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REVIEW

Recent Developments in Textile Reinforced Polymer Composites

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This article provides an overview of using textile materials as reinforcement in polymer composites. A considerable amount of research studies on this topic have been conducted to date. The different types of textile materials and polymer matrices used in composite development have been discussed. The fabrication techniques used in the development of composites, the properties, testing methods and the specific standards have been critically reviewed. Furthermore, the suitable applications of textile reinforced polymer composites are reviewed. This review highlights the potential of textile materials in polymer matrices as reinforcement for various applications, including automotive, aeronautical, defence, construction industries, *etc*.

Keywords: Textile, Polymer composites, Mechanical properties, Applications.

INTRODUCTION

The invention and development of composite materials have increased man's interest in the better replacement of materials. Composite materials can be defined as a combination of a matrix component and reinforcement to obtain better performance and improved properties than the individual components [1]. Recently, the use of fiber-reinforced polymer composites is steadily expanding in various fields, including constructions, wind energy, leisure, civil infrastructure, sporting, automotive and aerospace [2]. Moreover, these composites are popular due to their simple fabrication methods [3].

The polymer matrix composites are considered as suitable substitutions for conventional materials such as wood, metal and glass because of their properties, including high mechanical properties, high thermal stability and high specific strength to weight ratio [4]. Fiber-reinforced polymer composites with superior properties are developed by combining various reinforcements and matrices [5]. Thereby, the intentional properties for specific applications are achieved. Textile composites are made with textile as a reinforcement and a matrix component. Textile composites are being developed for use in a wide range of engineering applications [6].

According to the literature, the use of natural fiber as reinforcement is not a modern approach. Natural fibers have been in use for centuries [7]. Conversely, with the evolution of high-performance fibers, polymer composites reinforced with synthetic fibers have gained widespread use in various applications. Synthetic fibers which are non-biodegradable, while natural fibers are biodegradable. However, both natural and synthetic fibers are used in composite reinforcements according to their particular application. Recently, due to stringent environmental regulations and sustainability goals, different waste fibers have been attracting more attention because of their low cost, low density, excellent specific mechanical properties and recyclability [8].

Most of the reinforcements used in composite materials are closely related to textile forms such as fibrous reinforcement and textile materials, particularly when the fibrous reinforcement is concerned [9]. Fiber, yarn and fabric are a few widely used textile reinforcement forms in reinforced composites. The term "textile" comprises all kinds of yarns or ropes, all kinds of fabrics (woven, knitted, non-woven), industrial and technical textiles, including geotextiles, medical textiles and textile composites [9].

Textile fiber is the smallest visible element of textile production, which can be classified into two large groups: natural and synthetic. Textile yarn is a long continuous length of interlocked fibers with or without a twist used in textiles production. The textile fabric is a cloth. Generally, textile fabrics are three basic types as woven, knitted and non-woven fabrics. Woven fabrics are typically made with two or more arrangements of yarns that are intertwined at right angles to each other. Woven fabrics have better dimensional strength in both weft and warp directions [10]. Furthermore, the reinforcing phase of a composite is responsible for a considerable extent of the strength of the composites [11].

The knitted fabric comprises interloping yarns in a weft or warp direction. Each method produces various types of knitted fabrics. Non-woven fabric is not woven with a single yarn and knit together but directly through the physical method of bonding together. According to an earlier classification of textile reinforcements, there are four categories of reinforcements, including discontinuous chopped fibers, continuous filament yarns, simple fabrics (2D) as well as advanced fabric (3D) [9]. However, the reinforcement arrangement in the matrix defines the properties of the final composite [12].

With the increasing consumption of clothing items, textile production has increased over the years. Millions of tons of waste are generated annually in the textile and clothing industry. Discarding such massive amounts of waste is a considerable issue faced by the industry. At the same time, it has been identified as one of the most polluting industries globally [13]. Hence, in recent years, increased emphasis has been placed on developing recycling and upcycling techniques to manage surplus or unused textile material [14].

Using waste textile in composite manufacturing is a significant way to address large volumes of waste. It reduces the environmental impact while giving value-addition to the waste. As such, the use of textile waste in composite manufacturing has grown as a substitute for conventional materials. Over the years, attention has been given to the exploration of novel high-performance materials for reasonable prices. Today, textiles produced by braiding, weaving and other various unidirectional techniques are not limited to apparel manufacturing but are also used in composite manufacturing because of their excellent mechanical properties.

