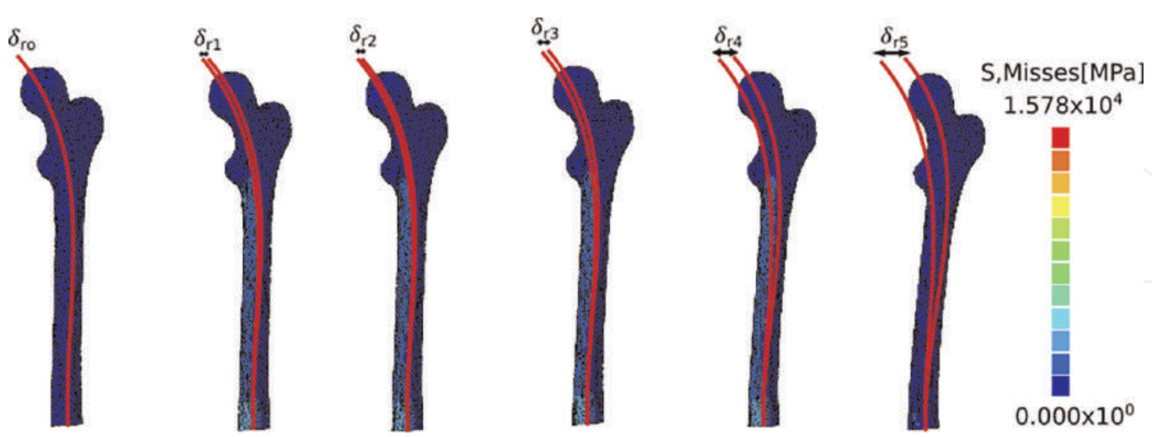

Figure 11.
Contour plots for the deformation of the model of the braid-reinforced femur bone under stance configuration.

The deformation in the fractured femur shown in **Figure 10** shows that the femur bone deformation would be higher than that of the intact femur, there was also evidence of the bone yielding at lower stress levels portrayed by the levels of von Misses stress contour plots.

The reinforced femur structure (**Figure 11**) however, illustrated lower deformations as compared to both the intact femur model and the fractured femur model.

