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Reinforced Polymers with Natural Fiber

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Abstract: The interest in obtaining new composite materials with diverse properties has created a growing interest in natural fibers as reinforcement in polymers, which has generated an impact in sectors such as automotive and construction, displacing synthetic fibers. Properties such as low density, low cost, and renewable make these fibers an attractive alternative to reduce environmental impact. Their application in polymers, such as polypropylene, polyethylene, and epoxy resins, has allowed the modification of polymeric composite materials' mechanical and physical properties (NFRP). This review focuses on investigating the status of natural fiber-reinforced polymers. It analyzes their worldwide demand, chemical characteristics, physical and mechanical properties, and various applications in different sectors and industries. In addition, the advantages and disadvantages of NFRPs are highlighted, highlighting their potential for new applications.

Keywords: natural fibers; reinforced polymers; composites; properties

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1. Introduction

The use of fiber-reinforced polymers (FRP) has been in construction industry applications for several years; its use has spread to different sectors over time. FRP composites are composed of fibers that act as reinforcement or fillers in a polymer matrix. These fibers can be inorganic or of organic origin. The predominant focus has been using synthetic fiber-reinforced polymer composites (SFRP) in high-performance applications, such as aerospace or automotive, where mechanical properties and light weight are critical, considering that the application of these reinforced materials should not be in areas where the physical and mechanical properties are not highly demanding. However, the high cost and high energy demand associated with producing these reinforcing materials pose challenges in terms of environmental sustainability. The lack of adequate recycling of these materials can also pose environmental problems in case of excessive use [1].

The use of natural fibers as reinforcing material has experienced a progressive replacement of synthetic fibers in various applications, such as the automotive, maritime, aerospace, and construction industries, among others [2,3]. This transition is largely due to the intense research carried out in recent years to develop more biodegradable and environmentally friendly materials that offer improved characteristics and attractive physical and mechanical properties. These improvements include lower density, higher strength, processing flexibility, and higher stiffness while reducing the associated costs [2–4].

Composites made from natural fibers, compared to those made from glass fibers, exhibit a notable advantage in terms of light weight due to their respective densities. Natural fibers have densities ranging from 1.2 to 1.6 g/cm3, while glass fibers have densities ranging from 2.16 to 2.68 g/cm3 [5,6] This difference in density gives composites with natural fibers a significant advantage in applications where weight is a critical factor. By reducing the density of the reinforcing material, components made with natural fibers become lighter.

The manufacture of natural fibers consumes about 82% less energy compared to glass fibers [6]. In addition to their low density, natural fibers offer a number additional benefits that make them an attractive option in various applications. These advantages include their non-abrasive property,

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which minimizes wear and prolongs the service life of surfaces in contact with these materials. Also, their non-toxic nature makes them safe for handling and use in applications that require environmentally and health-inert materials. Another property is an electrical insulator. In addition, natural fibers have good resistance to high temperatures. These properties together make natural fibers a valuable and versatile option for various industrial applications, offering a range of characteristics to suit different needs. In the polymer sector, natural fiber reinforcement has become an essential adoption in the automotive and construction industries [7–12].

Therefore, it is essential to achieve new research in developing and studying thermoplastic and thermoset composites reinforced with natural fibers. The main objective of this review is to present an analysis of the current development of NFRPs. The worldwide demand for the production of vegetable fibers and their relevant chemical and physical properties are presented. The different types of NFRP are also addressed, along with their advantages and disadvantages, physical and mechanical properties, and current applications. In addition, the author's views on the prospects for applying these natural fiber-reinforced materials are provided.

2. Classification of Vegetables Fibers

Vegetable fibers, often called continuous filaments or discrete elongated pieces, resemble yarns or ropes and can be spun into filaments, threads, or ropes. These versatile fibers have applications as components in composite materials and manufacturing paper sheets or felt [13]. The classification of plant fibers encompasses three main types: fibers from seeds, high-availability fibers, and low-availability fibers. Each category comes from different plant sources, as detailed in Figure 1 [14]. Table 1 shows the global production of some fibers worldwide.

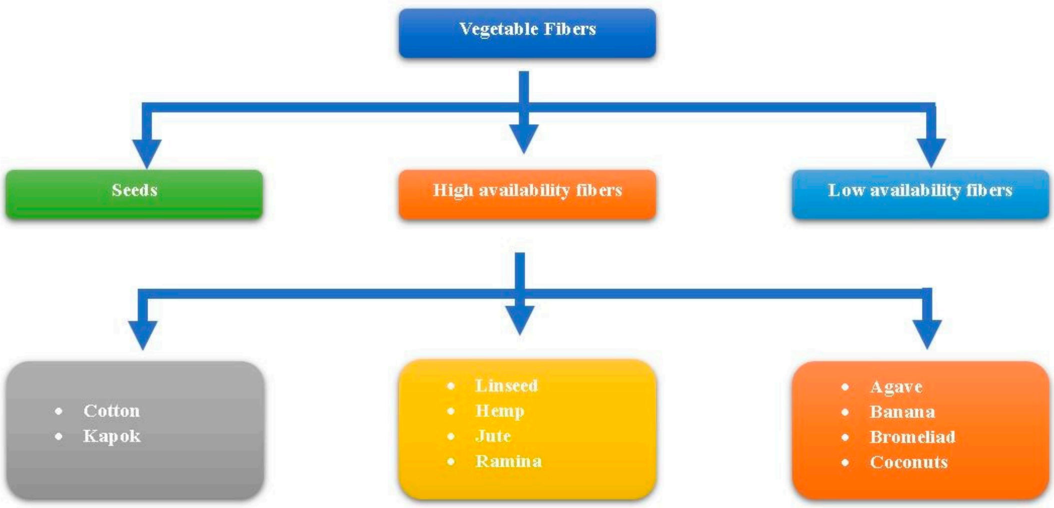

Figure 1.