Numerous works on the fabrication of textile composites have been published in the literature. This review article focuses on the recent developments in textile-reinforced polymer composites. The article details textile materials used as reinforcements, matrix materials used in textile reinforced composites, processing techniques of the textile composites and properties that have been tested. Different applications of textile composites were also considered to establish an understanding of the direction of future work. This review article examines the highlights and recognizes gaps in the earlier studies related to natural and synthetic textile composites. It gives valuable tabulated data for future research in various fields where textile reinforced composites are considered.

Reinforcements used in textile reinforced polymer composites: In literature, various types of textiles have been used as reinforcement in composite development. Recently, with the increase of environmental awareness, researchers have been encouraged to use natural fibers as reinforcement in composites instead of synthetic materials [15,16].

Natural fibres as reinforcements: In a study, researchers have developed composites using flat knitted cotton spacer fabrics [17]. Spacer fabrics are obtained by weaving or knitting. They have assessed the impact of fabric crosslink shape on the mechanical performance of the developed composites. In order to obtain biodegradable composites, some researchers have used both reinforcement and the matrix from biodegradable sources. For example, wool textile fibers reinforced biodegradable polyester based composites have been developed in a previous study [18].

For fique textile fiber reinforced polymer composites, both experimental testing and numerical modelling for the flexural behaviour have been conducted previously [19]. Fique fibers woven configurations are used in another study. They determined the tensile properties of the composites and compared the experimental data with numerical modelled results [20]. Flax textile fibers are now widely used to reinforce polymer composites. Studies report composite manufacturing with flax-fabric with 3 × 3 twill weave fabric without any surface treatments [8]. In another research, the researchers appraised six types of fabric reinforcements, including two quasi-unidirectional fabrics and four balanced twill fabrics made from flax, woven fabrics collected from the linen textile industry [21].

Commercially available flax and hemp fiber textiles are surface treated and used for composite development with epoxy. The study shows that the acetone dipping treatment, alkali treatment and laundry detergent washing treatment improve the tensile strength of the composites. Polysilazane treatment and PVA coating of fibers reduce the tensile strength of the composites [22]. Composites reinforced with hemp spun yarn have also been carried out successfully [23]. Twill and plain woven hemp fabric have been used as reinforcement composites since hemp is a fibre with excellent mechanical properties [10]. However, it is important to note that fabric reinforcements are preferred for higher mechanical properties than fiber reinforcement [24].

Hemp fabric reinforced polyester composites have been developed in a previous study with surface treatments. Fiber surface treatments have been carried out using alkalization, silane and acetylation to increase fiber-matrix adhesion properties. This study concluded that alkali-treated hemp fabric reinforced composites show better mechanical properties than the other composites [25]. Yan *et al*. [26] studied the effect of alkali treatment of flax fabric/epoxy composites on mechanical properties. Alkali treatment is one of the most used treatment methods used to increase surface roughness [27]. Miller [28] studied composites reinforced with three kinds of continuous bidirectional woven natural fiber textiles. These three textiles include strongly woven hemp linen, a lightly woven hemp burlap and a jute burlap. In another study, the authors investigated the use of plain-woven jute and sisal fabrics composites with PLA and PP matrices and compared the properties with glass fabric reinforced composites using the same matrices. When considering the results, the mechanical properties of PLA composites are higher than PP composites. Sisal composites have shown higher mechanical properties than jute composites. Both sisal and jute composites had inferior mechanical properties compared to their respective glass fiber composites [7].

A study investigated unsaturated polyester composites reinforced by jute/cotton hybrid woven fabrics and their properties as a function of fiber alignment and roving fabric features. The researchers concluded that jute fiber endorses a more significant reinforcing effect while cotton fiber prevents catastrophic failure [29]. Sen & Reddy [30] have developed natural jute textile reinforced polymer composites and compared the properties with glass and carbon fiber-reinforced polymer composites. They have carried out experiments on strengthening reinforced concrete beams with textile wrapping using natural jute fiber textile composite. The results show the jute fiber reinforced polymer composites have potential in the structural strengthening of materials. In another study, woven basalt fiber reinforced epoxy composites have been compared to the woven glass fiber reinforced epoxy composites. The study suggests the possibility of replacing glass fiber composites with basalt epoxy composites in the design of aircraft secondary structures [31].