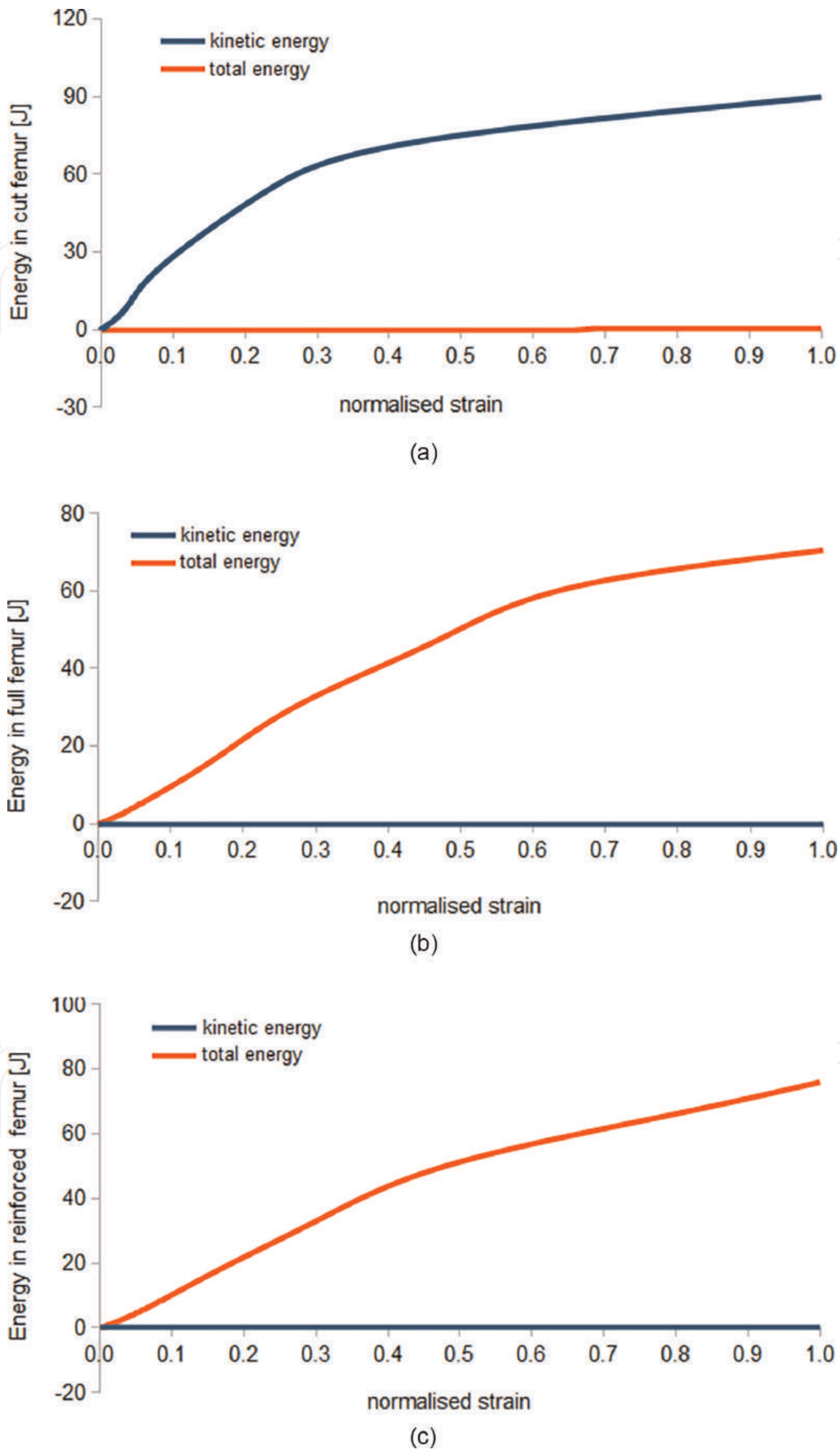

Figure 12.
The illustration of quasi-static energy analysis for the simulations for (a) intact femur bone structure; (b) fractured femur bone structure; and (c) reinforced human femur bone structure.

The results predicted in simulation models shows a trend where the load values were higher than the values in the fall configuration, these results were consistent with the findings elsewhere [17] where the fracture load in a stance configuration recorded higher loads than in a fall configuration of the femur bone. The results further established that even though the force applied to the femur was able to deform the bone to some extent, the reinforced bone structure was able to withstand the loads better. This was illustrated by the small deflection and minimum yield stress in the reinforced femur. This is further supported by the large deflection in the femur bone with the obliquecut, when the cut was reinforced using the braided structure the deflection decreased.

6. Quasi-static analysis

The simulation results shows that the models were not affected by viscous energies as portrayed in **Figure 12**.

7. Conclusion

The reinforced fractured femur portrayed improved strength and stability which could be attributed to the braided structure. There was also evidence from deformation results that showed that when reinforced the fractured femur, deformed less. Further, the use of finite element methods was found to be appropriate in the study of the feasibility of reinforcing fractured femur with braided structure.

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Chapter

A Review of Significant Advances in Areca Fiber Composites

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Abstract

This chapter provides a comprehensive review of the recent developments in the design of areca fiber composites. The physical, mechanical, and thermal properties of areca fiber and its composites are explained here. The species of Areca fiber represents the Arecaceae/Palmae family (like the coconut/palm trees), with regard to its physical and mechanical properties. Researchers identified that areca fiber holds prospective applications as an alternative to reinforced polymer composites in the automotive, aerospace, and construction industries. Surveys on bio-softening, adhesion, the effects of fiber length, chemical treatments of long areca fibers, the influence of mercerization on the tensile strength of long and short areca fibers, and areca husk have been done. Several researchers have utilized various natural fibers in developing bio-composites. Furthermore, the reinforced composite of natural fiber is a prospective research area, considering its mechanical properties, tensile strength, lightweight, nominal pricing, biodegradable/eco-friendly nature, and ease of procuring raw materials compared to synthetic fiber-reinforced composites. However, little research has been done on areca leaf fibers as a feasible fiber. This chapter provides information on the development and investigation of the mechanical behaviour of a natural fiber-reinforced epoxy composite of areca fiber with various configurations of areca fiber orientation.

Keywords: areca fibers, natural fibers, mechanical properties, hybrid composites, chemical treatment, thermal properties

1. Introduction

Synthetic fibers have been found to show excellent properties that describe their wide areas of application in different industries. But such fibers can pose environmental issues, with regard to landfills, owing to their non-biodegradability [1]. Natural fibers have been intended to be used in composites owing to environmental considerations in the form of individual or hybrid reinforcement fibers. Prior to being utilized in composites, natural fibers have been obtained from nature in the form of animals, plants, and minerals, using different techniques, like chemical and thermal modifications.