- Vegetable Fibers:

Vegetable fibers are extracted from various plants and have been used for centuries in a variety of applications. Among them, hemp (Cannabis sativa) is one of the most versatile and widely used in the manufacture of reinforced polymers. Hemp stands out for its high mechanical strength and lightweight, which makes it an excellent choice for applications where the strength-to-weight ratio is important.

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Table 1. World production of natural fibers [15,16].

Type of fiber	Fibers extracted from	Countries of origin	World production (10^3 ton)
Flax	Bast	Canada, France, Belgium, Spain	830
Hemp	Bast	China, France, Philippines, Poland, Spain	214
Jute	Bast	India, Egypt, Guyana, Jamaica, Ghana, Malawi, Sudan, Tanzania, Brazil, China, Bangladesh	2300
Kenaf	Bast	India, Bangladesh, USA, Iraq, Tanzania, Jamaica, South Africa, Cuba, Togo, Thailand	970
Ramie	Bast	China, Brazil, Philippines, India	100
Abaca	Leaf	Philippines, Ecuador, Costa Rica, Colombia	70
Curaua	Leaf	Brazil, Venezuela, Guyana, Columbia	>1
Pineapple	Leaf	Philippines, Thailand, Indonesia	74
Sisal	Leaf	Brazil, East Africa, Haiti, Venezuela, Antiqua, Kenya, Tanzania, India	378
Coir	Seed	India, Sri Lanka, Philippines, Malaysia, Brazil	100
Cotton	Seed	China, India, USA	25,000
Oil Palm	Seed	Malaysia, Indonesia	40
Bagasse	Grass	Brazil, India, China	75,000
Bamboo	Grass	India, China, Indonesia	30,000

Fibers are obtained from different sources and can be obtained naturally, and each of them may differ in their properties, but generally there are some similarities between them. Table 1 lists their advantages and disadvantages, and Table 3 shows the chemical composition of some fibers reported in the literature to obtain composites materials with different polymers.

Table 2. Advantages and disadvantages of natural fibers [17].

Advantages	Disadvantages
• It is a renewable and highly available material. • Good mechanical properties, especially tensile strength. • Good performances as a thermal, acoustic, and electrical insulators. • Biodegradability: Natural fibers tend to be biodegradable under certain conditions. • Reactivity: The hydroxyl groups constituting the cell wall provide sites for water absorption and availability for chemical modification.	• Lower strength properties compared than synthetic polymers, especially its impact resistance. • Variation in quality due to influence on environmental conditions. • Moisture absorption causes an increase in volume in the fibers. • Limited maximum processing temperature. • Limited durability, with some treatments, can be improved. • Low heat resistance.

Table 3. Chemical composition of some vegetable fibers.

Fiber	Cellulose [wt%]	Lignin [wt%]	Hemicellulose [wt%]	Pectin [wt%]	Wax [wt%]	Moisture [wt%]	Ash [wt%]	Micro-fibrillar angle [°]	Ref.
Abaca	56-63	7-9	20-25	-	3	-	-	20-25	[13]
Bamboo	26-43	1-31	30	-	-	9.16	-	-	[18]
Banana	83	5	-	-	-	10.71	-	11-12	[18]
Coir	37	42	-	-	-	11.36	-	30.45	[13]
Cotton	82.7-91	-	3	-	0.6	7.85-8.5	-	-	[13]
Curauá	73.6	7.5	9.9	-	-	-	-	-	[18]
Flax	64.1-71.9	2-2.2	64.1-71.9	1.8-2.3	1.7	8-1.2	-	5-10	[19]
Hemp	70.2-74.4	3.7-5.7	17.9-22.4	0.9	0.8	6.2-1.2	0.8	2-6.2	[18]

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Jute	61-71.5	12-13	17.9-22.4	0.2	0.5	12.5-13.7	0.5-2	8	[20]
Kenaf	45-57	21.5	8-13	0.6	0.8	6.2-12	2-5	2-6.2	[13]
Rachis	42.75	26	-	-	-	-	-	28-37	[18]
Ramie	68.6-91	0.4-0.7	5-14.7	1.9	-	-	-	69-83	[13]
Rice husk	38-45	-	12-20	-	-	-	20	-	[18]
Sea Grass	57	5	38	10	-	-	-	-	[18]
Sisal	78	8	10	-	2	11	1	-	[13]

3. Physical and Mechanical Properties of Vegetables Fibers

Vegetable fibers contain micro levels of fibers and matrices; their main composition is a combination of cellulose, lignin, and hemicellulose matrices; the properties of the natural fiber, such as mechanical strength and flexibility, are given by the structure of the different components in the fiber (Figure 2).