Synthetic fibers as reinforcements: Although environmental concerns have given rise to the development of composite materials with biodegradable materials, synthetic fibers in composite reinforcement are still very popular. Many studies have been conducted on polyester textiles reinforcements in textile composites [24,32,33]. In one study, three types of woven fabrics made with polyester yarns were used as the warp threads while glass fibers, flax fibers and nylon 6,6 fibers were used as the weft yarns respectively. Furthermore, 100% polyester non-woven fabric was used in the same study for composite development [32]. Spacer fabrics produced with polyester yarns also have been used in composite development [34].

Earlier studies revealed that the nylon textiles can be used for reinforcement by cutting continuous nylon fibers into staples. They have analyzed the effect of nano-silica on developed nylon/PP composites. The study shows that nylon/PP composites can be reinforced effectively with nano-silica. And this incorporation of nano-silica has improved the mechanical properties [35]. Another study has used nylon and silk plain woven fabrics as reinforcement materials in elastomeric composites. Developed eco-friendly silk textile reinforced natural rubber composites have shown better properties compared to the synthetic nylon textile reinforced natural rubber composites [36]. Furthermore, waste nylon/spandex offcuts collected from the textile industry have also been used as reinforcement in heat insulation materials made with thermoset polyurethane matrix [37].

Another attempt has been made to use polyamide 6 (PA_6) matrix with plain and satin woven fabrics in composites development [38]. In another study, composite plates were made with textile material obtained from recovered short fiber comprising 85% PNA (polyacrylonitrile) plus 15% PA (polyamide) or PE (polyester) fiber. They developed four different materials with two fabric layers and one layer from the one of other materials including cork, polystyrene and polyethylene. They have assessed the sound absorption performances of these composites [39]. 3D woven fabric waste has also been used to reinforce the composites. Two types of fabrics have been used to develop the composites and the properties have been compared. Thereby, normal cotton and garnetted waste cotton has used [40].

Since textile waste occupies around a considerable percentage of landfill space, the utilization of textile waste in the composite industry is a significant approach. Several studies have used textile waste as reinforcement in composites to give an alternative solution to the global textile waste crisis. Umar *et al.* [41] used cotton-woven fabrics as reinforcement, where the warp yarn of all the reinforcements was cotton and weft yarn was also cotton produced from fibrous textile waste. This waste has been obtained from two various sources such as knitting waste and comber noil waste from spinning [41]. Although using cotton fibers as reinforcement in composites provides many advantages, the composites usually have weak mechanical properties [42].

In another study, waste cotton reinforced LDPE composites was developed and the effect of different treatment methods have been analyzed. Five different chemical treatments have conducted such as alkaline treatment, silane treatment, alkali-silane, maleic anhydride and alkali-maleic anhydride. It could be observed that the most effective coupling agent is maleic anhydride for the developed composites [43]. Another study has focused on the development of eco-friendly composite materials from wool textile waste and biopolymers [44].

Previous work [45] has reported the conversion of textile bulk waste, collected from the local municipal solid waste and industrial waste streams into fiber fleece to be used in composites. The mixed textiles comprised primarily of cotton, wool, polyester (PE) and nylon fibers. A fine mixture of randomly oriented fiber fleece was achieved and utilized in its dry raw state and no pre-treatment has been applied. Literature also reports using a mixture of materials to develop hybrid composites. When considering polymer composites, hybrid composites are those that consist of one reinforcing material with a mixture of matrices or two or more reinforcement fibers with a single matrix component. In some cases, both of these approaches may be combined [46]. Arun *et al.* [47] used silk-based textile fabric (12-16 µm of fiber diameter) to make a hybrid composite together with plain weave e-glass fabric (10-12 µm of fiber diameter).

Accordingly, a study has focused on making glass fiber/waste cotton fabric-reinforced hybrid composites to evaluate the effect of hybridization effect on the composite properties. They used shredded cotton waste fabrics and analyzed the effect of maleic anhydride coupling agent on glass-waste cotton hybrid LDPE composites. The mechanical properties have been increased with the addition of the coupling agent [46,48]. The researchers have used the chopped (size of 15 mm × 15 mm) waste cotton fabric to reinforce the composites to obtain homogeneity of the reinforcement in the polymer matrix [46].