Areca fiber is chiefly obtained from the fruit areca, frond, and stalk leaf. The world today is facing the problem of growing new and propelled innovations and methods to eliminate or utilize solid wastes, particularly with polymers that are non-reversible in nature. The methods adopted in splitting up the wastes do not seem economical and tend to generate chemicals that prove harmful. Taking into account these factors, reinforcing polymers using natural fibers seems the only option that could result in solving the issue. Regular strands are easily available and reusable, have less thickness, and are ecofriendly. They possess high tensile properties and can be used to substitute the customary strands. The strong demerit of using characteristic strands for strengthening plastics is the contrariness, causing weak bondage between normal filaments and lattice gums and thus leading to low pliable characteristics. A number of theories and surface modification methods have been evolved to improve fiber-network interfacial holding and enhance malleable characteristics of the composites. Further, it is proved that the strength and stiffness of the natural fiber polymer composites are mainly influenced by the loading of fiber. Up to a particular extent, there is a rise in mechanical properties with increasing fiber weight ratio. In order to evaluate the tensile properties of natural fiber reinforced composites, mathematical models/finite element models are being adopted as a necessity.

Natural fiber comprises cellulose, lignin, pectin, and so on. Owing to the presence of such constituents, natural fiber possesses unique features and special properties and gives high moisture percentage, which would in turn influence the fiber–matrix bonding. In order to find a solution for this problem, certain techniques of chemical treatment have been evolved and investigated so as to satisfy the properties of other man-made fibers [2–6]. When considering end uses like electrical insulation, the areca/betel nut fiber reinforced composites exhibit higher merits with regard to the latest development of composite materials [7].

The requirements of high strength to weight ratio in components prompted the development of composites, which necessitated high performance and efficiency, and in turn led to advances in different polymer matrix composites having different fiber reinforcements like carbon fiber, glass fibers, aramid, natural fibers, hybrid, and so on. Natural fiber composites assume a crucial role taking into account the factor of environment-friendly materials and the necessity to manufacture different sustainable engineering and industry-oriented components.

Owing to their good mechanical properties and biodegradability, natural fibers have a crucial function as a reinforcement agent and are readily available in many parts of the world. A number of natural fibers such as jute, kenaf, sisal, hemp, bamboo, areca, pineapple, banana, and coir are being considered important for several research studies due to their availability and cost effectiveness for the design of a cost-effective reinforcing material [8–11]. A number of properties arise from the use of various natural fibers as a reinforcement agent in composite materials and can effectively be utilized for different end uses.

2. Evaluation of the physical, thermal, and mechanical properties

The different parts of plants like bast, leaf, seed, stalk, fruit, grass, and wood yield cellulosic or lignocellulosic fibers. Fruits of plants yield fibers that are normally short, light, and hairy; bast (found in the stem or trunk) yields long fibers that offer strength to the plant or tree. Sturdy and rough fibers are obtained from leaves and are normally utilized in the transportation and automotive sectors. Fiber length is considered important for use of the fiber, particularly in the traditional fiber industries [12]. High-quality fabrics can be designed from yarns spun by long fibers (clothing, laces, domestic textiles, tents, sailcloth), whereas fibers like cotton, flax, hemp, ramie, and sisal can be used for production of coarser fabrics such as bagging, floor coverings, and carpets. Fibers such as jute, sisal, cotton, and hemp can be considered for cordage fiber, tying twine, rope, and binder twine [13, 14]. Also, sisal and coir fibers can be utilized in brushes and for weaving to produce hats, mats, baskets, and rugs [15]. Such fibers have also been utilized as fillers in upholstery, for seams in vessels, barrels, and piping and as reinforcement for plastic and wallboard.

Moreover, natural fibers can be used with wood pulp in manufacturing paper [16]. Investigations on natural fibers, particularly kenaf, jute, and bamboo, have increased over the past few years [17–23]. For instance, an investigation relating to the ballistic impact resistance of kenaf reinforced polyvinyl butyral composites; a study of flexural strength and ductility of kenaf reinforced concrete composites; work relating to the influence of kenaf hybridization with oil palm fiber reinforced an epoxy matrix on the tensile, flexural, and impact properties of the obtained composites; and research with regard to processing and manufacturing of kenaf reinforced that epoxy composites are worthy of consideration [24–26].

Studies have been carried out on fiber hybridization relating to kenaf and fiberglass to find out its influence on the tensile and impact properties of the materials so produced [27]. Besides, a number of workers also reported on the use of natural fibers in the design of industrial safety helmets [28].

Previous investigations on natural fibers have shown scanty research carried out on areca and other species from the Palmae family having identical properties. Despite the abundance of areca palm in South East Asia and the Pacific region, its fiber has not still attracted much attention and is presently being less used than other palm tree fibers [19].

