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Review

Natural Fibre Composites and Their Applications: A Review

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Abstract: There is significant work published in recent years about natural fibres polymeric composites. Most of the studies are about the characterization of natural fibres and their comparison with conventional composites regarding mechanical behaviour and application performance. There are dozens of types of natural fibres with different properties influencing their use, or not, in specific industrial applications. The natural origin of these materials causes, in general, a wide range of variations in properties depending mainly on the harvesting location and conditions, making it difficult to select the appropriate fibre for a specific application. In this paper, a comprehensive review about the properties of natural fibres used as composite materials reinforcement is presented, aiming to map where each type of fibre is positioned in several properties. Recent published work on emergent types of fibres is also reviewed. A bibliometric study regarding applications of natural fibres composites is presented. A prospective analysis about the future trends of natural fibres applications and the required developments to broaden their applications is also presented and discussed.

Keywords: natural fibres; green composites; automotive applications; industrial applications

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1. Introduction

In the last few years, there have been a stringent consumer's awareness towards new products from renewable sources. Green marketing, new directives on recycling, social influence and change of cognitive values has led the consumer towards environmentally friendly products.

In particular, composite materials are being developed and redesigned aiming to improve and to adapt traditional products and introduce new products in a sustainable and responsible way [1]. This paper examines and discusses the last published trends in the context of fibres-reinforced bio-composite materials while providing an insight about natural fibres for bio-composites, with the focus on properties and their applications. Natural fibres are mainly either plant or animal sourced. The first is essentially comprised of cellulose, whilst the latter is protein-based. However, in the composites industry, natural fibres are often referred to as vegetable fibres.

One of the issues of natural fibres is the scattered information and the differences in mechanical properties reported. Also, the lack of standards for both producers and users of these materials regarding methods to collect, treat, process and post-process natural fibres adds to the complexity of selection. These issues are in fact, critical deterrents for generalized use of natural fibres in different applications. To address this gap, in this paper, a review of different mechanical properties of natural fibres and their applications is presented.

This paper is structured in four sections as follows: first we give an overview about natural fibres, focusing on their benefits and functional properties. Then, in Sections 2 and 3, we describe the suitable applications and future trends. Finally, we discuss and conclude the paper with some final remarks.

2. Natural Fibre-Reinforced Bio-Composites

In general, depending upon the nature of the constituents, bio-based composites can be classified either as partly eco-friendly or green (Figure 1). Green composite implies that all its constituents are obtained from renewable resources, potentially reducing the carbon dioxide emissions and the dependence on petroleum-derived materials. While partly eco-friendly means that one of the constituents, either fibre or matrix, is not obtained from renewable resources [1].

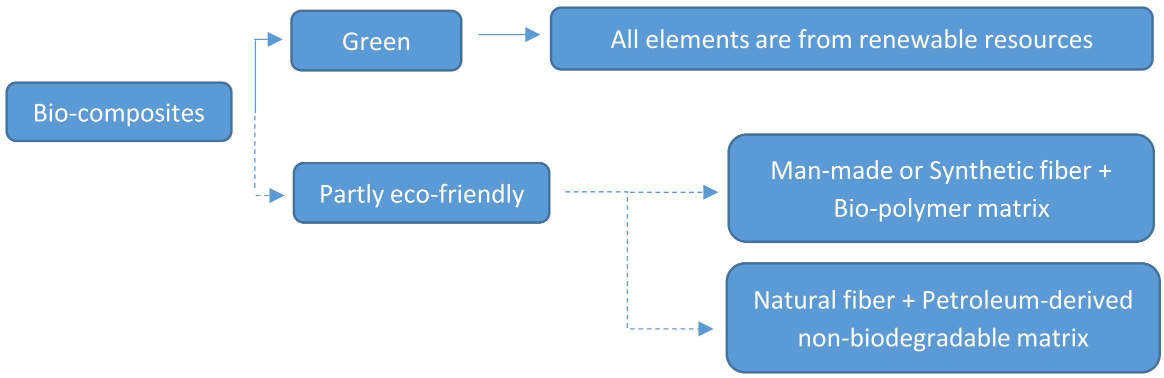

Figure 1. Classification of bio-composites. Adapted from: [1–3].

The performance of the natural fibre composites depends directly on the fibres counting, length, shape, arrangement and also the interfacial adhesion with the matrix [4].

Natural fibre reinforcement may be divided in accordance with the length, dimension and orientation, as demonstrated in Figure 2. This can either be in the form of fibre or particle. The fibre itself is characterized as continuous or discontinuous (i.e., chopped) depending on its length-to-diameter (l/d) ratio. Commonly, the fibre-reinforced phase arrangement is classed as woven or non-woven. A woven fabric is characterized by continuous interlacing of perpendicular yarns, in a regular pattern. Yarns are structures consisting of several interlocked fibres. The twist angle is responsible for the cohesion of the fibres and yarn strength up to a certain point, beyond which, the maximum fibre strength decreases due to the increase in obliquity [5]. Moreover, the increase of the fibre twist angle is correlated with a decrease of fibre-resin bond strength, lower permeability and consequently poor mechanical properties [6]. When continuous fibres are used, the fibre architecture can have more than one-dimension [7]. In the one-dimensional architecture, the twist angle and the level of alignment of continuous-filament yarns play a significant role in determining the maximum applied load. For this reason, unidirectional composites tend to be weaker in the transverse directions [4,5]. Given these attributes, for a known state of stress, these anisotropic structures can exhibit at least 3 to 4 times better mechanical properties than their isotropic counterparts [8].

A non-woven arrangement is a flat structure without interwoven strands, consisting of a mat directionally or randomly oriented and placed together using heat, chemicals, pressure or combination of these thereof as adhesion promoter, the mat or woven can either be composed of continuous or chopped unidirectional fibres, randomly chopped fibres or suspended particles [7,9]. In particular, mat composed with randomly chopped fibres (whiskers) does not have any preferential stress direction but they are the preferable choice for large-scale production due to the high availability, ease and cost effectiveness when manufacturing complex parts of isotropic nature [10]. Several reports show that natural fibres can compete as reinforcement materials for products not fit to receive loads (non-performance) and semi-structural parts. In fact, automotive industry is gaining preference for lightweight products in order to improve fuel efficiency [11], such as non-structural automotive applications with natural fibres [12].

