Review

A Review on Natural Fiber Bio-Composites, Surface Modifications and Applications

Mohammed Zwawi

Department of Mechanical Engineering, Faculty of Engineering, King Abdulaziz University, Rabigh 21911, Saudi Arabia; mzwawi@kau.edu.sa

Abstract: Increased environmental concerns and global warming have diverted focus from eco-friendly bio-composites. Naturals fibers are abundant and have low harvesting costs with adequate mechanical properties. Hazards of synthetic fibers, recycling issues, and toxic byproducts are the main driving factors in the research and development of bio-composites. Bio-composites are degradable, renewable, non-abrasive, and non-toxic, with comparable properties to those of synthetic fiber composites and used in many applications in various fields. A detailed analysis is carried out in this review paper to discuss developments in bio-composites. The review covers structure, morphology, and modifications of fiber, mechanical properties, degradable matrix materials, applications, and limitations of bio-composites. Some of the key sectors employing bio-composites are the construction, automobile, and packaging industries. Furthermore, bio-composites are used in the field of medicine and cosmetics.

Keywords: natural fibers; surface modifications; renewable; bio-degradable

1. Introduction

Increased focus is being placed on the need to reduce global warming, environmental damage, and pollution. The scientific community has been paying significant attention to developing environmentally friendly and bio-degradable materials that can replace the non-renewable materials that pose a threat to the environment [1,2]. Bio-composite materials have become the center of attention due to their environmentally friendly and biodegradable nature [3,4]. A number of hazards and shortcomings are associated with synthetic composites. They have larger carbon footprints and need a large amount of energy for fabrication [5]. A variety of inorganic fibers, including nylon, Kevlar, polypropylene, and glass, are used in synthetic composites [6]. Fossil fuel depletion also endangers the sustainability of these synthetic materials in the long term [7].

The dangers of climate change have made us focus more on reducing global warming, which made many developed countries pledge to limit the increase in average worldwide temperature below 2 °C [8]. Unlike synthetic materials, bio-composites can be degradable without emissions of poisonous gases or substances [9]. Microbes degrade biomaterials into an organic substance through compositing along with the release of minerals, water, and CO_2 [10,11]. Industries are encouraged to use bio-friendly materials to have a better impact on the environment [12]. These bio-composite materials are promising candidates to overcome contemporary environmental issues, [1] reduce energy demand, [13] and to reduce carbon footprints [14,15]. On average 17% less energy is required to produce natural composites than synthetic counterparts [7].

The global bio-composite market's projected growth rate is 9.59%, to reach a USD 41 billion net worth by 2025 [16]. The automobile and construction industries are two major sectors for bio-composites. Bio-composites are eco-friendly, degradable, renewable, non-abrasive, non-toxic, and have low densities [17]. These materials are used in cars to reduce the overall weight and to enhance fuel efficiency. Bio-composites are utilized to

manufacture door panels, armrests, seatbacks, and trays [2]. They are also used externally for trim parts and brake shoes. Bio-composite parts are better at sound absorbance and shatter resistance [18].

Fibers used in bio-composites are produced from agricultural products and byproducts, which are subsequently intermixed with different polymer-based matrices [19]. Biodegradable and renewable polymer matrices are mixed with natural fibers known as lignocellulosic fibers [20]. Natural fibers are mostly used as reinforcements but also can be used as matrix material [21,22]. Bio-composites fall under the category of polymer matrix composites. Polymer matrix composites are made up of natural (PLA, PHA, PCL) or synthetic matrix materials (thermoplastic, thermosetting plastic), with one or more reinforcements such as carbon fibers, glass fibers or natural fibers in the case of bio-composites [23,24]. Cellulose fibers are organic and are produced from biomass [25] and associated derivatives of agricultural products [26]. Cellulose is currently considered one of the most studied and used polymers, followed by lignin [27]. Approximately 40–60% of plant matter consists of cellulose, in addition to hemicellulose, lignin, and pectin [28]. The basic cellulose unit is anhydro-D-glucose, which contains three hydroxyls responsible for hydrophilic nature [29]. Cellulose offers superior mechanical properties, while lignin reduces water sorption and enhances thermal stability [30]. Lignin serves to bind plant parts together, thereby acting as a cementing material. It also influences the structure and properties of plants [20]. The lumen is a hollow central cavity in a fiber cell, responsible for reducing the density, increasing thermal insulation, and noise-resistance properties [31]. Microfibril is a primary structural unit in the cell wall of a plant. The angle at which the microfibril fiber connects with the cell wall directly influences the mechanical properties and acts as a reinforcing element arising from the linear linkage of crystallites [32]. Certain types of lignocellulosic fibers exhibit mechanical properties and overall strength comparable to that of synthetic fibers such as fiberglass [33].