It has been found that less substantial research has been conducted with regard to the optimization of surface treatment, production technique, and application of areca fiber as a reinforcing material in composites. At present, very little literature is available on areca fiber used as reinforcement in composites, which implies that in spite of its innumerable merits, the fiber is at present used less. The fiber enjoys merits like recyclability; renewability; sustainability; economy; wide availability; high-potential perennial crop; inherited qualities; superior properties; mechanical properties that compare well with those of other fibers like kenaf, jute, and coir; and also complete biodegradability [29]. Statistics shows that the annual world production of areca nuts is 1,073,000, and approximately 2.5 g of areca husk could be extracted from every areca betel nut [9]. The annual statistics on world natural fiber production shows the least production of areca husk fibers in comparison with other natural fibers, like jute, coir, and kenaf, which could be ascribed to the consumption of betel nuts in the tropical Pacific and Eastern Africa and Asia.

Areca catechu is known by various names like areca palm, areca nut palm, and betel palm. It is also called Pinang in Malaysia. *A. catechu* is found largely in the tropical Pacific, Eastern Africa, and Asia, particularly in Malaysia, Philippines, India, and Sri Lanka. As per the statistical data provided by the Food and Agriculture Organization of the United Nations, India, Myanmar, Bangladesh, China, and Indonesia are considered the major producers of betel nut [30]. Sri Lanka and India are the two countries where *A. catechu* trees are well grown, and the people of these countries use betel nut as a complement to betel leaves smeared with limestone paste [31]. But betel nut fibers are used as housing insulation material in a traditional way in certain countries [32]. Areca fruit finds a number of medical applications that include dental implants, drugs for wounds, healing of sores, diphtheria, heavy menstrual blood flow, diarrhea, and ulcers [33]. On the other hand, biodegradable disposable plates are made from areca leaf sheaths, which fall naturally from the trees, or green waste. As the use of plastic is banned in India, areca plates are widely used. Besides India, other countries including China, Vietnam, Ukraine, Sri Lanka, Malaysia, and the United Arab Emirates manufacture these plates.

The areca tree can reach a height of 10 to 20 m, with an erect stem that is single and thin, having a diameter ranging between 10 to 15 cm with impressions of annulated scars of fallen leaf sheaths or fronds.

The leaves span a length between 150 and 200 cm; having many pinnate-shaped leaves, the upper part normally shows 8 to 12 fronds. Fully grown areca trees measure up to 15 m. But the conditions of soil mainly influence the growth of such trees [34, 35]. *A. catechu* is a monocotyledonous plant that belongs to the species of the *Areca* and plant family of *Arecaceae* or *Palmae* [36]. It relates to the species of oil palm, date palm, coconut palm, and others. On the whole, the plants from the Palmae family can be considered tropical trees, shrubs, and vines, normally with a tall columnar trunk, bearing a crown of huge leaves. Many investigations have been carried out on the use of plant fibers extracted from the plant family. They point to the prospect of *A. catechu* fibers to be used as an option as reinforcement in natural fiber-based composites [37–40].

2.1 Thermal properties of areca fibers

In the design of natural fiber composites, thermal stability is considered crucial. It can decide the selection of compatible processing techniques for fibers and composites. Hence, thermal properties act as a guideline during the entire design process and prevent the temperature from rising above the degradation temperature of the fiber, since it could decrease the performance of the fibers and the composites.

The fiber is found to be thermally stable up to 230°C, as evinced by lack of weight loss after the minor loss caused by moisture evaporation. Beyond this point, there is occurrence of polymerization and degradation processes of hemicelluloses and cellulose up to 330°C. Analysis of the DTG curve shows small peaks at 273.4 and 325.8°C and reveals the pyrolysis, decomposition, and degradation of hemicelluloses and cellulose. It is found that the kinetic activation energy for areca fibers falls in the range set for natural materials.

The value is indicative of areca fibers possessing excellent thermal stability, which permits it to undergo the polymerization process in the production of composites. At a temperature of about 325°C, the burning of fiber has been evinced, which is a reasonably high temperature for polymer processing to manufacture composites.

2.2 Mechanical properties of areca fiber

Single fiber tensile testing has been used to evaluate the mechanical properties and provide some basic information necessary for the design of the potential use of plant fibers. Areca fibers have been compared with coir and palm leaf fibers with regard to the mechanical properties, particularly tensile strength. This could be attributed to its high crystallinity index and spiral angle. Considering application in reinforcement, the greater strain and low modulus of areca husk fiber offer superior toughness. The results indicate that areca fiber can substitute reinforced polymer composites, similar to other representatives from the family of *Palmae/Arecaceae*.