Experiments on wool yarn waste reinforcement for a hybrid composite with tetra pack packaging waste have conducted recently. The properties of the developed composites have been compared with commercially available wood particle boards.

The results have shown the developed composites have comparative properties with the commercially available wood particleboards [49]. As a different approach, woven jute fabric reinforced polyester composites have hybridized with woven carbon fabric and fishbone powder [50].

A recent project has focused on using pre-consumer cotton textile wastes including cutting waste in garment manufacturing and rejected fabrics collected from the textile and apparel industry, as a shoddy web for the reinforcement. Collected pre-consumer cotton textile waste was processed in the rag-tearing machine to extract the fibers. The extracted fibers from the waste textiles are called 'shoddy' [51]. In another study, textile waste fibers consisted of a minimum of 70% cotton content from a garment recycling company that had been used as reinforcement [52]. Waste alpaca fiber reinforcement has been experimented with by another group of researchers. They converted the alpaca fibers into powder using a mechanical milling method without applying any chemicals [53].

Matrices used in textile reinforced polymer composites: Various matrix materials, both thermoset and thermoplastics have been used in textile composites. Thermoplastic polymers are those which can be softer when heated and rigid when cooled [54]. Different types of thermoplastic matrices could find such as LDPE, HDPE, PP, PLA and PHBV. Several studies have used low-density polyethylene (LDPE). The matrix element has used in the granular form [42,43,46,48,55]. In another study, pure high-density polyethylene (HDPE) has been used [56].

In the literature, there are several examples of PP matrix used in textile reinforced composites [8,14,35,40,45]. Another study has used PP and PLA thermoplastic matrices in sisal and jute textile composite manufacturing. The study shows the composites made with PLA show better mechanical properties compared to the respective PP composites. Also, PLA composites were less flammable than the respective PP composites [7]. For the development of thermoplastic composites, polylactic acid (PLA) has also been used as a biodegradable polymer matrix [10,57]. Ecovio® F Blend C2224, a blend of PLA and PBAT with a ratio of 55/45 wt. % has been used in another research [58]. PLA and PBAT are the biodegradable thermoplastic polymers, where PBAT is used to modify the brittleness of PLA by melt blending. The thermoplastic matrices PLA [7,23] and PA_6 microparticles are also found in the literature as the polymer matrices used in composite development [59].

Miller [28] has used the thermoplastic PHBV polymer matrix. A renewable bio-based polymer PHB has been used in composite development with bidirectional woven hemp fabrics [60]. Discarded cotton/PET (50:50) fabrics have used to develop composites with thermoplastic copolyester/polyester bicomponent fibers as the matrix [61]. The bicomponent fibers are defined in the literature as extruding two polymers from the same spinneret with both polymers contained within the same filament [62].

Studies have conducted on textile reinforced polymer composites with thermosetting matrices such as polyester, epoxy and phenolic. These polymers are irreversibly hardened on heating [63]. Various studies have also been conducted using various resins and hardeners. Researchers have used unsaturated polyester resin for the matrix component [17,33,41,64]. Cobalt naphthenate as the hardener for curing and methyl ethyl ketone peroxide as the accelerator for speed up the cross-linking has been used with unsaturated polyester resin [41]. To continue the unsaturated polyester resin in the liquid state. Turki *et al.* [17] used styrene solvent and organic peroxide have used as the curing agent (1 to 2% of resin volume).

However, most of the time various types of epoxy resins have used. For example, epoxy acrylate resin with curing agent methyl ethyl ketone peroxide (MEKPO) [22], a medium viscosity epoxy resin (LAPOX L-12) and its curing polyamine hardener (K-6) [47], thermoset epoxy resin R744 [19,20], epoxy resin Z-1 and its curing agent 20 [51], Huntsman Araldite LY 1564 epoxy with its hardener Aradur 3486 [24] were used in different studies.

Other studies reported using epoxy resins as well [31,50, 65-67]. Another research group has used polyester resin with two additional constituents; the catalyst (methyl ethyl ketone peroxide) and the accelerator (cobalt naphthenate) and epoxy resin in the form of Kemapoxy 150 which is found in form of two constituents; resin and hardener [32].