A fibre-reinforced composite depends as well on the contribution of some additional characteristics such as: matrix properties, fibre-matrix ratio, filler material, coupling agents and processing techniques [13]. As a consequence of imperfections in the manufacturing process, multi-layered fibre-reinforced composites are prone to early failure because of low adhesion between laminas that is, delamination [14].

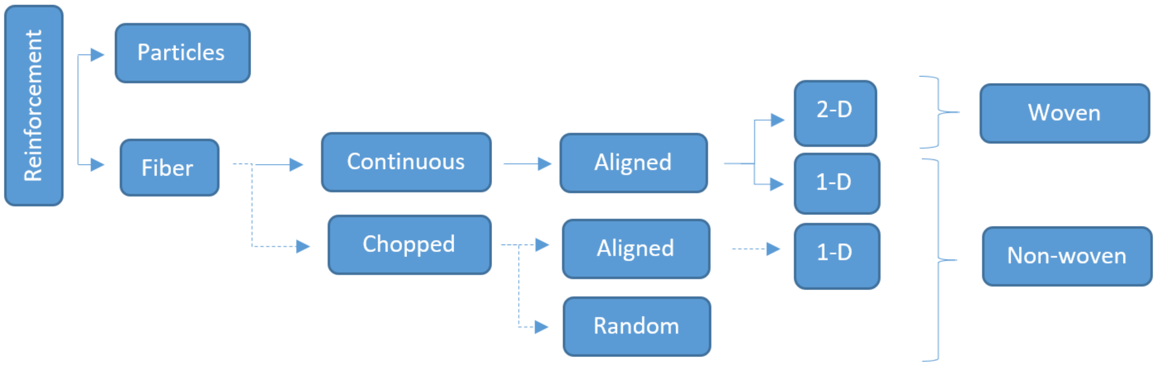

Figure 2. Type of natural fibre reinforcements. Adapted from: [7,15].

2.1. Bio-Polymeric Matrix

The mechanical performance of a bio-composite also depends on the properties of polymeric matrix (thermoplastic or thermoset). The raw material to produce these polymers can either be from bio-based sources (plant or animal) or synthetic (oil by-product).

In the literature the term bio-polymer has multiple and overlapping meanings, including but not limited to: bio-based, biodegradable or both [1,3,16,17]. Others expressions, though not incorrect, like "bio-based polymer" or "renewably-sourced polymer" are also used to refer a polymer that contains carbon sourced from a renewable plant source or biomass [18,19].

The commonly accepted definition covers that bio-polymer is a polymeric material where a significant constituent has biological source (C14 isotope) and can be biodegradable or not [20]. Biodegradable means that the polymer bio-degrades through the actions of living organisms or non-enzymatic hydrolysis [3]. It must be mentioned that not all biodegradable substances are compostable [20].

For commercial and research purposes, transparent conformity assessments can be carried out to label correctly a certain polymeric resin using international ISO standards [21], as presented in Table 1.

Table 1. International Organization for Standardization (ISO): bio-based, biodegradable and compostable standards. Adapted from: [17,22–24].

Label	ISO Standard	Description
Bio-based	16620:2015	Specifies the general principles and the calculation methods for determining the amount of bio-based content in plastic products, using a radiocarbon method
Biodegradable	14852:2018	Specifies a method, by measuring the amount of carbon dioxide evolved, for the determination of the degree of aerobic biodegradability of plastic materials
Compostable	17088:2012	Specifies procedures and requirements for the identification and labelling of plastics and products made from plastics

For instance, the commercially available biodegradable bio-based polymers are essentially either based on starch or polylactic acid (PLA) or cellulose ester or bacterial polyhydroxyalkonate (PHA) or protein [19].

Currently, biopolymers represent an extremely small percentage of the global polymer market, approximately 6% [25]. Further market penetration depends greatly on a wide range of factors such as feedstock cost, crude oil prices, technology feasibility, favourable government regulations and policies [26,27].

The polymer material selection implies a prior study of the mechanical properties, chemical resistance, dimensional stability, manufacturing process, always with a target on future ability to recycle or biodegrade. End-of-life recycling effectiveness depends on the heterogeneous nature of its elements.

On one hand, thermosets have a wide range of applications due to their good adhesion, high thermal and chemical resistance and excellent mechanical properties. On the other hand, unlike thermosets, thermoplastics can be melted. When heated, the Van der Waals and hydrogen bonds are temporarily broken allowing molecular manoeuvrability. Thermoset matrices are indeed difficult to recycle and reuse but some studies have reported that thermosetting polymers might be reused [27]. Another study refers that a more environmentally friendly product can be achieved through the inclusion of biodegradable fillers [28].

In general, economic and environmental factors are primarily responsible for driving the recycling pathways. A number of articles focus on recycling composites through mechanical, chemical, thermal processes or any combination thereof [29,30].

2.2. Natural Fibres

Natural fibres can be classified based upon their origin into the following groups: animal, mineral and plant, as shown in Table 2. Plant fibres are the most commonly accepted fibres by the industry and the most analysed by the research community. This is mainly due to the short growth period, renewability and wider availability [12]. The vegetable fibres are composed of cellulose, hemicellulose and lignin, which can be extracted from bast, leaf, seed, fruit, wood, stalk and grass/reed.

Table 2. Natural Fibre Classification. Adapted from: [31–33].

Natural Fibre	Cellulose/Lignocellulose	Bast	Flax, Hemp, Jute, Kenaf, Ramie
		Leaf	Abaca, Banana, Pineapple, Sisal
		Seed	Cotton, Kapok
		Fruit	Coir
		Wood	Hardwood, Softwood (e.g., Eucalyptus)
		Stalk	Wheat, Maize, Oat, Rice
		Grass/Reed	Bamboo, Corn
	Animal	Wool/Hair	Cashmere, Goat hair, Horse hair, Lamb wool
		Silk	Mulberry
	Mineral	-	Asbestos, Ceramic fibres, Metal fibres

In this paper the focus is on the vegetable fibres since all the others either have restricted application or are indeed forbidden by law. In fact, animal fibres are not commonly used and asbestos was banned due to risks of exposure and risks associated with human health [34,35].