On the other hand, chemical modification also determines the mechanical properties of the fiber. The untreated and alkali-treated fibers in selected concentration and weight have been characterized, and the changes undergone by the removal or minimization of non-cellulose components, like hemicellulose, lignin, and wax pectin, and other impurities from the fiber surface have been described [41–43]. The modification results in surface roughness and fibrillation due to the exclusion of cementing materials that lead to improved mechanical properties of the fiber reinforced composite [42]. 5% alkali-treated fiber has been found to exhibit the greatest tensile strength and modulus based on tensile characterization of untreated and treated areca leaf stalk fibers. This could be attributed to the disruption of hydrogen bonds in the fiber network. But a reduction in tensile strength has been observed with a rise in alkali concentration above the optimum. The tensile strength of individual fibers has been enabled by the increase in the pores and pits on the surface of fibers. Also, benzoylation treatment is found to yield better tensile properties in comparison with the alkali-treated and untreated short areca sheath fibers. The FTIR studies reveal that the absorption of alkali and benzyolation treatments have decreased the (−OH) groups compared to in the case of the untreated fiber, due to the removal of hemicelluloses. Further, the presence of phenyl nucleus has been noticed, while the C − H deformation from lignin confirmed its removal, and the aromatic ring associated with the C − O bond demonstrated the removal of hemicellulose and pectin.

3. Fabrication of natural fiber reinforced composites

3.1 Composites reinforcement of the fibers in the polymeric matrix to improve strength, stiffness, and fatigue resistance

A number of conventional methods have been adopted for the production of natural fiber reinforced composites. Among these, the pultrusion technique is apt for pulling continuous fiber rovings through a resin bath by using a puller. But filament winding is suitable for the product in the circular form of continuous fiber roving drawn through a resin bath by a puller. In the case of hand lay-up or wet lay-up, each layer of fiber is wetted by the resin with a roller to consolidate. It is an open molding process. A closed vessel or pressure gradient is used in an RTM, for streaming and then soaking with reaction resin the long or woven fibers. In the case of natural fibers, compression molding can be used, with fibers that are continuous or discontinuous, accompanied by temperature, pressure, and high volume. For preparation of thermos-setting resin, sheet molding compound (SMC) and bulk molding compound (BMC) have been commonly adopted, whereas glass mat thermoplastic (GMT) has been adopted in the case of thermoplastic polymer. Injection molding can be adopted in the preparation of polymer composites using short natural fibers in particle or powder form. The molten composites are injected into the mold, which is ejected after cooling. The fabrication selection of natural fiber reinforced polymeric composites is chosen on the basis of a few factors considered.

Very little research has been reported on the areca fiber reinforced polymer composites. Such composites are made by areca fiber reinforced polyester through utilization of hand lay-up, cured for 1 day at room temperature [37]. Compression at a temperature of 115°C for 30 min is used for the production of areca fiber mats with PLA laminate composites [44]. But hand lay-up has been used for 300–325 μm fabricated areca fiber reinforced vinyl ester resin and oven-cured at 80°C for 2 h [45]. The areca fiber reinforced polypropylene composites have been prepared by extrusion and hot molding press [46].

3.2 Mechanical properties of areca reinforced polymeric composites

The mechanical properties of areca reinforced polymer composites with different fiber loading and matrixes have been determined. The influence of adding untreated and treated betel husk fibers, in various percentages, to polypropylene composites has been studied [46]. The findings reveal that tensile, bending, and impact properties have been excellent with 30 wt% fiber loading. Hence, the formulation has been selected for further study, comprising washing with detergent and alkali for surface treatment. In comparison with untreated and detergent-washed fibers, alkali-treated fiber showed excellent properties. However, a 40 wt% areca husk fiber reinforced unsaturated polyester composite has been observed to give enhanced mechanical properties. On the other hand, a rise in the fiber loading resulted in fiber pull-out and debonding and decreased the load-bearing capacity of the composite. It has been found that chemically treated areca reinforced composites showed better mechanical properties, like tensile, flexural, and impact strength [47]. It can be described on the basis that the chemical treatment removes impurities, like pectin, fat, and lignin, from the natural fiber and subsequently improves the fiber-matrix bonding and enhancement in the mechanical properties of the composite. Also, regression studies carried out to assess the mechanical properties of untreated and treated short areca sheath reinforced polyvinyl alcohol (PVA) thermoplastic matrix have shown that 27 wt% fiber loading reveals optimum mechanical properties. It is found that benzyl chloride treatment is the perfect alternative to the various prospects of surface treatment in the case of areca sheath fiber [48]. Also, the influences of various chemical modifications in removing impurities (pectin, fat, lignin) from areca husk fiber at different compositions have been further used in polypropylene for enhancement of its mechanical properties. The results strengthen the fact that caustic, potassium permanganate, benzoyl chloride, and acrylic acid treatments improve the mechanical properties of the fibers. Depending on the studies of flexural, tensile, and impact strength properties, it has been observed that the 60 wt% fiber formulation gave the greatest values in flexural and tensile testing, whereas the 50 wt% fiber formulation showed the best effects for impact strength. The treatment with acrylic acid has been observed to be the most suitable chemical modification and has been the most effective in improvement of the tensile, flexural, and impact properties of the areca husk fiber reinforced polypropylene composites. Also, the physical, mechanical, and thermal properties of betel nut husk fibers extracted from raw fruit and used to reinforce an epoxy matrix have been studied.