Mbrace saturant, an epoxy encapsulation resin used as a composite strengthening system, has also been reported in the literature [30]. Thermosetting standard bifunctional resin based on diglycidyl ether of bisphenol A (DGEBA) was also used in a previous study. This study has used an amine hardener and an accelerator based on polyamine hardener with the resin [21]. Few studies were also conducted on textile-reinforced elastomeric composites. For example, Dong *et al.* [68] used silicon rubber for the matrix with polyester fiber reinforcement. Smitthipong *et al.* [36] used whole natural rubber (from *Hevea brasiliensis*) and purified natural rubber as the different matrices with silk and nylon textile reinforcements.

Processing techniques used for textile reinforced polymer composites: In the literature, there are several methods have used for the development of textile reinforced composites. Some studies have used injection molding [35,56,69]. Injection molding provides a low cycle time and high precision for the developing composites. It is also very effective for the thermoplastic matrices. Some studies have used the vacuum bag molding technique at a vacuum pressure of -1 bar [41]. Usually, this process is conducted with the assistance of a hand lay-up technique. The preforms are made with hand lay-up and placed between the vacuum bag and the mold. The air between the vacuum bag and mold is drawn using a vacuum pump [70]. In another study, two different methods have been used to fabricate the composites: hot platen press and autoclave methods [21].

Several researchers [17,30,32,47,71,72] have manufactured textile reinforced composites with hand layup technique. In this hand lay-up method, the fiber preforms are placed in a mold and the resin is applied using hand tools like brush and roller. The roller forces the resin into the reinforcing fabric to develop a better interaction of fiber and matrix [73]. Several authors [42,46,48,74,75] have also used the extrusion method using a single-screw extruder. In extrusion, the polymer material is fed into the extruder in the form of pellets. This process is mostly used for thermoplastic polymers. But thermosets and elastomers may also be used in extrusion [76].

Vacuum-assisted resin infusion molding (VARIM) has been another manufacturing technique [24]. Several authors have also mentioned using the vacuum-assisted resin transfer molding (VARTM) technique [22]. The VARTM is popular because it does not allow air to remain in composite structures [77]. Two studies also reported a usage of modified VARTM technique [64].

However, most of the studies have been published on using a compression mold with a hot press [7,10,33,45,49-52,78-80]. The compression molding technique has used most frequently because it provides a short cycle time, is automated with dimensional stability and has higher productivity. This method is mostly used in developments in the automotive industries [81].

The composites have categorized according to the thermoplastic and thermoset matrix, which are shown in Tables 1 and 2, respectively. The textile type used as the reinforcement, polymer matrix material and used fabrication method have mentioned.

Properties tested for the textile composites: Researchers have tested different properties in textile reinforced composites to identify the suitability of materials for a wide range of applications. The most commonly tested properties, test methods and International standards used for testing the composite shave are shown in Table-3.

In addition to the commonly tested properties in Table-3, several other properties are also found in the literature. In a study on the photostabilizer additives on the textile fiber reinforced polymer composites, authors have conducted a colour measurement test following ASTM D 2244 using a Data Color 3890 spectrophotometer [42]. In terms of mechanical properties, in addition to the tensile and flexural properties, a group of researchers has tested internal bond strength on EN 319 [49].

For the chemical characterization of raw materials used in composite manufacturing, ICP-MS-IC has also been used [45]. Since the researchers have added wood as a secondary filler, they have used ASTM D 1037 to test flexural properties by three-point bending test [45]. For chemical characterization of natural rubber in silk textile fiber-reinforced elastomeric composites, researchers have used a nitrogen content analysis and lipid content analysis by Kjeldahl method and extraction methods, respectively. In the same study, dynamic mechanical thermal analysis (DMTA) has been conducted in a single cantilever mode [36].

For the analysis of the mechanical properties of glass and silk-based textile hybrid composite made with epoxy matrix, a research team has used Edge notched tensile test (ASTM E 1922) and short beam bend test (ASTM D 2344) [47]. In another study, the air permeability of polyester spacer fabrics has been tested. Further to this, the atwise compression test, exural test as per the ASTM C 393, drop weight impact test as ISO 6603 and ISO 7765 has been conducted [64]. In order to understand the effect of cotton fibers on the flow in waste cotton reinforced LDPE composites, the melt flow index (MFI) analysis has been conducted according to the ASTM 1238 [55]. Rheological analysis using a rheometer has been conducted in previous studies [53,55].