Table 4 presents some of the most relevant mechanical properties of various vegetable fibers compared to synthetic fibers.

Table 4. Properties of different natural fibers [14].

Vegetable Fibers	Density (g/cm³)	Diameter (μm)	Tensile Strength (MPa)	Module of Young´s (GPa)	Breaking strain (%)
Abaca	1.5	10-30	400	12	3-10
Alpha	0.89	-	350	22	5.8
Bagasse	1.25	490	70	17	3-5
Bamboo	0.88-1.1	100-200	391-713	18-55	1.3
Banana	1.35	50-250	500-550	12-20	5-6
Coconuit	0.8	100-450	131-175	4-13	15-40
Coir	1.2	10-16	175	4-6	30
Cotton	1.5-1.6	20	287-597	5-13	7-8
Curagua	1.38	66	913	50-70	3.9
Date palm	1-1.2	14-18	97-196	2.5-5.4	2-4.5
Flax	1.5	50-100	345-1035	50-70	2.7-3.2
Hemp	1.1	120	389-900	35	1.6
Henequen	1.49	180	430-580	10.1-16.3	1.6
Ixora	1.2-1.3	10	500-600	-	5-6
Jute	1.3	260	393-773	23-27	1.4
Kenaf	1.31	106	427-519	23-27	1.8
licuri	-	132-165	287-597	5-13	7.8
nettle	1.5	20-80	650	38	1.7
Oil palm	0.7-1.55	150-250	248	25	3.2
Palmira palm tree	1.2	300-320	276	8.99	3.08
Piasava	1.4	-	134-143	1.07-4.59	7.8-21.9
Pineapple	0.8-1,6	25-34	400-627	14.5	1.44
Ramia	1.5	34	560	24.5	2.5
Sisal	1.5	50-80	511-635	9.4-22	2.0-2.5
Softwood kraft	1.5	-	1000	40	4.4
Spider silk	0.014	2-8	875-972	11-13	17-18
Talipot	-	80-800	143-263	10-13	5.1
Vetiver	1.5	100-220	247-723	12-49.8	1.6-2.4
Wool	-	20-30	120-174	2.3-3.4	25-35
Linen	1.4	12-60	8000	50-70	2.7-3.5
Synthetic fibers					
Aramid	1.4	-	3000-3150	63-67	3.3-3.7

Carbon	1.4	5-9	4000	230-240	1.4-1.8
E-Glass	2.5	9-15	200-3500	70	2.5
S-Glass	2.5	5-25	4570	86	2.8

The properties of materials reinforced with natural fibers are obtained from the volume fraction of the components, type of fibers, and distribution of the components in the solid. Heat treatment in diverse fiber-polymer composite materials is being investigated to improve the properties of these materials. These treatments may include chemical modifications, heat treatments, or external coupling agents that improve the bonding between the fibers and the matrix [21].

Another crucial aspect in developing materials reinforced with natural fibers is the prediction of Young's modulus and composite strength. Several mathematical models established for specific systems have been implemented, allowing comparisons with experimental data obtained through mechanical tests.

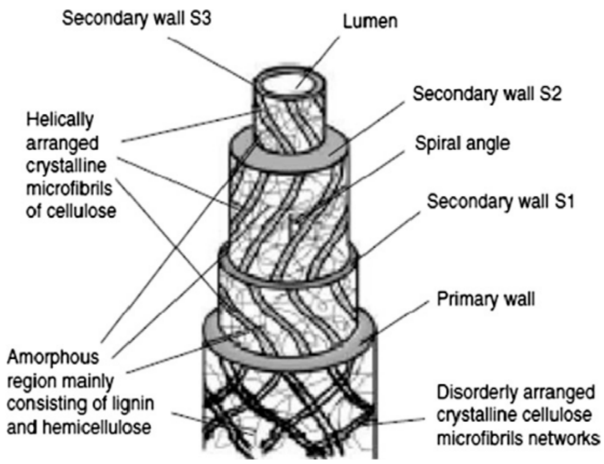

Figure 2. Schematic of the structure of a natural plant fiber [24].

It is important to note that while the incorporation of natural fibers can significantly improve certain properties of the composite material, there are also challenges in terms of fiber homogeneity and dispersion. These factors can affect the variability of properties and require careful optimization during the manufacturing process. To advance the field of natural fiber-reinforced materials, a multidisciplinary approach encompassing materials engineering, polymer chemistry, and solid mechanics is needed. In addition, the application of advanced characterization techniques, such as electron microscopy and image analysis, is essential to understanding the structure and mechanical behavior of composites [21].

4. Applications of Vegetable Fibers

Botanical types are widely used to classify natural fibers. According to Rowell R. [25], this approach identifies five specific types of natural fibers: (i) bark fibers, such as jute, flax, hemp, rami, and kenaf; (ii) leaf fibers, such as banana, sisal, agave, and pineapple; (iii) seed fibers, such as coir, cotton, and kapok; (iv) grass and reed fibers, such as wheat, corn, and rice; and (v) other types, such as roots and wood. It is important to mention that some crops can produce more than one type of fiber. For example, jute, flax, hemp, and kenaf have both bark and kernel fibers, while agave, coconut, and oil palm have both fruit and stalk fibers. Likewise, cereal grains also contain both stem and kernel fibers Table 5, [23].