Fiber percentages of different concentrations have been incorporated into the composites, and it has been found that 5% fiber loading yielded the highest tensile strength and hardness. It has been found that there is a degradation of thermal and mechanical properties at excessive fiber loading of 8% fiber content. It is caused by a lack of interface bonding between fiber and matrix that created a disruption in load transfer. It is observed that the incorporation of 10 wt % betel nut husk fiber in a vinyl ester matrix considerably decreased the flexural strength and also added to a high increment in the tensile and impact properties, mainly for the fiber extracted from raw and ripe areca fruit. In the case of matured fruit, the tensile and impact properties of the extracted fiber have been found to be lower in comparison with the matrix, due to the presence of high lignin content, which influenced brittle fracture.

However, composites have been designed on untreated short areca sheath fibers with varying proportions of fiber weights of fiber reinforced polypropylene composites, using hot and cold compression molding, and it has been observed that the

10 wt% fiber formulation gave excellent tensile strength and the best weathering resistance for the formulations investigated. Likewise, random fiber orientation with the hand lay-up method has been used to prepare the 30 vol% untreated areca sheath fiber reinforced epoxy resin composites, so as to assess the flexural strength by 3- and 4-point bending tests. The findings have been validated by the numerical simulation method.

The formulation is useful for end uses that need less load bearing structural and non-structural capacity [49]. The compatibility of areca fiber and the matrix has been studied, and it has been reported that the interfacial bonding and adhesion bonding between the fiber and the matrix can result in better mechanical properties and good stress transfer.

Just as other natural fibers, areca fiber also exhibits certain demerits, particularly with reference to compounding difficulties owing to the inherently polar and hydrophilic nature of the fiber that results in non-uniform distribution, thus weakening the properties of the composite. During the production of composites, the fiber degradation that occurs at the processing temperature of the matrix imposes another practical constraint. Fiber wettability is another aspect to be considered, which affects its compatibility with the matrix. The surface tension and matrix viscosity are determined by wettability.

Hence, it is imperative that the surface tension of the reinforcing fiber exceeds that of the matrix so as to maintain the interfacial strength. The other aspects to be taken into account are low microbial resistance and susceptibility to rotting so as to attain the successful preparation of a long-lasting composite. The bonding of the fiber matrix and surface wetting gets affected due to the natural waxy substance on the surface of the fiber [50].

3.3 Areca-based hybrid composites

The hybridization of different fibers, of natural or artificial origin, that are reinforced in a same polymer matrix results in a hybrid composite. In the case of reinforced polymer composites, the hybridization of areca fibers with other fibers has been considered in this case. Compression molding has been used for the production of hybridization of areca husk-coir fiber reinforced unsaturated polyester and areca husk-sisal fiber reinforced epoxy composites [51, 52]. On the other hand, the hot press method has been adopted to produce areca husk-glass fiber reinforced polyethylene composites.

3.4 Mechanical properties of areca-based hybrid composites

Explanation has been provided regarding the hybridization of areca fibers with other fibers for the manufacture of reinforced polymer composites. Compression molding technique has been adopted in the hybridization of areca husk-coir fiber reinforced unsaturated polyester and areca husk-sisal fiber reinforced epoxy composites [53]. On the other hand, the hot press method has been adopted in the production of areca husk-glass fiber reinforced polyethylene composites. Taking into account the drastic rise in the number of plastic wastes, which create an adverse effect on the ecosystem, environmental considerations have prompted a push in bio-composite studies. Studies have been conducted on the tensile, flexural, impact, and hardness of composites made by 20 wt% natural fiber loading comprising 10 wt% caustic-treated areca fiber, coir fiber, or a mixture of both dispersed in a polyester matrix.