Moreover, there are some relevant previous studies suggesting that some fibres may have a potential ability to work as reinforced candidates in near future, for example, roselle (hibiscus sabdariffa), sugarcane (saccharum cilliare), pine, bagasse, henequen, alfa, among others (for additional fibre list see references [13,32,36–42]).

The natural fibres are usually referred to have several benefits over synthetic fibres such as availability, low cost, low density, acceptable modulus-weight ratio, high acoustic damping, low manufacturing energy consumption, low carbon footprint and biodegradable [2]. Some authors state the evidences for clear benefits, for example, natural fibres cost much less and require much less energy to produce than traditional reinforcing fibres such as glass and carbon [43]. However, natural fibres have negative aspects due to their low consistency of properties and quality. These fibres have higher variability of physical and mechanical properties, higher moisture absorption, lower durability, lower strength and lower processing temperature [13,19,44–46].

The large variety of properties are mainly dependent upon plant species, growth conditions and method of fibre extraction. Moreover, properties depend on the fibre cell geometry of each type of cellulose and its degree of polymerization [47]. It should be noted that linear cellulosic macromolecules are linked by hydrogen bonds and are closely associated with hemicelluloses and lignin which confer stiffness to fibre. Not only holds fibres together but also the cellulose within the fibre cell wall [48]. Figure 3 exhibits the influence of constituents on the properties of fibre.

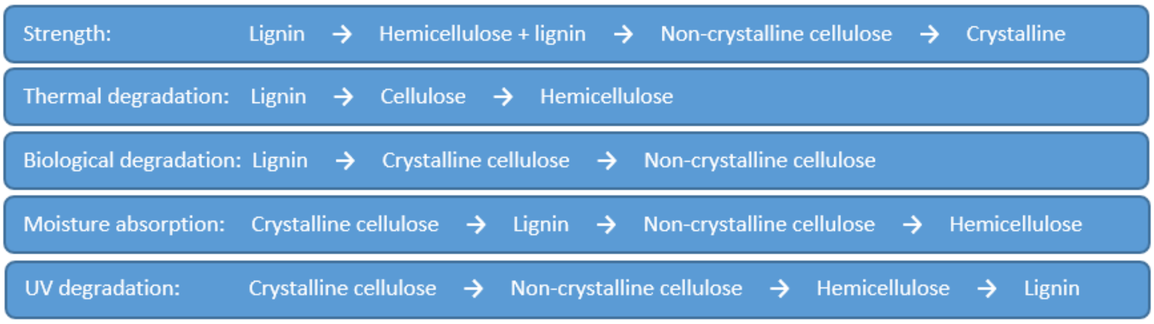

Figure 3. Plant constituents influence. The rightward-pointing arrow indicate an increase. Adapted from: [47].

The bast fibres are the most widely used non-wood lignocellulosic fibres due to their superior technical characteristics and ease of extraction from raw resources [49], usually by retting and manual extraction techniques [50]. The manual extraction produces crops with good quality but the process can be a lengthy and a laborious task [51]. Some authors also name them as stem fibres, because they are obtained from the pseudo-stem of the plant, that is, those obtained from the outer cell layers of the stem.

The general natural fibre life cycle phases are extraction, processing, fabrication, use, disposal and recycle. There are several limiting factors for a large-scale production and use of fibres. These factors affect several stages of the natural fibre's life cycle: large variability of soil composition and morphology, fibres hydrophilic nature, degradation by microorganisms, service life and sunlight. The physical and chemical properties of natural fibres are linked to plant source, cultivation location, climate conditions, harvest window, use of Genetic Modified Organisms (GMO), pesticides and fertilizers [52,53].

Usually, natural fibres require several treatments to overcome some of the mentioned limitations, namely to improve fibre-matrix interfacial adhesion. Several techniques have been reported, such as water-repellent chemicals, coupling agents and heat treatments, by modifying the surface morphological, topological properties, roughness and water absorption index of the fibres [54–56]. As a result, research and technological effort has been reported fostering the improvement of crops quality and fibres performance on technical and economical perspective, aiming to provide new solutions and applications [57].

Despite the referred limitations, fibres are taking a growing interest by researchers. The bibliometric analysis in Figure 4 shows the number of research articles resident in the Science Direct database that meet the defined cross-reference search criteria (by search term: "fibre name" composite and by title or keyword: "fibre name", including name alternatives for example, coir/coconut and pineapple/pine), from the year 2016 up to September 2018. For this study fibres with more than 20 publications in a given year were selected. For most of the fibres, the number of publications in 9 months of 2018 supersedes the number of publications in the whole year of 2017. Nevertheless, for the other ones the number of publications in 2018 is already very near the 2017 number, so it is expected that the number of publications in 2018 would be higher than that of 2017.

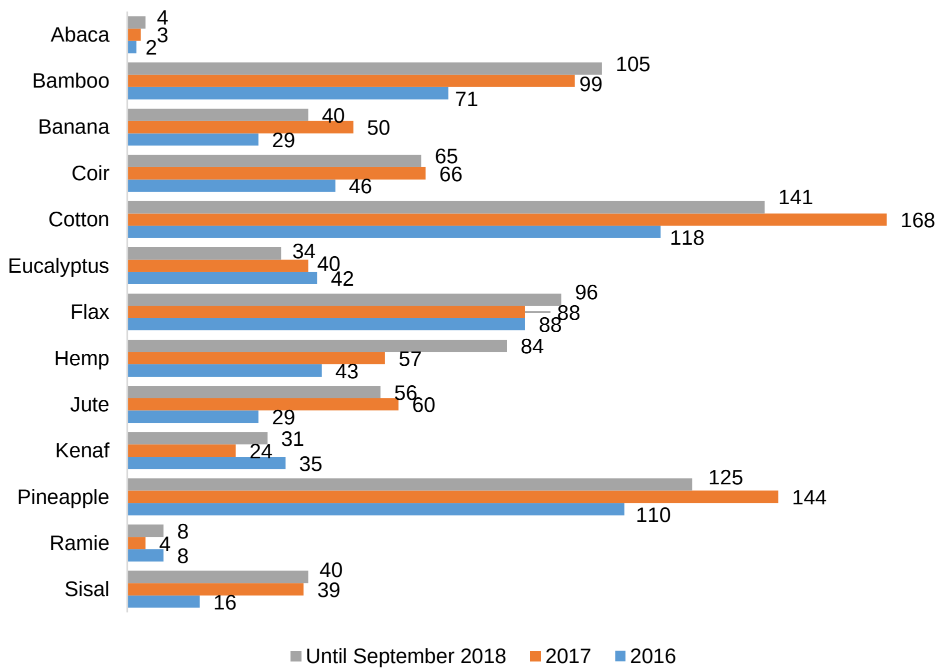

Figure 4. Number of research articles about natural fibres on composites. Cross-reference search criteria (by search term: "fibre name" composite and by title or keyword: "fibre name", including name alternatives).