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Table 5. Types of vegetable fibers and their use.

Natural fibers	Applications	Ref.
Abaca	They include textiles, clothing, functional papers such as money, magazine paper, checks, and composite materials	[25]
Bamboo	They include lactic acid, construction, vinegar, charcoal, methane, composite reinforcement, footwear, food, textiles, pulp and paper production, shock absorbers, and bioenergy sources.	[26]
Banana/Musa	Banana/Musa They include products such as ropes, placemats, paper cardboard, rope threads, tea bags, high-quality textile fabrics, paper money, mushrooms, arts/crafts, ropes, cushion covers, tablecloths, curtains, natural wastewater absorbents colored, oil absorbent, lightweight compounds, and biofertilizers	[27,28]
Biduri	Biduri Heat insulating materials	[29]
Coir	Coir They are fillers used as reinforcement in composite materials and lightweight composites.	[27–30]
Collagen fiber	Collagen fiber Their application is tissue manipulation and the use of sewing thread for surgery.	[30]
Cotton	Cotton Their applications are in fabrics, clothing, and threads in the furniture industry as covering materials.	[25]
Derris scanden	Alternative reinforcing agents to replace synthetic fibers in polymer matrix composites are being investigated.	[31]
Hemp	These include bags, tarps, carpets, ropes, furniture materials, fabrics, textiles, garden mulches, fleeces and felts, lightweight composites, composites, and the geotextile and geotextile insulation industry.	[32]
Jute	These include bags, sacks, carpets, carpet upholstery, geotextiles for transport or construction, electrical insulation and ropes, tarpaulins, packaging, furniture materials, fabrics, and lightweight composites.	[30]
Pineapple	Pineapple Included are bags, tablecloths, mats, ropes, paper pulp material, tote bags, composites, lightweight duck cloth, conveyor belt cords, coasters, and other interior design products and applications in livestock breeding and agriculture.	[33]
Kenaf	There are products made from pulp and paper.	[30]
Ramie	They include textiles, paper, pulp, yarn, biofuel, fabric, oil, resin, wax, foods made from seeds, composites, livestock and agriculture.	[30]
Silk	Cloth and silk thread are found	[30]
Wool	The party favors and wool thread is included. [32]	[30]
Sorghum bagasse	These include particle board, sugar production sources, and pulp and paper.	[29–36]

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Several previously cited researches have addressed the use of natural fibers as a fundamental element in the creation of composite materials, being applied in contexts such as the improvement of automotive interiors (such as roofs, side panel coatings, rear panels, and seats) [37,38].

In the natural fibers, the presence of polar groups such as hydroxyls, as well as components such as dead cells, wax, and oil, together with their limited fire resistance, results in an initial incompatibility between natural fibers in their raw state and polymers, which can lead to the formation of aggregates. Additionally, natural fibers' high water absorption capacity leads to lower interface strength compared to composites based on glass or carbon fibers. Developing environmentally friendly composite applications is crucial to thoroughly understanding the fundamental properties and constituents of natural fibers. In addition, specific attributes such as length, flexibility, and strength must be satisfied to employ natural fibers in textile manufacturing.

Abaca-derived fibers have significant potential as a raw material in the textile industry due to their robustness and ability to resist moisture and salt water [29]. On the other hand, Biduri fibers present a hollow structure that acts as a kind of air medium or trap, which could be beneficial in applications where heat flow needs to be regulated and controlled [39]. In addition, Biduri fiber is hypoallergenic, soft, and hydrophobic [29].

Munawar et al. [40] have documented that ramie fibers, pineapple, and sansevieria leaves demonstrate natural thermal insulation qualities, renew their origin, and are in harmony with the environment. Also, sansevieria leaves are revealed as superior-performance plant fiber composite components, given their remarkable potential in terms of mechanical properties. In a separate study, Kandachar and Bruwer [41] report that hemp fiber, thanks to its exceptional strength and stiffness, is particularly suitable as a reinforcing agent in biocomposites, Natural Fiber Reinforced Plastics (Composites).

Natural fiber-reinforced composites use natural fibers themselves as the reinforcing component. These fibers are characterized by their abundance, renewable nature, biodegradability, and lower density compared to other synthetic materials used for reinforcement [42,43]. Some of the natural fibers commonly used as reinforcement include rice husk [44], henequen [45], banana [46], abaca [47], birch fibers [48], Hemp [49], jute [43–50], sisal [52,53], flax [54,55], curaua fibers [56], sour-weed [57], among others.

The composite manufacturing process involves a combination of components, including the matrix phase, which consists of natural resins, thermoplastics, and thermosets [58]; this matrix phase plays the role of binder, fusing the elements to form the composite. Among the natural resins used are wheat starch, corn starch, potato starch, biodegradable polyesters, and poly acids, among others [59]. On the other hand, thermosetting polymers include options such as epoxy, polyesters, and phenolics, among others. In addition, thermoplastic polymers, such as polycarbonate, polyvinyl chloride, nylon, polystyrene, polyethylene, among others, are also used in this mixture [49–58].

When employing plant fibers as reinforcement, it is essential to consider crucial factors, including fiber thermal stability, total fiber volume, fiber fraction or percentage, fiber size, fiber orientation, texture, wetting capacity, and moisture content [37].