Thermoplastic polymer matrices, such as polypropylene and polyethylene, are hydrophobic and offer low compatibility with natural fibers. Surface treatments decrease the fibers' surface energy to optimize the strength and properties of the composite [34]. Bio-composite performance is ultimately dependent on the fiber/matrix interphase. Adhesion between the matrix and fiber determines the final properties of the composite [35]. The mechanical properties of a composite depend on the amount and type of filler being used, how fiber adheres to the material, and the final fiber orientation in the matrix [36]. The properties of these lignocellulosic fibers are also dependent on the origin of the plant species, fiber, location of the plant, environment around the plant, and methods to extract the fibers [20].

Polybutylene succinate (PBS), polylactic acid (PLA) [9,37], poly hydroxyalkanotes (PHA) [38], and poly(ε-caprolactone) (PCL) [39] are commonly used biodegradable matrices in bio-composites. Synthetic matrix materials are not biodegradable. Some synthetic matrix materials are polyethylene, polypropylene, polycarbonate, polyvinylchloride, nylon, acrylics, and carbon steel Kevlar, epoxy resins, etc. [40]. Out of these, due to its eco-friendly and degradable nature, PLA has attracted significant attention. PLA is synthesized via direct starch fermentation. The use of a ring-opening approach to polymerize cyclic lactide dimers is preferred for PLA with a higher molecular weight. PLA is crystalline, transparent, and brittle in nature [9]. PHA is generally produced using a microbial process in carbon substrate, and it degrades easily at room temperature. However, it has mostly limited use due to the high cost [38]. PBS belongs to aliphatic polyesters and is produced by two-step polycondensation. PBS is semi-crystalline with an aliphatic structure and is biodegradable due to the presence of odd ester bonds. However, like PLA, it has a higher production cost [41,42]. PCL is developed from crude oil through the ring opening polymerization of caprolactone monomers [39]. The action of microorganisms degrades it with water, CO_2, minerals, and methane. PLA exhibits inferior properties in comparison with PBS and PCL, with higher production costs [43].

Green bio-composites have pros and cons. Limitations of bio-composites include poor fire resistance [2], restricted processing temperature, low thermal resistance [32], high hydrophilicity, low mechanical and thermo-physio properties [40], and poor fiber–matrix adhesion [44,45]. Due to their hydrophilic nature, these composites tend to absorb water from the immediate environment [32], causing the composite to swell. Stem fiber, leaf fiber, and seed fiber are the three main fibers [20]. The most common natural fibers are hemp, doum, coir, jute, almond shells, rice husk, oat husk, wheat straw, switchgrass, corona, kenaf, coconut, bamboo, bagasse, banana, sisal, sugarcane, oil palm empty fruit bunch [20,46–61].

2. Lignocellulosic Fibers

Lignocellulosic fibers consist of cellulose, hemicellulose, lignin, pectin, waxes, extractive, and trace elements [62,63]. Figure 1 shows the different structural constituents of a plant fiber.
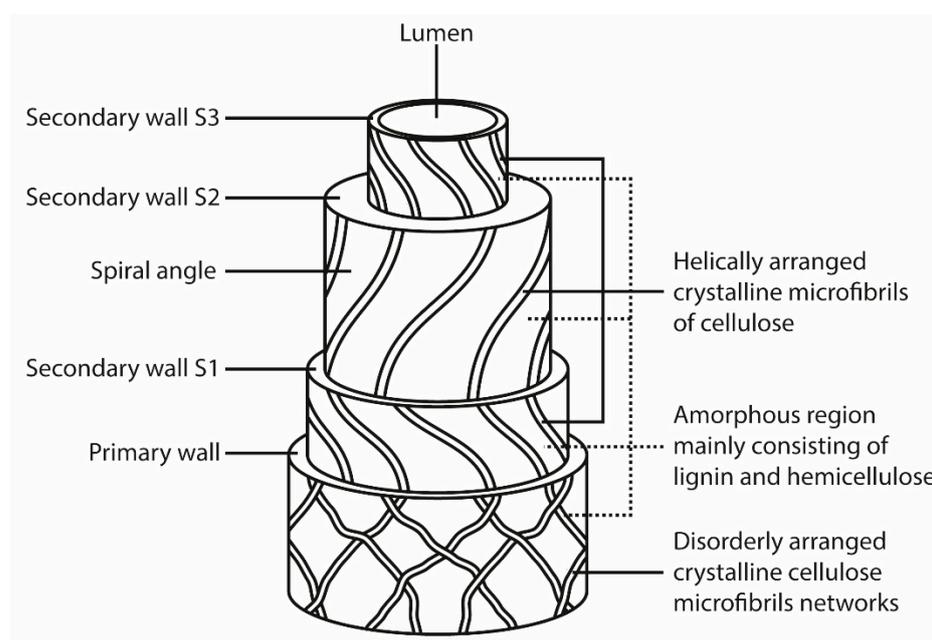
Figure 1. Shows structural constituents of a natural plant fiber. Reprinted with the permission from the publisher [64].