Cotton is the natural fibre with a higher number of publications by the research community, followed by pineapple and bamboo. Fibres like coir, flax, hemp and jute also receive very high attention from researchers. Contrarily, species like abaca and ramie are the ones with less articles published, among the selected natural fibres. These numbers may be explained through the main characteristics of each fibre (Table 3). The factors influencing the significant differences in publication intensity are as follows: the origin and the amount of plant area available throughout the planet (cotton, bamboo vs. pineapple, abaca), the readiness to be used as composite reinforcement material (sisal, hemp vs. ramie, banana) and overall mechanical properties (flax, jute vs. eucalyptus, banana). In recent years, natural fibres have become increasingly popular among researchers due to their sustainability and renewability characteristics.

Table 3. Summary of Natural Fibres characteristics. Adapted from [45,58–69].

Fibre	Description
Abaca/Banana	Abaca, also known as manila hemp, is a plant closely related to banana. Abaca plant looks similarly but unlike banana its fruit is not for human consumption, being not viable economically. Unlike banana, abaca plant grows only for fibre cultivation [45].
Bamboo	Bamboo have been receiving interest because it has a high strength to weight ratio [58], one of the fastest growing plants, requires less water, no use of pesticides or herbicides and is harvested at its base, leaving the root intact. Also, the fibre surface is round and smooth and its l/d ratio is high. It is light, stiffer and stronger than glass fibre [59]. A U.S. Department of Energy report clearly demonstrate that the energy consumption to produce a bamboo fibre mat represents a small fraction (17%) of the energy needed for the glass fibre counterpart [60].

Table 3. *Cont.*

Fibre	Description
Coir	Coir has great attractiveness because it is more durable than most natural fibres, free of chemical treatment, its strong resistance to salt water and availability [61,62].
Cotton	Cotton fibre has an excellent absorbency [65]. Cotton represents 46% of world production of natural and chemical fibres [66].
Eucalyptus	Eucalyptus fibre is widely available but has low resistance to mould and fire attack. These bark fibres are adequate for insulation purposes [67].
Flax	Flax fibre has better specific tensile when compared with glass fibre. In addition, it has low density, high strength and stiffness [68].
Hemp	Hemp fibre has excellent mechanical strength and young's modulus [68]. Good insulation properties [69].
Jute	Jute fibre exhibits high aspect ratio (l/d), high strength to weight ratio and good insulation properties [68].
Kenaf	Kenaf fibre has low density and high specific mechanical properties [68].
Pineapple	Pineapple fibre has excellent mechanical, physical and thermal properties [63].
Ramie	Ramie fibre might have better specific strength and specific modulus than glass fibre. But it is not so popular when compared with the others natural fibres because it requires expensive pre-treatments [64].
Sisal	Sisal is easily cultivated with short renewal times. The fibre has high tenacity and tensile intensity, abrasion resistance, salt water resistance, acid and alkali resistance [68].

There are several studies pointing out the lower cost of natural fibres comparing with synthetic fibres but the correct comparison must be done in their application in a part and considering its production and life cycle cost or impact. Different mechanical properties will require different mass of each fibre, different fibres quality and reliability will cause different wastes and scrap during production of composites and different needs for part replacing during life time. Nevertheless, several studies refer that the natural fibres have in general a lower cost than synthetic fibres [55,70]. There is a study in particular that presents a general comparison of natural fibres with carbon and glass fibres [43]. Following those authors natural fibres cost much less and require very less energy to produce which leads to cost and energy advantages over traditional reinforcing fibres such as glass and carbon fibre (Table 4).

Table 4. Energy and cost of different fibres [43].

Fibres	Cost (US$/ton)	Energy (GJ/ton)
Natural fibre	200–1000	4
Glass fibre	1200–1800	30
Carbon fibre	12,500	130

Table 5 summarizes some of the physical and mechanical properties of the natural fibres. Despite the fact that there is an attracted attention for eucalyptus forestry, the fibre properties are not in Table 5, because no related information in the publications gathered is found. The properties variation range is high for most of the fibres because of their natural origin depending on the type of soil, harvesting conditions, weather and post-treatment [71]. Bamboo shows the lowest density while abaca, pineapple, hemp and ramie have some of the highest ones among the natural fibres in the Table 5. Jute and coir have the lowest average diameter and bamboo and ramie are on average the thickest ones. Moreover, ramie is on average the longest fibre. Contrarily, banana, bamboo and coir are usually short-length fibres. The tensile strength variation among fibres has low amplitude, being cotton the one with the lowest average value and pineapple the strongest one in this property. Regarding the Young's modulus the amplitude is higher, with ramie showing a very high value comparing to the other ones and coir and cotton showing a very low value. Despite ramie is the stiffest fibre considering the Young modulus, it has one of the lowest elongations at break, with coir having the highest value. Cotton is the one with higher moisture content and hemp and flex the ones with the lowest values.

Two recent review studies were used to list the natural fibres properties. During the last years several reviews have been published [72–78], promoting their use and raising awareness of natural fibres advantages. Still, these authors did not include the required information for ease of comparison and topicality. The emerging potential of natural fibres provides a steady progress towards knowledge and insight, generating data to support further researches and developing new approaches to overcome the challenges. The two recent studies used are comprehensive and based on a significant list of references, reflecting and incorporating the findings from older studies. Nevertheless, those publications [72–78] should be also considered for a complete review of the information available and its evolution over time.

Table 5. Properties of some natural fibres Adapted from: [79,80]. [a] average value between parenthesis.