The biodegradation capacity of plant fibers can contribute to ecosystem health and to their low cost and high performance, which meets the economic objectives of the industry. At the end of their life cycle, when polymers are reinforced with natural fibers for combustion or landfill processes, the amount of CO2 released by these fibers is balanced with the amount of CO2 absorbed during their growth [8–62].

Synthetic fibers of glass, carbon, and aramid, reinforced with polymeric matrices, offer significant advantages in terms of stiffness and strength-to-weight ratio in many applications compared to conventional construction materials. However, despite these advantages, researchers are working on developing natural composites for the widespread use of synthetic fiber-reinforced polymer composites, which are facing a decline due to their high initial costs. An additional significant challenge is that the production of synthetic composites consumes much energy and hurts the environment by the pollution generated during the production and recycling of these synthetic materials. A list of various plant fiber-reinforced polymer resins, as reported in various studies, is presented in Table 6.

Table 6. Compilation of different plastic resins reinforced with natural fibers.

Natural fiber reinforcement	Polymer resin (Matrix)	Properties studied	Ref.
a) Sisal: 40% b) Kenaf: 30%, 40%, 50% c) Hemp: 40% d) Jute: 40% e) Coir: 40%	Polypropylene	• Tensile strength • Flexural strength • Impac strength	[62]
a) Sisal fiber yarns: 10%	Polypropylene	• Tensile strength • Thermal gravimetric analysis (TGA)	[63]
a) Kenaf fiber: 20%	1) Thermoplastics natural rubber 2) Polypropylene/ ethylene-propylene-diene-monomer	• Tensile strength • Flexural strength • Impact strength	[64]
a) Coir fiber	Epoxy-CY205	• Tensile strength • Flexural strength • Impact strength • Fractography	[65]
a) Coir fiber	Polyester resin	• Tensile strength • Fractography	[66]
a) Sisal fiber: 10%, 20%, 25%, 30%.	Rubber seed oil-based polyurethane	• Spectroscopy analysis • FT-IR • Thermal gravimetric analysis • Water adsorption behavior	[67]
a) Sisal fiber b) Glass fiber hybrid	Epoxy resin	• Hardness • Impact strength • Frictional coefficient • Chemical resistance • Compaction test • Moisture absorption • Compression strength	[68]
a) Sisal b) Banana c) Jute d) Enzyme retted flax fibers (fiber fraction:20wt-45wt%)	Polypropylene	• Flexural strength • Izod and Charpy test • Morphological study	[46]
a) Kenaf b) Jute (fiber fraction: 10%, 20%, 30%, 40%, 50%, 60%, 70%)	Polypropylene	• Tensile strength • Flexural strength • Fiber volume fraction • Void content and surface morphology	[69]
a) Abaca fibers b) Jute fibers c) Flax fibers	Polypropylene	• Tensile strength • Flexural strength • Charpy test (Impact) • Odour measurement • Morphology	[70]

a) Kenaf fiber: Weight fractions (10%, 30%, 50%, 70%)	Poly lactic acid (PLA)	• Flexural strength • Dimensional stability and water absorption • Dynamic mechanical analysis (DMA) • Differential scanning calorimetry (DSC) • Thermogravimetric analysis (TGA)	[71]
a) Kenaf fibers	Epoxy resin	• Pull-out test • Tribological properties	[72]
a) Kenaf fibers	Epoxy resin	• Thermogravimetric analysis	[74]
a) Pineapple	Polypropylene	• Tensile strength • Flexural strength	[74]

5. Advantages of Plant Fiber Reinforced Plastics

Environmentally friendly composite materials have found diverse commercial applications due to their advantages, such as lower abrasiveness for processing equipment, renewability, lower energy consumption in processing, lightweight, non-toxicity, easy availability, low cost, and biodegradable properties. However, there are challenges to overcome, such as thermal stability, moisture absorption of natural fibers, and poor adhesion between these fibers and the matrix material, which are vital factors to consider in developing these materials [75]. The choice of natural fiber-reinforced materials as composites is due to several fundamental reasons [76].

I. Composites show good adaptability in different conditions since when any fiber is combined with other materials, it improves its mechanical properties significantly compared to other materials.

II. The tensile strength of composites is approximately 4 to 6 times higher than steel or aluminum, making them high-strength materials.

III. The strength-to-weight ratio of composites is higher than other materials, which makes them ideal for applications where high strength with reduced weight is sought.

IV. Composites have a high stiffness-to-mechanical strength ratio compared to other composite materials, making them structurally efficient.

V. Composites are lighter than other materials, such as wood and metals. These properties are widely used in manufacturing automobiles and airplanes since their lighter weight improves fuel efficiency and increases travel speed.

VI. Composites offer excellent resistance to environmental and chemical damage, making them ideal for applications in harsh environments.

VII. Composite materials exhibit high impact resistance, making them suitable for applications requiring increased shock and impact resistance.

VIII. Their ability to eliminate joints and simplify integrative designs makes them attractive in applications where reducing parts and assemblies is desirable.

IX. Composites exhibit exceptional corrosion resistance and good flame retardancy, making them suitable for applications where high protection against corrosive environments and fire hazards is needed.

X. composites offer good insulation and excellent thermal properties, making them useful in applications where effective temperature control is required.