2.1. Cellulose

Cellulose is the most abundant form of living terrestrial organism. Purer forms of cellulose include cotton and hemp fibers, while in wood, stalks and leaves, cellulose is found in combination with lignin and hemicellulose. Apart from plants, some bacteria and fungi are found to have cellulose as well. In plants, cellulose is located in a secondary wall that consists of linear homopolysaccharide composed of anhydro-D-glucose ($C_6H_{11}O_5$). Linkages of 1,4-*b*-D-glycosidic join them with a degree of polymerization near 10,000, and each repeating unit contains three hydroxyl groups. Cellobiose is a repeating unit and a dimer of glucose [65]. Hydrogen bonding between hydroxyl groups (with water elimination [66]) is responsible for the 3D crystallinity of the structure and the hydrophilic nature [29,64,67]. The length of the 1,4-*b*-D-glycosidic linkages is dependent on the cellulose source [67]. Hydrogen bonding aids in a highly ordered structure. Hydrogen bonding between chains is very strong in crystalline regions, responsible for the high strength of fiber and making it insoluble in most of the solvents. In amorphous regions, these chains can bond with other molecules, such as water. Cellulose is hydrophilic, although it is insoluble in water; water absorption causes swelling. Cellulose properties are influenced by factors such as the type of plant, fiber modification, age of the plant, extraction methods,

chemical composition, location of the plant, the maturity of the plant, and microscopic and molecular defects [66,68].

2.2. Hemicellulose

Hemicellulose is different from cellulose due to different sugar units. Hemicellulose is a branched non-crystalline or amorphous structure, different from a linear cellulosic structure. It has a degree of polymerization between 50 and 300, considerably less than cellulose. Hemicellulose acts as a compatibilizer to support microfibrils, cellulose, and lignin [69]. It is hydrophilic in nature, soluble in alkaline solution, and easy to hydrolyze in acids [64]. Hemicellulose may differ from plant to plant with different constituents [70]. Table 1 shows constituents of different natural fibers.

Table 1. Constituents of different natural fibers.

Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Wax (%)	Reference
Abaca	56–63	21–25	7–12	0.8	3	[23,71–73]
Alfa	45.4	38.5	14.9	-	2	[71,72]
Areca	57.35–58.21	13–15.42	23–24	-	0.12	[74]
Bagasse	32–44	19–24	22	10	-	[71,75]
Bamboo	26–43	20.5	21–31	-	-	[23,71]
Banana	62–64	12.5	5–10	4	-	[31,75–77]
Barley	31–45	27–38	14–19	-	2–7	[31]
Coir	45.6	20	45	4	-	[71,72,78]
Corn	38–40	28	7–21	-	3.6–7	[31]
Cotton	82.7–90	4	0.75	6	0.6	[71,72]
Curaua	70.7–73.6	9.9	7.5–11.1	-	-	[23,71,72,75]
Eucalyptus	41.7	32.56	25.4	8.2	0.22	[79]
Flax	62–72.5	14.5–20.6	2.5	0.9	-	[23,71,75]
Hemp	81	14–22	4–13	0.9	0.8	[23,71,80]
Henequen	60–77.6	28	8–13.1	-	0.5	[71,72]
Hibiscus	28	25	22.7	-	-	[81]
Isora	74	-	23	-	1.1	[71]
Jute	59–71.5	12–20	9–13	0.2	0.5	[23,71,82,83]
Kenaf	53.5	21–33	17–21.5	2	-	[71,78,84]
Phromium	67	30	11	-	-	[71]
Pineapple	80.5	17.5	8.3–12.7	4	-	[23,71]
Ramie	72	5–16.7	0.6–0.8	2	-	[71,80]
Rice husk	28–36	23–28	12–14	-	14–20	[81]
Sisal	60–73	11.5–14	8–11	1.2	-	[23,71,85]
Sorghum	27	25	11	-	-	[31]
Wheat	33–38	26–32	17–19	-	6.8	[79]