The hybridization of natural fibers to reinforce polymer composites results in improved mechanical performance, in comparison with individual fiber-based polymer composites [54]. But it has been observed that, in certain instances, individual fiber-based polymer composites have shown superior mechanical properties as compared with hybrid composites because of the micromechanical behavior of the individual components of the reinforcement [55]. The areca husk reinforced polyester composites have been observed to be superior in comparison with hybrid areca/coir fiber reinforced polyester composites. Another research reported on 5% caustic treated areca fiber hybridized with glass fiber, in selected proportions, having 20% fiber loading in a thermoplastic matrix of polyethylene, and it has been investigated so as to study the effect of surface modification on the physico-mechanical properties of the composite. Depending on the comparison with the properties of polyethylene considered as a standard test sample, it has been found that the tensile and flexural properties have considerably improved for the formulations having selected proportions. The areca fiber coated with caustic showed a considerable enhancement in mechanical properties. With the rise in proportion of the glass fiber three times, it showed an improvement in tensile strength, Young's modulus, flexural strength, and hardness but not in impact energy.

A work has reported on a study of the tensile, bending, and impact testing results for hybrid areca and jute reinforced epoxy composites, made with the hand lay-up method and consisting of a tri-layer, having areca fibers as surface layers and jute as a central layer. The tensile and bending strengths obtained at different levels, with epoxy LY 556 as the control specimen, have shown that the hybridization of areca and jute, with the epoxy matrix, considerably decreased the tensile and bending strengths of the composites.

However, work has been carried out on the hybridization of areca husk and sisal fiber, with a similar kind of epoxy, and it is observed that there is a slight decrease in tensile strength. However, there has been drastic rise in the flexural strength. It has been observed that there is a rise in the tensile and flexural strengths due to an increase in the content of betel nut fiber rather than that of sisal fiber. The effect of chemical modification with NaOH for composites comprising 20% areca frond, 20% sisal, and 60% of the same epoxy has been studied, and the findings show that the caustic-treated composites have revealed improved mechanical properties, like tensile and flexural strength, absorbed energy, and hardness, in comparison with the untreated specimen [56]. It has been observed that the entire spectrum of the composite properties is considerably influenced by the fiber content [57].

4. Evaluation of mechanical properties

Despite the modulus being dependent on the fiber properties, the tensile strength is sensitive to the grid properties. It is necessary to have a solid interface, low anxiety fixation, and fiber introduction so as to improve the strength. On the other hand, the elastic modulus is determined by fiber concentration [5–7, 58].

For certain tribological uses, treated betel nut fiber reinforced polymer composites have been regarded better in comparison with chopped strand mat glass fiber-reinforced polyester; betel nut polyester composite possesses mechanical properties identical to those of the glass-polyester composite. Thus, betel nut fibers possess a great prospect to replace glass fibers and for small load applications [59–61].

With regard to the high tensile strength applications, chemically treated areca fiber reinforced natural rubber composite, and also uses related to high dimensional stability, low-density property of raw betel nut husk fiber is used for lightweight applications [60–62]. Natural fibers have economy and biodegradability, can be reutilized, and are eco-friendly materials. Natural fibers can be a better choice over glass and carbon fibers owing to their eco-friendliness and biodegradable nature. Betel nut and *Sansevieria cylindrical* in PP (polypropylene) composites have found applications where strength and cost considerations are important [63].

Likewise, areca fiber and maize powder reinforced PF composites have been used in packing industries, low-cost housing, and domestic uses [64]. Areca sheath fiber is used in structural and non-structural areas like suitcases, post boxes, grain storage, automobile interiors, partition boards, and indoor uses [65].

4.1 Uses

From the aforesaid explanations, uses of naturally available, eco-friendly, renewable and reproducible, nontoxic, economical, and easily available reinforcing material (areca/betel nut fibers) composites, it can be summarized that areca fiber offers a good alternative for wood in indoor uses, and the following points have been listed that are present in the literature. Due to a rise in the volume fraction of fiber in the composite, there is a rise in dielectric strength of betel nut (Bn) composites. It is a rather uncommon phenomenon that has not been noticed in a number of natural fiber composites. Hence, based on the availability, cheaper and good dielectric strength of Bn fiber composite can certainly be considered for electrical insulation applications [66]. Further, hybrid composites with Bn and *S. cylindrica* in EP can be used in diverse applications as structural materials.