In addition to the abovementioned advantages, natural fiber-reinforced composites also offer significant environmental benefits. Natural fibers are derived from renewable sources, such as plants; these materials reduce dependence on non-renewable resources and contribute to carbon footprint mitigation compared to traditional petroleum-based composite materials. Using natural fibers in composite materials can also promote the local economy and sustainability of the agricultural industry, as many fibers come from crops. Incorporating these materials into the industry can create economic opportunities for rural communities and encourage sustainable agricultural practices [5–11].

Another advantage of natural fiber-reinforced composites is their biodegradability. As concerns about environmental pollution and polymer waste increase, the ability to decompose naturally at the end of their useful life without leaving toxic residues. It represents a significant advance in the search for more sustainable solutions. It is essential to mention that while natural fiber-reinforced composites offer many advantages, there are also specific challenges to overcome in their development and application. The natural variability of the fibers, which can depend on factors such as the type of plant or the extraction process, can affect the uniformity and consistency of the material's properties.

Therefore, continued research and development in this area is essential to optimize and refine the manufacture of natural fiber-reinforced composites, addressing the above challenges while maximizing their environmental and economic benefits.

6. Mechanical and Physical Properties of Composites

The mechanical properties of thermoplastic composites can be enhanced by improving fiber-matrix compatibility. These composites have also been shown to be biocompatible, making them promising options as biomaterials [77]. Several investigations have been carried out to study the effect of different factors on the mechanical behavior of polymer composites reinforced with natural fibers.

To improve the adhesion between the fibers and the polymer matrix, compatibilizers such as maleated ethylene, maleated polypropylene and some linear polymers grafted with acrylic are used [78,79] , for example, in the case of HDPE composites with cellulose fiber at fiber concentrations between 10% and 30%, it has been observed that the incorporation of maleated ethylene produces a notable increase in tensile strength and tensile modulus. This positive effect is attributed to the coupling reaction, specifically an ester bond, between the maleated ethylene and the hydroxyl groups of the cellulose. This reaction improves the bonding between the fiber and the matrix, leading to a significant improvement in the mechanical properties of the composite [78]. In addition to compatibilizers, other factors such as fiber content and orientation, type of fiber used, surface treatments and processing techniques can also influence the mechanical behavior of composites reinforced with natural fibers.

It is important to note that the design and development of thermoplastic composites reinforced with natural fibers is a constantly evolving field of research. The optimization of the compatibility between the fiber and the matrix, as well as the search for new and more effective additives and treatments, are active areas of study with the aim of further improving the mechanical and functional properties of these materials. Furthermore, the study of their biocompatibility opens up exciting prospects for their application in biomedical and healthcare applications.

Reddy S. S. and Husain S.P. [80], conducted a study on the development and testing of natural fiber reinforced composites using polyester resin. According to their findings, the mechanical properties of polymer composites reinforced with sisal and hemp increased with increasing fiber fraction and fiber weight. The combination of hemp and sisal composites showed the best results. The interfacial adhesion between the matrix and the fibers mainly influenced the tensile properties of the composites reinforced with natural fibers (both thermoplastic and thermoset). In addition, it was found that chemical modifications of composite materials can improve their mechanical properties. Similar investigations on natural fibers such as bamboo, hemp, flax and kenaf also reveal that the mechanical properties of fiber-reinforced composites depend on various fiber parameters, including loading, length, aspect ratio, orientation and adhesion to the matrix. Sakthive M. and Ramesh S. [10], focused their study on the mechanical properties of polymer composites reinforced with natural fibers, specifically banana, coconut and sisal. They found that natural composites reinforced with banana obtained the best performance among the various combinations of natural

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fibers. These composites proved to be suitable for the manufacture of automotive seat shells, among other applications.

On the other hand, Carrasco et al., [21] investigated the mechanical properties of HDPE/wood fiber composites, evaluating two types of coupling agent: Epolane C-18 and Silane 174. The results indicated that the use of Silane coupling agents produced composites with better mechanical properties compared to wood fiber composites treated with Epolane or without any treatment. Pedroso and Rosa [81] fabricated recycled LDPE blends with corn starch and studied their mechanical, thermal and morphological properties. The addition of corn starch to the LDPE reduced the flow index and tensile strength, while the modulus increased. It was observed that the largest decrease in the melt flow index and tensile strength was most evident in the blends with 40 and 50 wt% corn starch.