Fibre	Density (g/cm^3) [a]	Diameter (μm) [a]	Length (mm) [a]	Tensile Strength (MPa) [a]	Young's Modulus (GPa) [a]	Elongation at Break (%) [a]	Moisture Content (%) [a]
Abaca	1.5	10–30 (20)	4.6–5.2 (4.9)	430–813 (621.5)	31.1–33.6 (32.35)	2.9	14
Bamboo	0.6–1.1 (0.85)	25–88 (56.5)	1.5–4 (2.75)	270–862 (566)	17–89 (53)	1.3–8 (4.65)	11–17 (14)
Banana	1.35	12–30 (21)	0.4–0.9 (0.65)	529–914 (721.5)	27–32 (29.5)	5–6 (5.5)	10–11 (10.5)
Coir	1.2	7–30 (18.5)	0.3–3 (1.65)	175	6	15–25 (20)	10
Cotton	1.21	12–35 (23.5)	15–56 (35.5)	287–597 (442)	6–10 (8)	2–10 (6)	33–34 (33.5)
Flax	1.38	5–38 (21.5)	10–65 (37.5)	343–1035 (689)	50–70 (60)	1.2–3 (2.1)	7
Hemp	1.47	10–51 (30.5)	5–55 (30)	580–1110 (845)	30–60 (45)	1.6–4.5 (3.05)	8
Jute	1.23	5–25 (15)	0.8–6 (3.4)	187–773 (480)	20–55 (37.5)	1.5–3.1 (2.3)	12
Kenaf	1.2	12–36 (24)	1.4–11 (6.2)	295–930 (612.5)	22–60 (41)	2.7–6.9 (4.8)	6.2–12 (9.1)
Pineapple	1.5	8–41 (24.5)	3–8 (5.5)	170–1627 (898.5)	60–82 (71)	1–3 (2)	14
Ramie	1.44	18–80 (49)	40–250 (145)	400–938 (669)	61.4–128 (94.7)	2–4 (3)	12–17 (14.5)
Sisal	1.2	7–47 (27)	0.8–8 (4.4)	507–855 (681)	9–22 (15.5)	1.9–3 (2.45)	11

Despite some clues that natural fibre properties can be derived from the analysis of Table 5, some comments must be made regarding the comparison of data from different authors. In the published documents analysed in this study, the adopted measurements standards are not always reported and the authors do not say often if the measurements have been conducted on a single or bundle of fibres. This information is important because the calculation of properties depends directly on the cross-section. Another important aspect regarding the comparison of natural fibres properties is related with the process of obtaining the fibres from the plants. Many extraction techniques have been reported such as mechanical, chemical or a combination of both, some of them are rudimentary processes and there is no scientific consensus or standards allowing a robust comparison. In addition, natural fibres require the modification of the roughness and the surface physio-chemistry of fibres to improve functional properties such as wettability and dimensional stability, therefore increase their adhesion with hydrophobic matrix [81–85]. Typically, these may consist of water or dew retting on stalks or decorticated fibres plus mechanical scutching and chemical processing [71,83] but again there are no standard procedures. Table 6 shows some of the chemical treatments available in the market and its effects. Meanwhile, most researchers apply peroxide treatments on natural fibres due to its simplicity and relatively good mechanical properties [83].

Hence, it is important to know the degree of uncertainty associated with the values of Table 5. A publication clearly suggests that some measurements of strength and stiffness obtained by some authors might be underestimations [13]. So, as a tentative to summarize the findings regarding the natural fibre properties listed in Table 5, one can conclude that there is an important variability in the properties of most of the fibres and there is a relevant amplitude of properties among fibres. There is not one type of natural fibre that can be considered better than the others, meaning that the selection of the proper fibre depends largely on the application requirements and type of composite to be produced, fibre availability to answer to the product demand volume and the guarantee of properties levelling among different crops or batches (depending on the fibre origin, plant processing and post-treatments).

Moreover, fibres cost, translated most of the times in price to the composite producer, is also an important aspect for natural fibres selections that will be analysed in the next paragraphs.

Table 6. The effect of chemical treatments on the functional properties of natural fibre. Adapted from: [83,86,87].

Treatment	Effect
Alkali	Reduce the lignin content. Improve fibre-matrix adhesion, thermal stability and heat resistivity [86,87]
Acetylation	Improve tensile and flexural strength [83]
Benzoylation	Improve hydrophobicity [83]
Enzyme	Reduce the lignin content [83]
Grafting	Improve UV-protective properties, hydrophobicity and mechanical properties [83]
Isocyanate	Surface modification [83]
Mercerization	Reduce the moisture regain and improve the mechanical properties [83]
Methacrylate	Improve tensile and flexural strength [83]
Ozone	Affect surface energy and contact angle [83]
Peroxide	Reduce the moisture regain [83]
Plasma	Improve hydrophobicity [83]
Silane	Improve hydrophobic and mechanical properties [83]
Sodium chlorite	Improve tensile strength, young's modulus and elongation at break [83]

Based on several recent references, Table 7 displays a comparison on the price of each fibre in the market. This data was only based on the scientific publications found, meaning that a comprehensive study including natural fibres suppliers was not included. Nevertheless, it is possible to understand that there is a strong price variation depending on the type of fibre, meaning that it is not correct to generalize the price of natural fibres. There are also contradictions between these values and the ones in Table 4, that stated the natural fibres price ranging from 200 to 1000 US$/ton. Fibres like cotton, flax, hemp and ramie exhibit the highest price, being higher than the one of glass fibre in Table 4. Contrarily, coir, abaca and kenaf prices are far lower. The usefulness of compiling this data is to have the relative level of cost for each kind of fibre.

Table 7. Price per tonne of some natural fibres. Adapted from: [66,80,88]. [a] Mean value between parenthesis.

Fibre	Price (US$/ton) [a]	Fibre	Price (US$/ton) [a]
Abaca	345	Hemp	1000–2100 (1550)
Bamboo	500	Jute	400–1500 (950)
Banana	890	Kenaf	300–500 (400)
Coir	200–500 (350)	Pineapple	360–550 (455)
Cotton	1500–4200 (2850)	Ramie	2000
Flax	2100–4200 (3150)	Sisal	600–700 (650)

Despite the comments regarding price variability and uncertainty, the authors of this paper propose an analysis to support natural fibres selection based on cross analysis of properties and price. In Figure 5 the interrelationships between tensile strength, Young modulus and specific strength (ratio between tensile strength and density) are presented. Pineapple fibres show a very interesting position being the one with higher tensile strength with a relative low price. On the other side, ramie, cotton and flax show lower mechanical behaviour with a much higher price. Regarding the specific strength pineapple fibres keep a good position but bamboo fibre shows a higher value for the same kind of cost. Sisal also have a good performance when combining these two characteristics. Regarding the Young modulus with price analysis ramie higher mechanical behaviour is impaired by its higher price, assuming pineapple and bamboo fibres exhibit a good combined behaviour in this analysis.