3. Fiber Modification

Fiber modification helps to overcome various problems of natural fibers, such as poor fiber/matrix adhesion [35], moisture absorption [81], low fire resistance [82], inferior mechanical properties [83], low thermal resistance, and restrictive processing temperatures [32]. A wide number of methods are used to overcome these problems.

3.1. Fiber/Matrix Adhesion

Fiber addition in a matrix significantly alters the properties of the matrix due to the dependency of bio-composites properties on the fiber/matrix interface. Strong interface bonds must be ensured to achieve the majority of desired mechanical properties. Many physical properties are considerably improved with strong fiber/matrix adhesion [35]. A poor fiber/matrix interface results in reduced mechanical and physical properties. The hydrophilic nature of fiber is one reason for poor interfaces, which leads to poor fiber dispersion in a matrix. Hydrophobic matrix material and hydrophilic fibers are incompatible, which reduces the composite's ability for stress transfer between the matrix and fiber. Fiber dimensional changes lead to microcracking, thereby affecting fiber/matrix adhesion [76,82,83]. Many techniques (e.g., surface treatments) have been employed to enhance fiber/matrix adhesion. In addition to improving fiber/matrix adhesion, surface treatments also reduce moisture sensitivity. Surface treatments employ methods such as solvent extraction, physio-chemical treatments, corona discharge, plasma discharge, laser, gamma-ray, and UV bombardment, and chemical modifications by the condensation of coupling agents on a surface or their placement by free radical technique [20,84]. Physical techniques modify the surface to increase interface bonding for better matrix and fiber adhesion [23]. Corona discharge modifies natural fiber's surface energy and improves its compatibility with matrix material [85]. Tensile properties are significantly enhanced with the corona treatment of hemp fiber [86]. Plasma treatment also improves fiber/matrix compatibility. In plasma treatment, the charge is indued on the surface, and various gases can induce different modifications. Surface energy is improved due to surface cross-linking. Plasma-treated flax fibers have demonstrated enhanced fiber/matrix adhesion [87]. Interfacial adhesions were improved in jute fibers by oxygen plasma treatment with the induction of hydrophobic characters in fibers [88]. Chemical methods improve fiber/matrix adhesion by introducing new groups between incompatible fibers and matrices [23]. Silane treatment is an efficient method to improve fiber/matrix adhesion using SiH_4 [89]. Maleated coupling improves a composite's strength by improving the fiber/matrix interface [90]. Another method is a bacterial modification, which improves fiber/matrix adhesion through better mechanical interlocking. The use of cellulose produced from bacteria is considered a green method for surface modification and provides new means to modify fibers [91]. Alkali treatment or the Mercerization process is used to induce rough surfaces at the fiber/matrix interface [92]. The alkaline treatment works by altering hydrogen bonding in the structure and removing some lignin, waxes, and oils to expose short-length crystallites [93]. Alkaline-treated fiber has an increased concentration of exposed cellulose and surface roughness for better interlocking [94,95]. High alkali concentration has adverse effects on fibers, which can weaken and damage the fiber. Optimum concentration must be ensured to have most of desired mechanical and physical properties [96]. Benzoyl treatment is also used to improve fiber/matrix adhesion [97]. Detailed discussion on this method is present in the next section. Isocyanate with a functional group ($-N=C=O$) readily reacts with the hydroxyl group in lignin and cellulose to form strong covalent bonding. Isocyanate acts as a promoter and a coupling agent to provide better fiber/matrix adhesion [98]. Graft copolymerization is an effective surface treatment. Vinyl monomers are grafted on the surface, improving fiber/matrix adhesion [99,100]. Permanganate treatment forms reactive manganate ions. These ions react with hydroxyl groups in cellulose to initiate graft polymerization. This treatment provides chemical interlocking at the fiber/matrix interface to improve adhesion [101].