Men et al., [82] developed a copolymer based on corn starch grafted onto polystyrene (starch-g-PS) using [EMIM]Ac ionic liquid as solvent and potassium persulfate. The resulting copolymer showed that the polystyrene side chains were evenly distributed over the starch backbone, suggesting that dissolving starch in ionic liquid before grafting polystyrene is a methodology for the synthesis of amphiphilic copolymers. Another study developed by Bing Zeng et al., [83] shows the elaboration of a mixture of poly(butylene succinate) (PBS) with thermoplastic starch (TPS), to improve the miscibility between TPS and PBS, the PBS reagent (RPBS) was first synthesized with the NCO terminal group and then mixed with thermoplastic starch. It was observed that the composite polymer obtained from the mixture improved its mechanical properties, tensile strength up to 10 times more than TPS, using only 10 wt% of RBS, water absorption decreased as the percentage of RPSB increased, thus the applications of these materials could be expanded. On the other hand, authors such as Chegdani et al., [84] studied the tribological properties of polypropylene reinforced with different types of natural fibers (bamboo, sisal and miscanthus), observing a viscoelastic behavior of the fiber that contributed to a deformation on the surface of the material during machining, increasing the surface strength in the contact area. Amri et al., [85] added graphene oxide to a bioplastic based on cassava starch, observing improvements in tensile strength and Young's modulus with increasing graphene oxide concentration, although elongation tended to decrease. Chaka et al., [86] studied the compressive strength of recycled PET reinforced with natural banana and sisal fibers, showing that natural fiber-based composites were 36% lighter than glass-reinforced polymers and showed a maximum compression set of 3.1 MPa, suggesting that the use of natural fibers is a viable and economical alternative for the recycling of plastics such as PET. Khan et al., (2014) observed the mechanical properties of composites using okra as reinforcement in a matrix with phenol-formaldehyde and concluded that 30% okra fiber in the composite obtained the maximum tensile strength and deflection values.

Studies such as that of Bansal et al., [87] formulated a composite based on sesame residues and low density polyethylene, observing that gamma irradiation improved the mechanical properties of the composite, especially the test with 30 wt% of sesame irradiated with 125 kGy showed significant improvements [88]. According to the mechanical tests the test with 30 wt% sesame seed irradiated with 125 kGy was the one that showed improvements in its mechanical properties. Another similar study was conducted by Rahman et al., [88] in which, they studied gamma irradiations on polypropylene reinforced with okra fiber and polypropylene with jute fiber, both with 40% fiber concentration. The results showed that polypropylene with okra fiber improved its mechanical properties such as tensile strength, tensile modulus, elongation at break, impact resistance compared to polypropylene with jute fiber. Singh A. S. and Thakur V., [89] investigated the mechanical properties of natural fiber-reinforced polymers, finding that the tensile strength, compressive strength and wear resistance of urea-formaldehyde resin increased significantly when reinforced with fiber. Flax fiber showed a wide application potential in the fabrication of polymer composites reinforced with natural fibers. Maleque et al., [90] developed an aluminum composite reinforced with coconut fiber for brake pad applications in the automotive industry, observing that better mechanical properties were obtained with 5% and 10% coconut fibers. Alaneme et al., [91] studied the mechanical properties and corrosion behavior of the hybrid composite of aluminum reinforced with silicon carbide and bamboo leaf ash, the results showed that the hardness, ultimate tensile strength and percentage elongation of the hybrid composite, decrease with increasing bamboo leaf ash content. In addition, they showed high corrosion resistance compared to the simple reinforced composite. Sen T. et al, [92] studied various industrial applications of natural hemp, kenaf, flax and ramie fibers, while Shinji Ochi, [93] investigated the tensile properties of bamboo fiber reinforced biodegradable plastic, concluding that the tensile strength of composites increases with increasing fiber content up to 70%, showing an extremely high tensile strength of 265 N/mm^2. Natural fibers have been cultivated and used mainly in rural developing countries in the manufacture of bags, brooms, fishing nets and filters [76]. Depending on the natural fiber, a long list of variations in its properties can be found [94]. Table 7 lists the physical and mechanical properties of various composites.

Table 7. Physical and mechanical properties of natural fiber reinforced polymers.

Fiber	Tensile strength (MPa)	Elongation at break (%)	Young´s modulus (GPa)	Density (g/cm^3)	Ref.
Yute	400-800	1.5	10-30	1.46	[95]
Sisal (Henequen)	400-700	05-14	09-12	1.45	[96]
Coconut fiber	175	30	4-6	1.2	[97]
Hemp	550-900	1.6	70	1.48	[98]
Cotton	287-597	2-10	6-10	1.21	[99]
Pineapple	413	1.6	6.21	1.526	[100]
Abaca	980	10-12	9.0-28	1.5	[9]
Kenaf	930	1.6	53	1.45	[21]
Ramie	511-635	3.6-3.8	9.4-22	1.5	[76]
Oil palm	71	11	1.703	-	[76]
Flax	500-1500	2.7-3.2	27.6	-	[76]
Banana	10.854	6.085	1.63	1.02	[101]
Bagasse	290	1.1	17	1.25	[76]
Kevlar 49	3650	2.5	124	1.44	[76]
Date palm	97-196	2-4.50	2.50-5.40	1-1.20	[102]
Bamboo	73-505	4.11	10-40	4.3	[103]

7. NFRP´s Applications

Today, natural fiber reinforced composites (NFRPs) are gaining ground in various industries due to their outstanding qualities. These qualities include low density, biodegradability, recycling potential, acceptable specific strength, convenient availability, reduced tool wear during the molding process, improved acoustic properties, reduced cost and ease in the manufacturing process. Although NFRPs find applications in several areas, they stand out mainly: a) the automotive industry, b) construction, and c) the sports industry. Although in other areas their presence may be less significant, it is in the automotive industry where the demand is most notorious. In this section, we will concentrate exclusively on automotive applications.