Woven basalt/epoxy composites have been tested for tensile and shear properties following ASTM D 6856 [31]. To measure the void content of flax/PP composites density measurement & micrographic image analysis were done [8]. Grab test (ASTM D 5034) is also mentioned in the literature to analyze the mechanical properties [38,79,95]. The fiber

TABLE-1
TEXTILE BASED THERMOPLASTIC COMPOSITE

Textile type	Matrix	Fabrication method	Ref.
Cotton	LDPE	Extrusion	[42]
Cotton, wool, acrylic, polyester, polypropylene, nylon & elastane mixture	PP	CM by hot press	[45]
Silk and nylon	WNR & PNR	CM by hot press	[36]
Cotton	LDPE	Extrusion	[55]
Glass/cotton hybrid	LDPE	Extrusion	[16]
Cotton	PP	CM by hot press	[14]
Silk and cotton	PA_6	Injection molding	[82]
Cotton	LDPE	Extrusion	[48]
Cotton	PP	CM by hot press	[40]
Cotton	LDPE	Extrusion	[43]
Natural textile	HDPE	Injection molding	[56]
Wool	PP	CM by hot press	[83]
Hemp	PLA	CM by hot press	[10]
Hemp	PHB	CM by hot press	[84]
Hemp	PLA	CM by hot press	[23]
Manicaria saccifera natural fabric	PLA	Extrusion	[75]
Nylon	PP	Injection molding	[35]
Jute	PP	CM by hot press	[85]
Conventional woven fabrics (plain, satin) and a novel stitched plain textile structure	PA_6	CM by hot press	[86]
Hemp & jute	PHBV	CM by hot press	[28]
Woven jute & sisal	PP & PLA	CM by hot press	[7]
Cotton	Blend of PLA & PBAT	CM by hot press	[52]

TABLE-2
TEXTILE BASED THERMOSET COMPOSITE

Textile type	Matrix	Fabrication method	Ref.
Cotton	Polyester	Vacuum bag molding	[41]
Polyester	Epoxy	VARIM	[24]
Hemp	Polybenzoxazine	CM by hot press	[78]
Flax	Epoxy-DGEBA	Hot platen press & autoclave	[21]
Polyester	Polyester	CM by hot press	[87]
Satin weave	Epoxy	VARI	[88]
Nylon/spandex	Polyurethane	CM by hot press	[37]
Polyester	Polyurethane	CM by hot press	[89]
Flax	Epoxy	Hand lay-up	[71]
Silk	Epoxy	Vacuum driven resin transfer moulding	[90]
Flax and glass	Epoxy	Hand lay-up	[91]
Polyester	Polyester	CM by hot press	[33]
Cotton	Polyester	Hand lay-up	[17]
Glass-polyester fabric blend, Nylon-polyester fabric blend, Flax-polyester fabric blend	Polyester or epoxy	Hand lay-up	[32]
Buriti leaf fibers	Epoxy-DGEBA	Mold in oven	[66]
Oil palm EFB, jute	Epoxy	CM by hot press	[92]
Jute, carbon	Polyester	CM by hot press	[50]
Flax	Epoxy	Hand lay-up	[72]
Flax & hemp	Epoxy acrylate	VARTM	[22]
Jute fiber	Mbrace saturant (epoxy encapsulation resin)	Hand lay-up	[30]
Glass, silk-based textile	Epoxy	Hand lay-up	[47]
Cotton shoddy web	Epoxy	CM by hot press	[51]
Polyester-3D knitted spacer fabric	Polyester	Modified VARTM	[64]
Woven basalt & woven glass	Epoxy	Wet hand lay-up	[31]
Flax fabric	Epoxy	Direct impregnation in a closed mold	[8]

volume fractions of the composites have been determined with ASTM D 3171 and the density of the composites has been determined by the Archimedes principle [28].

Applications of textile composites: Recently, using textile reinforced polymer composites in various areas has become a trend due to their comparative properties to conventional materials. One of the most trending applications with textile reinforced polymer composites is construction building materials because of their lower weight and high specific mechanical properties. Reusing and recycling textile waste materials in the construction industry is an excellent trend that can be identified recently.