3.2. Reducing Moisture Absorption by Natural Fiber

Strong polarized hydroxyl groups make natural fibers more hydrophilic. They absorb most of the moisture from the surrounding environment [102]. The fiber cell wall has many hydrogen bonds. As the water comes in contact with the fiber, old hydrogen bonds break, and new hydrogen bonds are formed between hydroxyl groups and water molecules which are responsible for water absorption [97]. Hemicelluloses are mainly

responsible for moisture absorption in natural fibers [103]. Hydrophilic natural fiber absorbs moisture, affects mechanical properties, gives dimensional instability, and develops internal stresses [32]. Capillary action and water intake fills voids in the composite, giving dimensional instability to the composite [20]. Moisture absorption causes swelling and microcracks [104]. The hydrophilic nature of fibers prevents the use of bio-composites in various potential applications [105]. Moisture absorption makes the composite a breeding ground for fungi, bacteria, and harmful insects [106]. Apart from water absorption, micro gaps and cracks can be a result of poor processing conditions, incompatibility between the fiber and matrix, and poor environmental and service conditions [107]. Water absorption in bio-composites is, somehow, a complex process due to the involvement of a hydrophobic matrix and hydrophilic fibers. Diffusion and percolation are two main mechanisms of water intake. In diffusion, water molecules are transported from higher concentration areas to low concentration areas due to their random motion [108,109], while in percolation, water is passed through pores of the composite [110]. Moisture absorption and composite swelling are directly proportional to fiber thickness and size [111]. Water absorption in composites decreases the Young's modulus, the stress at maximum load, and various other mechanical properties [112]. Fiber must be modified physically and chemically to overcome moisture absorption issues. Compatibilizers and adhesion promotors showed promising results to reduce moisture absorption [113]. Hydrothermal treatment increases the crystallinity of cellulose in natural fiber and extracts hemicellulose content, effectively reducing moisture intake. The Duralin process is also employed to reduce the moisture content and swelling of the composite [114]. Acetylation of natural fiber is a renowned esterification method, originally used to prevent the cell walls of wood cellulose from water. Acetylation introduces the acetyl functional group (CH_3COO^-) with acetic acid as a byproduct [115]. In this method, acetic anhydride replaces hydroxyl groups responsible for the hydrophilic nature of fiber [116]. This method is useful to decrease the moisture absorption properties of the composite [117]. Acetyl-treated fibers exhibit better resistance to tensile strength loss during treatment [118]. Benzoyl treatment is another method used to improve fiber/matrix adhesion, thermal stability, and to decrease the hydrophilic nature of the fiber. Benzoyl chloride is used in fiber treatment. This method removes the majority of lignin and waxes, along with oily materials, to expose reactive hydroxyl groups at the surface. Benzoyl groups substitute hydroxyl groups, making natural fiber hydrophobic and improving adhesion properties [97]. Peroxide treatment is an effective method to reduce the moisture absorption in fiber. In this method, free peroxide radicals react with hydroxyl groups to achieve the desired results and to improve the thermal stability [119]. The sodium chlorite method has shown promising results to reduce moisture content and to enhance the hydrophobic properties of the fiber. Sodium chlorite is utilized in bleaching the fibers to form chlorine dioxide, which reacts with lignin to effectively remove it, and also reacts with hemicellulose to improve the hydrophobic nature [120,121]. Steric acid contains carboxyl groups, and these groups react with hydroxyl groups to decrease their hydrophilic nature. Pectin, waxes, and oily materials are also removed in this method [49,122]. Permanganate treatment releases manganate ions to react with hydrophilic hydroxyl groups of cellulose to improve water resistance natural fiber [123]. Triazine treatment uses triazine derivates with multifunctional groups to reduce moisture adsorption in fibers. Chlorine in multifunctional groups reacts with hydroxyl groups by esterification and provides a link between cellulose and the coupling agent to enhance hydrophobic properties of the fiber [124,125]. Fatty acid derivates are also used to improve the water-resistance of fibers. Oleoyl chloride is one of the fatty acids derivates which reacts with the hydroxyl group through esterification. Hydrophilic hydroxyl groups are removed by this method, giving hydrophobic characteristics to fibers [126]. Fungal treatment is considered one of the best methods to increase the water-resistance of a fiber. It is a green and eco-friendly method. Non-cellulosic components of fibers are removed by specific enzymatic actions, along with lignin and hemicellulose removal. Excessive enzymatic activity may lead to a decrease in fiber strength [127].