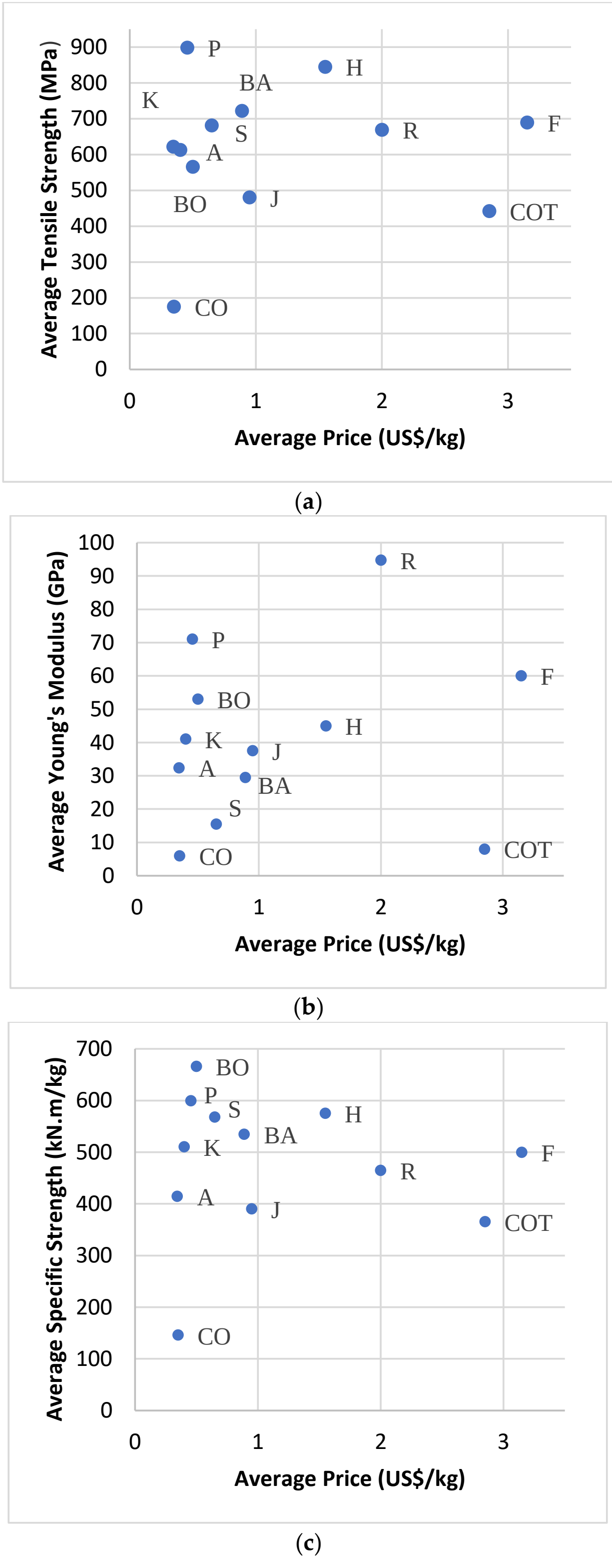

Figure 5. Interrelationships between mechanical properties and price (average values in Tables 5 and 6 were used). (**a**) Average Tensile strength (MPa); (**b**) Average Young's Modulus (GPa); (**c**) Average Specific strength (kN·m/kg) per Price (US$/kg), respectively. Legend: Abaca (A); Bamboo (BO); Banana (BA); Coir (CO); Cotton (COT); Flax (F); Hemp (H); Jute (J); Kenaf (K); Pineapple (P); Ramie (R) and Sisal (S).

Other kind of outputs can be derived from these analyses mainly if more reliable data is obtained from scientific and commercial sources. Nevertheless, they give an interesting picture of the differences and positioning of the several types of natural fibres, allowing to understand the importance of knowing and studying several natural fibres in the process of selecting them for composite applications.

Despite the variability and lack of robust scientific-based information regarding the natural fibres, there are a myriad of industrial applications of these fibres that are presented and discussed in the next section.

3. Applications

There are several industries such as automotive, construction, energy and aerospace, among others which are being challenged by the society and governments to make products which are more environmentally sound and reduce their dependence on fossil fuels [10,89,90]. In this perspective, the European Commission implemented a "European Guideline 2000/53/EG" that set a goal of improving automotive recyclability to 85% in 2005 for a vehicle by weight. This percentage was increased to 95% by 2015 [91]. This type of legislation is a significant driving factor towards the adoption of natural fibre composites. In this scenario, natural fibres are an attractive option for industries to meet socio-economic and environmental challenges. Furthermore, the use of natural fibres would create employment opportunity in rural and less developed regions thus helping in achieving the sustainable development goals by the United Nations, namely eliminating poverty, building inclusive and sustainable industrialization and fostering innovation, creating sustainable cities and communities and responsible production and consumption [92]. Therefore, natural fibres will play a vital role in socio-economic development of our society. In this section, applications where natural fibres are already in use and where can be used and what does the future holds in terms of their applications across many different industries is presented and discussed.

3.1. Industrial Applications of Natural Fibre Composites in the Automotive Sector

Nowadays, the increased importance of raw materials from renewable resources and recyclability or biodegradability of products is causing the transformation from petroleum-based synthetics to natural fibres in automotive applications [93]. The applications of natural fibre composites in the automotive sector can be traced as far back as the 1940s, when Henry Ford produced the first composite components in a car using hemp fibre [91]. The next referred application was in the 1950s, with the production of the body of the East German Trabant and other manufacturers also followed the same path including Daimler–Benz (1994) and Mercedes (1996) [91]. Natural fibre-based composites hold significant potential for automotive industry because the demand for light weight and environmentally friendly materials is higher. Studies indicate that natural fibre composites can contribute to a cost reduction of 20% and weight reduction of 30% of an automotive part [43]. Following those authors, light weight of components leads to lower fuel consumption, good recycling possibilities, reduction in waste disposal and greenhouse emissions which are some of main drivers for use of natural fibres. Natural fibre composites are mostly being used for interior parts such as dashboards, door panels, parcel shelves, seat cushions, backrests and cabin linings whereas the use of natural fibre composite parts for exterior applications is very limited [43]. As an example, the following Figure 6 shows the production of door from hemp fibre.