When it comes to biocomposites, using natural fiber, the environmental impact is also less. A good example is a composite developed with cotton textile waste and a bio-based resin, Ecovio®, a poly(butylene adipate-*co*-terephthalate)/poly(lactic acid) (PBAT/PLA) blend [52]. The obtained results have shown considerable promise in developing a new class of sustainable materials with developed biocomposites to build interior insulation applications as suitable for conventional building material.

The other composites made of textile waste bulk and PP have been compared with standard wood-based particle boards. Performance that is suitable for the development of load bearing applications and a load-bearing prototype has improved for flooring, walling and division arrangements. The non-load bearing prototypes may be improved for interior linings, including ceilings or sound absorbers [45]. However, according to the literature, the textile-reinforced composite materials are suitable for low and medium-load-bearing applications [9].

As another biocomposite, Miller [28] developed composites of PHBV, continuously reinforced with hemp linen, jute burlap and hemp burlap textiles. Results show the ability to apply bio-based composites to act as substitute materials to conventional construction materials based on mechanical properties. Fiber insulation materials have produced with cotton waste and other textile waste collected from factories, sunflower stalks and epoxy resin. The study has developed a useful construction material while providing an alternative solution for the expanding volumes of textile waste generated daily basis [97].

In earlier work, it has been investigated the applicability of jute textile FRP as a strengthening material through several mechanical characterization experiments and strengthening properties experiments provided by the bonding of jute textile FRP to beams over carbon bonding T-FRP & glass T-FRP [30]. According to their study, jute T-FRP can be regarded as a suitable strengthening material for the flexural strengthening of concrete structures. It could be an alternative methodology for fabric reinforcement in FRP, considering economic and environmental aspects of FRP.

Wool textile waste and food packaging waste hybrid composites have been compared with commercial wood particle boards. They indicate a high possibility and great potential to replace wood particle boards in construction and structural applications to address the growing issues of wastes along with renewability [49]. Different kinds of natural fibers such as hemp, sisal and cotton reinforced polymer composites can be used in manufacturing lightweight automotive parts [98].

TABLE-3
PROPERTIES TESTED FOR TEXTILE REINFORCED COMPOSITES

What properties are tested	Test method	Standard	Ref.
Tensile properties	Tensile test	ASTM D 638	[16,28,35,38,42,43,46,48,50,55, 56,59,71,72,75,79,84,86,93-95]
		ASTM D 3039	[10,14,20,22,24,40, 41,49,51,75,92]
		EN ISO 527	[7,21,30]
		–	[22,36,68,78,91]
Impact properties	Charpy impact test	EN ISO 179	[16,42,43,49,55]
	Izod impact test	ASTM D 256	[10,32,35,47,75,78]
	Drop weight impact test	ASTM D 3763	[40]
		ASTM D 7136	[7,96]
	Balanced impact tester	–	[41]
Flexural properties	3 point bending test	ASTM D 790	[14,16,19,20,28,35,42, 43,50,52,75,93,94,96]
		EN ISO 14125	[7,8,30]
		ASTM D 7264	[41,51]
		–	[17,78]
Shear Properties	Shear test	–	[23]
Physical properties	Density, Thickness swelling, Water absorption	EN323, EN322, EN317 and ASTM D1037	[49]
Thermal properties	Thermogravimetric analysis - TGA	–	[8,33,35,36,51-53,71,75]
	Differential scanning microscopy- DSC	–	[33,35,46,52,53,55,95]
Morphological and microstructure characterization	Scanning electron microscopy-SEM	–	[10,19,33,36,40,43-46,48,51-53, 55,56,71,72,75,78,88,92,95]
Crystallinity	X-ray Diffraction Analysis -XRD	–	[35,53,56,66]
Chemical characterization	Fourier Transform Infrared spectroscopy-FTIR	–	[33,36,45,53,66,96]
	NMR	–	[53]
Tribological properties	Friction & wear tests	–	[36]
Topographical properties	Topographical analysis	–	[45]
Viscoelastic properties	Dynamic Mechanical Analysis	–	[10,35,51,71]
Moisture absorption properties	Water Absorption (WA)	–	[21,45,52,84,91]
		ASTM D 570	[51,56]
	Moisture Regain (MR) and Moisture Content (MC) of the ?ber samples	ASTM D2495	[53]
	Thickness swelling (TS)	–	[45]
Wettability analysis/surface energy analysis	Sessile drop test	–	[45]
	Contact angle measurement	–	[36]
Fire resistance	UL 94 flame propagation test	–	[45]
		ISO 1210	[7]
	Limiting oxygen index (LOI)	ISO 4589	[7]
	Cone calorimetry	ISO 5660/ASTM E1354	[7]
Void content measurement	Void content test	ASTM D 2734	[31]
Sound absorption measurement	Sound absorption	EN ISO 10534	[39]