3.3. Thermal Degradation and Flammability Properties

Natural fiber constituents such as cellulose, hemicellulose, lignin, pectin, and waxes are responsible for degradation and poor thermal properties. Both thermal stability and moisture absorption properties are temperature-dependent [128]. Poor thermal properties lead to the degradation of fibers with the release of various volatile products [20]. Cellulose degrades between 260 °C and 350 °C, and hemicellulose between 200 °C and 260 °C, while lignin starts to decompose at 160 °C and continues to degrade up to 400 °C [18]. Natural fiber-based composites decompose with the release of toxic byproducts and heat [129]. Composite combustion releases toxic byproducts, smoke, char, combustible and non-combustible gases [130]. Properties such as thermal stability, fire properties and water resistance are dependent on the constituents of natural fibers. High cellulosic contents make natural fibers readily flammable [131]. Orientation and structural properties of fibers play a vital role in determining thermal and flammability properties. Flammability and thermal properties are improved with the addition of silica and ash [132].

High crystallinity, char production and low polymerization improve fire resistance. Char protects the materials' core from combustion and maintains structural integrity [133]. Composites undergo heating, decomposition, flame ignition, combustion, and propagation during the burning cycle [134]. Due to poor flammability, natural fibers have been limited to a few applications [131]. It is a challenge to find methods to overcome this issue, because few studies have been reported to address this problem. Flax fiber has the best fire resistance properties due to low lignin contents [135]. Thermal stability and the flammability of natural fibers is studied through various techniques, such as thermogravimetric analysis (TGA), vertical flame tests, cone calorimetry techniques, etc. The rate of flame spread, heat rate reserve (HRR), mass loss, and carbonization rate impact the flammability of fibers [82]. Some of the methods to minimize flammability and thermal issues are: the use of nanoparticles, fire retardant coatings, impregnation of natural fibers with fire retardants before manufacturing, the use of non-flammable binders, resins, polymer matrices, and the insulation of composites to prevent possible damage from heat or flame [136,137]. Ammonium, halogens, boron, phosphorous, bromine, aluminum and magnesium-based compounds, zinc borate, silica, graphite, and alkaline earth metal compounds are commonly used fire retardants. Phosphorous-based fire retardants exhibit auto-extinguish behavior in a composite [2,134,138]. Ammonium-based retardants produce char, while bromine-based compounds terminate chemical reactions for combustions [130]. Due to toxic byproducts, the use of halogens is not recommended [138]. Phosphorous-based fire retardants are not preferred due to environmental hazards and health issues [139]. Nanoparticles and nanocomposites have shown good flame and thermal resistance properties but are not cost-viable. The addition of flame retardants improves flammability properties by increasing the specific heat and thermal conductivity, preserving physical integrity, and reducing combustion heat in bio-composite [130]. The addition of flame retardants may have some adverse effects, such as poor fiber/matrix adhesion and the poor dispersion of fibers in a matrix [139]. Table 2 contains various research studies for bio-composites and surface modifications.

Table 2. Different research studies for bio-composites and modification techniques.