- Depending on the availability, cost-effectiveness, and good strength of areca fiber composites, they are utilized in the design of lightweight materials that are used in automobile body building, office furniture packaging industry, partition panels, and others compared to wood-based plywood or particle boards [67–69].

- Due to better outcomes with regard to wear of treated betel nut fiber reinforced polymer composites (T-BFRP) (98%) in comparison with chopped strand mat glass fiber reinforced polyester (CSM-GFRP) under dry and wet states, T-BFRP composite holds promise in certain areas of tribological uses.

- With regard to mechanical properties, the betel nut polyester composite is identical to the glass-polyester composite, and thus, betel nut fibers offer a very good substitute for glass fibers in mechanical end uses. Also, betel nut fibers offer superior support to the polyester matrix than other types of natural fibers.

- In the case of end uses related to a small load bearing, investigations have been conducted on caustic-treated areca fiber composites, which have been found to have enhanced mechanical properties to a certain extent in the areca fibers.

- In the case of end uses requiring high tensile strength, chemically treated areca fiber reinforced natural rubber composites have been considered.

- For end uses requiring high dimensional stability, low moisture and water uptake properties of dried BNH fibers are found to be advantageous for various applications, and low-density property of raw BNH fiber is used in applications requiring light weight.

- Certain investigations make it evident that areca fruit husk fibers are useful as a potential reinforcement in polymer composites due to their moderate tensile strength properties, better strength, and bonding properties with rough surface morphology in end uses requiring light weight.

- Hybrid composites with betel nut and *S. cylindrical* in PP (polypropylene) can be used in various areas like structural materials that are dictated by strength and cost aspects.

- In areas such as packing industries, low-cost housing, and domestic purposes, areca fiber and maize powder reinforced PF composite materials can be used as a communicative material for plywood.

- In the case of structural and non-structural uses like suitcases, post boxes, grain storage, automobile interiors, partition boards, and indoor uses, untreated chopped natural areca sheath fiber reinforced polymer matrix bio-composites are well adopted.

- In the case of end uses requiring high flexural strength, chemically treated areca fiber reinforced epoxy composites for applications where high impact strength is required, 60% fiber loading was considered.

5. Characterization

Natural fiber reinforced composites are found to offer resistance to electricity, possess good thermal insulating property, and are also resistant to corrosion [70]. It is found that as the volume fraction of the fiber increases, the tensile strength of natural polymer composites increases, as pointed by past research works on volume fraction [71]. It has been shown in the study of the tensile characteristic of the untreated areca sheath composite that the longer the fiber length, more is the strength of the composite. In comparison with untreated areca nut fibers, the fibers treated with caustic exhibit greater mechanical strength [72, 73]. The curing time of the composite also plays a vital role in determining the full potential strength of the composite. Studies have revealed that the strength of the composite increases with the curing time [7]. Investigations have been carried out with regard to other mechanical properties like impact strength, hardness, and flexural strength of the areca fiber composite, considering parameters like the influence of volume fraction, post curing time, and alkali treatment for effective bonding [14, 74]. The flexural strength increases with increase in fiber loading percentage. Fibers treated with caustic show a significant increase in flexural strength for references [8, 9, 68, 75]. Studies show that there is a rise in the impact strength due to the post-curing time, and it has been observed that with the rise in the curing time, the alkali-treated composites turned brittle [10, 57, 76, 77]. The finding aims on the tensile property of the non-chemically treated areca fiber sheaths that are immersed in water, hot pressed, and compressed with a thickness of 2.5 to 3 mm and are widely found in India as areca fiber plates. The study also aims to use this as a reinforcing agent in epoxy polymer composite to study its tensile properties and effects of the different combinations of the orientation angles of the fiber, which influences the tensile property of the composite.

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6. Conclusion

Studies have been carried out with regard to the physical, mechanical, and thermal properties of areca fiber and its composites. The available literature shows that areca fiber holds the prospect for use as an optional reinforcement in polymer composites. On the other hand, it has been found that certain other species from the family of Arecaceae/Palmae have not been studied since natural fiber reinforcement in polymer composites either, hence showing further options of natural alternative reinforcements to be studied in terms of their potential for utilization in fiber-based composites for the automotive, aerospace, and construction sectors. Areca fibers can be used as an alternative natural resource and as a promising reinforcement of polymer matrices to produce lightweight composite structures. Different natural fibers have been used by many researchers for the development of bio-composites, but areca leaf fibers as a feasible fiber have seldom been researched or spoken about.

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