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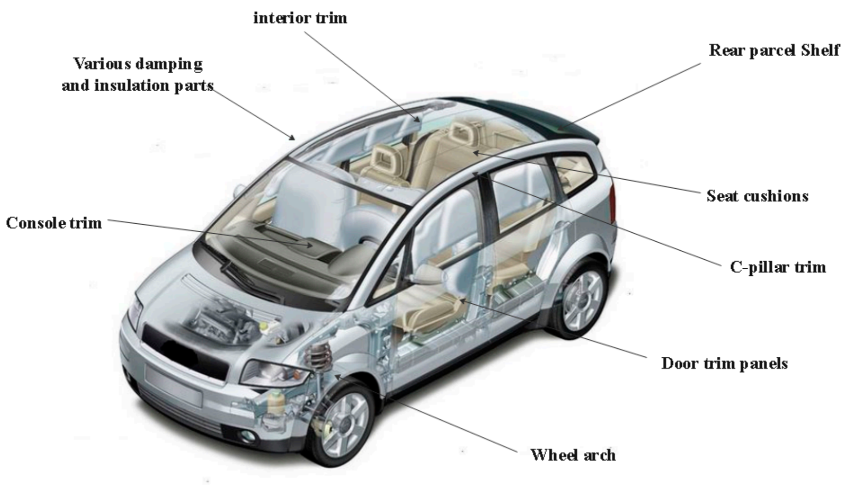

Figure 3. Applications of NFRPs in the automotive field [63–105].

Table 8. Compilation of NFRP applications in the automotive industry [106,107].

Manufacturer	Car model	Applications
Audi	A2, A3, A4, A4 Avant, A6, A8, Roadstar, Coupe	Boot-liner, spare tire-lining, side and back door panel, seat back, and hat rack
BMW	3,5 and 7 series and other Pilot	Seat back, headliner panel, boot-lining, door panels, noise insulation panels, and molded foot well linings.
Citroen	C5	Interior door paneling
Daimler	A, C, E, and S class, EvoBus	Pillar cover panel, door panels, car windshield/car dashboard, and business table
Fiat	Punto, Brava, Marea, Alfa Romeo 146, 156, 159	Door panel
Ford	Mondeo CD 162, Focus	Floor trays, door inserts, door panels, B-pillar, and boot-liner
General Motors	Cadillac De Ville, Chevrolet Trail Blazer	Seat backs, cargo area floor mat
Honda	Pilot	Cargo area
Lotus	Eco Elise	Body panels, spoiler, seats, and interior carpets
Mercedes Benz	C, S, E, and A classes	Door panels, glove box, instrument panel support, insulation, molding rod, seat backrest panel, trunk panel, and seat surface/backrest
Opel	Vectra, Astra, Zafira	Door panels, pillar cover panel, head-liner panel, and instrumental panel
Peugeot	406	Front and rear door panels, seat backs, and parcel shelf
Renault	Clio, Twingo	Rear parcel shelf
Rover	2000 and others	Rear storage shelf/panel, and insulations
Toyota	ES3	Pillar garnish and other interior parts
Volkswagen	Passat Variant, Golf, A4, Bora	Seat back, door panel, boot-lid finish panel, and boot-liner
Volvo	V70, C70	Seat padding, natural foams, and cargo floor tray

8. Challenges and Opportunities

Despite the wide variety of applications that natural fiber-reinforced composites have in the automotive industry and other sectors such as construction and sports, as well as in various products, there are still challenges in their large-scale implementation and development. Some of the main obstacles and areas of opportunity include improved mechanical properties, moisture and fire resistance, the inherent variability of natural fibers and complications in the manufacturing process. Adhesion between the fiber and matrix is a major concern, as it has a direct impact on delamination. Manufacturers should further investigate properties such as wetting, adhesion and weight ratio between fiber and matrix materials to prevent delamination in composites. Machining these composite materials also poses challenges, as fiber shedding and delamination are common problems observed by researchers during the machining process.

Despite the renewability and recyclability of the matrices and reinforcements used, solutions must be proposed to facilitate the recycling process and reduce operating costs [59].

9. Definitions

- Abaca: abaca or banana fiber is cellulosic fiber obtained from banana fiber (Musa sepi-entum). It is generally found in tropical countries such as the Philippines and Ecuador, and its production is based on banana crop waste [70].
- Bamboo: bamboo is a plant belonging to the grass family, its production is typically found in Indonesia, India and China [26].
- Banana/Musa: banana fiber, obtained by processing the bark of the banana tree, is a type of lignocellulosic fiber, its major production is located in India, with about 22% of world production [101].
- Coir: light and strong fiber, extracted from coconut husk, compared to other fibers, coconut fiber has more lignin and less cellulose and hemicellulose. The country with the largest production of coir is located in Kerala, India with approximately 60% of the world demand [65][32].
- **Cotton**: a fiber with a high amount of cellulose and a low percentage of hemicellulose, the countries with the highest cotton production are China, USA, India and Pakistan [25].
- **Hemp**: a fiber based on cellulose, hemicellulose, lignin and pectin. It is the second most cultivated fiber worldwide [49].

Abbreviations

FRP	Fiber Reinforced Polymer
PP	Polypropylene
PE	Polyethylene
NFRPs	Natural Fiber Reinforced Polymer
HDPE	High Density Polyethylene
Kgy	Unit of radiation in the English system, amount of energy absorbed by the system. [J/Kg].

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