The manufactured composites may effectively substitute for timber in furniture applications as a sustainable material. Other researchers have developed fique/epoxy composites to establish a baseline of these fique/epoxy composites' mechanical behaviour to propose structural engineering applications [19,20]. In 2016, a group of researchers had developed a flax/epoxy composite. It aimed to establish simple rules to optimize the reinforcement architecture for structural applications (sorption & mechanic aspects) [21].

The latest research has compared treated and untreated sisal fiber hybrid composite made with textile grade glass fibers and bio epoxy resin. The researchers have concluded at malic acid-treated sisal fiber-reinforced hybrid composite performs greater than the untreated sisal fiber-based hybrid composites. As they absorbed a little amount of moisture, they can use it in wet applications [99].

Woven reinforced sandwich composites have been developed for automotive applications [32]. The waste cotton/epoxy composites manufactured in a study presented the essential mechanical properties that need to be used in furniture material and certain visible and non-visible automotive constituents [51]. The composite material developed with 100% recycled wool fibers as reinforcement and copolyester/polyester bicomponent fibers as thermoplastic matrix might be used as internal finishing [100].

Another research group [7] has developed PP and PLA matrices' composites and reinforcement of jute, sisal and glass fibers as fabric/PP & fabric/PLA composites. Both jute and sisal composites had lower mechanical and flammability properties than their glass counterparts. For use in automotive, marine, aerospace, or construction fields, the composites need to pass commercial fire experiments, for which some kind of flame retardant treatments are needed. Composite materials reinforced with flat-knitted cotton spacer fabrics present a reasonable solution for lightweight composites including solar panels, blades of wind turbines and acoustic absorbers [17]. According to another study, bio-based natural rubber/silk composites might find interesting soft robotics applications and flexible, inflatable tubes [36].

Another researcher [41] concluded that cotton/unsaturated polyester composites can be a biodegradable and eco-friendly substitute for the glass fiber composite in the areas where mechanical stresses are low, such as automobile interior and door panel partitioning. A different study developed a hybrid composite using jute, carbon, fishbone and polyester matrix with the potential of structural and automotive applications [50].

Composite made with woven fabric comprising folded polyester yarn and epoxy has been proposed for 2/2 matt applications. The 2/2 warp rib woven fabrics reinforced composites can be proposed to be used in industrial applications and 3/1 matt, 3/1 warp rib woven fabrics reinforced composites can be proposed to be used as technical textiles [24]. Researchers have compared glass/epoxy and basalt/epoxy composites for different applications as a recent development. This study proposes a promising potential in replacing glass fiber composites with basalt fiber composites in aircraft secondary structures. For the basalt epoxy composite, improvements in the fiber-matrix adhesion and the development technique are further needed to improve their shear properties compared to glass fiber composites and fully exploit the potential of basalt epoxy composites in aeronautical applications [31].

There is a wide range of applications in the field of textile reinforced polymer composites. According to a comprehensive review by Sharma *et al.* [101], several composites' applications are; door-shutters, building panels and chipboards using jute fibers; sisal fibers in construction industries for making doors, roofing sheets and panels, hemp fibers in furniture and construction products, flax fibers in window frames and panels, cotton fiber in the furniture industry.

Conclusion

Textile composites can be the next generation materials for various applications including building interior insulation applications, construction materials, automotive, marine, aerospace, defense and aeronautical applications. It could also be used in structural applications such as furniture, flooring, walling and division systems, interior linings such as ceilings or sound absorbers. There are other exciting applications in soft robotics. Textiles have specific mechanical properties which can be a reinforcement in composites with higher performance. The environmental impacts may depend on the textile type, such as natural textiles or synthetic textiles. A proper selection of textile reinforcement, matrix and processing techniques can produce a material with a better performance. There is an increasing trend to use textile waste as a reinforcing material as sustainable alternatives. From an environmental point of view, using textile waste for the development of composites is an excellent solution to address the problematic situations occurred by massive amounts of textile waste generated globally.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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