Figure 6. Production of door from hemp fibre [94].

Different regions across the globe cultivate and use different types of natural fibres and sometimes they import or export to other regions as well. For instance, European automotive industry mainly uses flax and hemp, whereas jute and kenaf are mainly imported from Bangladesh and India, banana from the Philippines and sisal from South Africa, the United States and Brazil. Flax fibre has been the most relevant natural fibre for the German automotive industry [43]. Figure 7 shows the use of different natural fibres in European automotive industry with highest share of wood and cotton fibre followed by flax, hemp, kenaf and others. The European composites market as whole contains a 10–15% share of wood plastic and natural fibre composites [95].

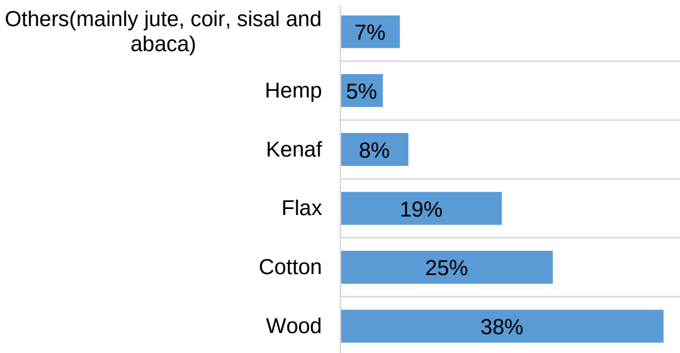

Figure 7. Use of Wood and Natural Fibres for Composites in European automotive industry in 2012 (total volume: 80,000 tons, adapted from: [95]).

Moreover, it is interesting to mention here that 15.7 million passenger cars were produced in the EU in 2011 in addition to 2 million other motor vehicles including trucks, transporters, motor bikes and so forth. Considering that 30,000 tons of natural fibres and another 30,000 tons of wood fibres were used in 15.7 million passenger cars, on average every passenger car in Europe is estimated to contain 1.9 kg of natural fibres and wood fibres each [95]. German automotive industry is the most important consumer of natural fibre parts within the European automotive sector, where each car produced in Germany on average contains 3.6 kg of natural fibres [95]. A bibliometric study was done for this paper about the applications of natural fibres mainly in automotive industry using keywords “natural fibres”, “applications”, “automotive industry”, “bio-composites” on the web and the findings are presented in Tables 8 and 9. Most of the components produced by natural fibres are interior components such as inner door panels, seat covers and insulations and so forth and most commonly used fibres are flax, hemp and kenaf. Moreover, the matrix used in combination with these natural fibres is polypropylene (PP) and PLA. Most of the automotive manufacturers already use natural fibres composites in their products, aiming to decrease cost, vehicle weight and the life cycle environmental impact, using these aspects commercially as a marketing advantage.

Table 8. Applications of natural fibres in automotive industry. Adapted from: [43,91,96–99].

Natural Fibres	Component Description	Reference(s)	Other Constituents
Bast fibres (flax, hemp, kenaf, jute, sisal, etc.)	Carrier for covered door panels, covered components for instrument panels, covered inserts, carrier for hard and soft armrests, seat back panels, door panels, door bolsters, headliners, side and back walls, seat backs, rear deck trays, pillars, centre consoles, load floors, trunk trim	[91]	Polypropylene (PP) and polyester
Abaca	Under-floor panel and body panels	[43,97]	-
Banana	Wrapping paper	[98]	-
Coconut	Seat bottoms, back cushions and head restraints, interior trim and seat cushioning, seat surfaces/backrests	[43,96,99]	Natural rubber
Coir	Car seat covers, mattresses, doormats, rugs	[99]	-
Cotton	Soundproofing, trunk panel, insulation	[43,96]	PP/PET
Fibrowood recycled	Plastic retainer for seat back panel	[91]	PP granules, thermoplastic
Flax	Seatbacks, covers, rear parcel shelves, other interior trim, floor trays, pillar panels and central consoles, floor panels	[43,96]	Mat with PP (floor panels)
Flax or Hemp	Carrier for covered door panels	[91]	Epoxy resin
Flax/Sisal	In the interior door linings and panels, door panels	[43,96]	Thermoset resin
Kenaf	Door inner panel	[97]	PP
Kenaf/Flax	Package trays and door panel inserts	[43]	-
Kenaf/Hemp	Door panel, rear parcel shelves, other interior trim, Lexus package shelves, door panels	[43]	-
Wood	Carrier for covered door panels, carrier for covered door panels, covered or foamed instrument panels, covered inserts and components, covered seat back panels, fibre in the seatback cushions, inserts, spare tire, covers	[43,91]	Acrylic resin and synthetic fibre
Wood Flour	Carrier for covered door panels, carrier for armrest, carrier for covered inserts	[91]	PP or polyolefin (POE)
Wool	Upholstery, seat coverings	[43,96]	Leather

3.2. Applications in Other Sectors than Automotive

Despite most prominent applications of natural fibre composites are in automotive sector [95] there are additional fields of applications of natural fibre composites mainly: textiles, medical, healthcare and pharmaceuticals, home and personal care, food and feed additives, construction and furniture, packaging, pulp and paper, bioenergy and biofuels. This section focuses on applications of natural fibre composites in other industries than automotive sector and some of these applications are presented in the in Table 10. This table shows the result of a bibliometric analysis done for this paper about the applications of natural fibres in different industries using keywords “natural fibres”, “applications”, “bio-composites” on the web. The lower weight and relatively lower cost of natural fibres are the main aspects referred to as the reasons for the use of natural fibre composites in these applications. There is a wide scope of activity sectors using natural fibres composites, from construction, pharmaceutical, sports and music instruments, involving their use to obtain panels, containers, boxes, casing and other type supporting and packaging objects.

Table 9. Natural fibre-based parts in different models of several automotive manufacturers. Adapted from: [11,99,100].

Automotive Manufacturer Companies (Models)	**Door Panels**	**Seat Parts**	**Boot Lining**	**Instrument Panel**	**Insulations**	**Others**
AUDI (A2, A3, A4, A6, A8)	☑	☑	☑			Hat rack, spare tyre lining
BMW (3, 5, 7)	☑	☑	☑		☑	Moulded foot well linings
Chrysler (Chrysler Sebring)	☑					
CITROEN (C5)	☑					
DAIMLER-CHRYSLER (A, C, E, S)	☑					Windshield, dashboard, business table, pillar cover panel
FIAT (Punto, Brava, Marea, Alfa Romeo 146)	☑					
FORD (Mondeo, Focus, Ford fusion, Lincoln)	☑	☑	☑			
General Motors (Cadillac De Ville, Chevrolet)		☑				Cargo area floor mat
LOTUS (Eco Elise)	☑	☑				Spoiler, interior carpets
MERCEDES-BENZ (C, S, E & A class truck)				☑	☑	Internal engine cover, bumper, wheel, box, roof cover, glove box
Mitsubishi	☑			☑		Cargo area floor mat
PEUGEOT (406)	☑	☑				
RENAULT (Clio, Twingo)						
ROVER (2000 and others)						Rear storage shelf/panel
SAAB (9S)	☑	☑				
TOYOTA (Brevis, Harrier, Celsior, Raum)	☑	☑				Spare tire cover
VAUXHALL (Corsa, Astra, Vectra, Zafira)				☑		
VOLKSWAGEN (Golf, Passat, Bora)	☑	☑	☑			Boot lid
VOLVO (C70, V70)		☑				Natural foams, cargo floor tray

Table 10. Applications of natural fibres in other fields. Adapted from: [100,101].

Fibres	**Applications**	**Reference**	**Composition**	**Manufacturer**
Coir	Containers, boxes, trays, packaging	[100]	Coir and natural latex rubber	Enkev
Flax	Green wall panel	[100]	50% recycled resin, reinforced with flax (25%) and E-glass (25%) roving	Innovation in green composites technology
Flax, Hemp	Racing Bicycle	[101]	Flax, Hemp and Epoxy	Museeuw Bikes
	Cases for musical instruments	[100]	Plastics (PLA and PP) and additives, natural fibres	Green line
Flax, Balsa, Wood	Summer and winter sports	[100]	Natural fibre and composite reinforcement material	Bcom
Hemp, Jute, Kenaf	Containers for shipping and storage, interior panels, load floors and underbody shields for cars and trucks, workspace panels and Furnishings for offices and homes, structural support for agricultural seedlings	[100]	Natural fibres and fiberized thermoplastic polymers	FlexForm Technologies
Kenaf	Mobile phone casing	[101]	Kenaf and PLA	NEC
Wood	Modular house construction	[100]	Wood plastic composites	Tech-wood International

4. Future Trends

This section is devoted to the future trends in terms of applications of natural fibres. However, it is important to point out there are only very few reports on use of the bio-based materials in the

European activity sectors. There is only a limited information and transparency about applications, markets and future market potential. Moreover, the latest market data is from 2012 and no information is available since then in the last five years [102]. There could be two reasons for this situation. First reason is that the industrial sector in general and the automotive sector in particular, do not see natural fibres as a part of the bio-based industries; consequently, there are no targets to increase the share of bio-based products. Secondly, the industrial sector is very sensitive about privacy and only a few producers disclose data while others prefer not to share any data and official statistics on shares of bio-based materials in the products [102].

Based on [95], the use of natural fibres is expected to increase significantly in future as they are starting to enter other markets than just the automotive sector. The production forecast scenarios are presented in Table 11 for 2012 and 2020. A significant difference in amount of natural fibre and wood-based composites can be observed for this period. However, it can be argued that the fast development will not take place if there are no substantial political incentives to increase the bio-based share of the materials used in products, mainly in automotive sector products. [95].

Table 11. Production (in ton) of wood based and natural fibre composites in 2012 and their forecast for 2020. Adapted from: [95].

Bio-Composites	Production (ton)		
	2012	2020 (without Incentives for Bio-Based Products)	2020 (with Strong Incentives for Bio-Based Products)
Wood-Plastic Composites			
Construction, extrusion	190,000	400,000	450,000
Automotive, compression moulding and extrusion/thermoforming	60,000	80,000	300,000
Granulates, injection moulding	15,000	100,000	>200,000
Natural Fibre Composites			
Automotive, compression moulding	90,000	120,000	350,000
Granulates, injection moulding	2000	10,000	>20,000

The potential of use of natural fibres, especially as composite reinforcement, depends largely on the increasing of regulation and its commercial characteristics, namely by creating standards for their production and post-treatment. The evolution of the knowledge regarding natural fibres will allow to standardize the kind of fibres available in the market and allow designers to have higher levels of trust concerning mechanical and chemical properties. The scientific community has a crucial role in relation to the releasing of accurate and fully characterized studies allowing a robust increase in fundamental knowledge about natural fibres.

5. Discussion and Conclusions

Natural fibres polymeric composites are an effective way of improving the quality of parts regarding the environment, economic and technical feasibility. However, to accomplish this goal, there are certain issues that need to be tackled.

A first issue is addressed in Section 2, where a comparison of the several natural fibres properties and price is presented. However, it is clear from this review that material properties are strongly dependent on the context namely, where the crop is cultivated, how the treatment is made, how it is processed and applied. Moreover, it is also evident from this section that several natural fibres are available in the market and whilst most have relevant mechanical properties, they also present very scattered properties. Again, this is due to the natural cycle but also due to each manufacturer using its own method to produce and use these natural fibres. It can also be noticed that several studies present results using different standards and some are not even clear about the standards used.

Another important observation is that several fibres are reported as more expensive than others, with the same performance in terms of mechanical properties. Fibres such as flax, ramie, cotton and hemp are reported to have costs that are superior to all the others but with no great advantage in terms of mechanical properties. Availability, reliability or other "ility" are responsible for this. Therefore, selecting the most suitable natural fibre for a particular application requires an integrated analysis followed by a decision-making process.

Despite all of these aforementioned issues, there are several markets and industries that have interesting applications of natural fibres. The automotive industry is the most active and knowledge-intensive sector which plays an important role in the development of non and semi-structural parts. But there are other industries which gradually branched out to products segment made of natural fibre composites as well, such as furniture, medical, sports, among others.

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