Composite	Fabrication Method	Key Findings and Mechanical Properties	Effect of Surface Treatments	References
Abaca–Roselle/Cardanol formaldehyde composite	Compression molding	Natural fibers improved thermal, wear resistance, and mechanical properties of the composite and improved the hardness, density, and tensile strength of the matrix material. Tensile and flexural properties improved due to the presence of carbon and silica.	Alkali treatment increased fiber/matrix adhesion due to the removal of impurities and increased mechanical properties.	[140]
Areca fibers/Pine resin composite	Solvent casting method	The tensile strength of the composite is affected by the adhesion of the fiber/matrix; 10 wt.% areca fibers and 90 wt.% pine resin exhibited better mechanical properties due to efficient stress transfer between fibers and matrix.	Alkali treatment increased fiber/matrix adhesion. Tensile strength increased by 25%, while impact strength increased up to 24% due to treatment.	[141]
Banana fibers/PLA/Nanoclay composite	Melt blending	Nanoclay and PLA improved composite stability, flame resistance, and thermal properties. Nanoclay formed a protective layer at the surface to prevent flame and acted as a thermal barrier to prevent degradation.	Silane treatment improved fiber/matrix adhesion by increasing the contact area of fibers.	[142]
Flax/epoxy composite	Vacuum infusion	Flax/epoxy composite is suspectable to water absorption due to high void content.	Sodium bicarbonate-treated fibers had less void content mainly due to the removal of impurities. With the increase in sodium bicarbonate concentration in fiber treatment, properties such as flexural, tensile strength and flexural moduli increased.	[143]
Hemp fibers/polycaprolactone bio-composite	Twin screw extrusion	Flexural, tensile and impact properties of composite are improved. With the increase in aspect ratio of hemp fiber, water absorption increased. Flexural strength increased by 169% and flexural modulus increased by 285% for the aspect ratio of 26. Hemp fibers increased the stiffness of the composite.		[144]

Table 2. *Cont.*

Composite	Fabrication Method	Key Findings and Mechanical Properties	Effect of Surface Treatments	References
Jute fibers/unsaturated polyester resin	Hand lay-up and compression molding	Jute fibers enhanced properties such as tensile, flexural strength, flexural modulus, and interlaminar shear strength. Untreated fibers lead to low density and low volume fraction.	Alkali-treated fibers showed an increase in tensile, flexural strength, flexural modulus, and interlaminar shear strength due to better fiber/matrix adhesion. Alkali treatment removes hemicellulose and increases interlocking points in fibers for better adhesion and stress transfer.	[145]
Jute fibers/clay/epoxy bio-composite	Compression molding	The addition of 15 wt.% clay improved mechanical properties due to uniform dispersion in a composite. Clay can agglomerate, which increases composite porosity and decreases fiber/matrix adhesion.	Alkali treatment improved fiber/matrix adhesion with increased cellulose after removing pectin, lignin, and other impurities. An increase in cellulose content leads to better interfacial adhesion.	[146]
Kenaf fibers/sea urchin spike filler/neem oil/epoxy composite	Hand lay-up	Neem oil made epoxy eco-friendly while sea urchin spike filler and kenaf fibers increased the toughness of the composite. The addition of neem oil leads to the formation of an interpolymer-penetrating network and ketone groups, which decreased hardness and overall tensile strength of the composite.	Amino silane-treated particles dispersed well in matrix material without agglomeration, which improved wear resistance and thermal degradation. Treated fiber formed a layer at the fiber/matrix interface, and high temperature was required to break this layer. Modified fibers increased the moisture resistance in the composite.	[147]
Ramie fibers/PLA composite	Hot compression molding	Low temperature and pressure in compression molding had led to poor fiber/matrix adhesion and wettability.	Alkali/silane-treated fibers composite had better tensile strength, modulus, and impact strength. Cellulose content increased due to the removal of impurities from fibers, which improved mechanical properties. Treated fibers had better stress transfer due to the formation of covalent bonds between fibers and matrix.	[148]
Sisal fibers/starch composite	Hot pressing	Compressive and tensile strength of the composite increased with the addition of sisal fibers. The addition of natural fibers increased the biodegradability properties of the composite.	Alkaline treatment increased fiber/matrix adhesion, which improved mechanical properties.	[149]

3.4. Mechanical Properties

Bio-composites are used in the automobile, construction, and packaging industries. Bio-composites are mostly used in non-load-bearing and non-structural applications due to limitations in mechanical properties [150]. The construction sector requires composites to bear high stress, compression, and tension [129]. Natural bio-composites exhibit reasonable mechanical properties such as stiffness, strength, flexibility, and Young's modulus [151]. Fiber type, fiber orientation, microfibril angle, treatment type, physical properties, and adhesion between the fiber and the matrix are essential characteristics in composites to determine mechanical properties [152]. The microfibril angle determines the stiffness of the fiber [18]. Natural fibers act as reinforcements to improve mechanical properties [152]. Fiber/matrix adhesion is the most critical factor for the determination of mechanical properties. Better adhesion improves the stress/load transfer between fiber and matrix. Tensile strength is mostly dependent on matrix properties, while modulus is dependent on fiber properties [153]. Mechanical properties of different fibers are listed in Table 3.

Table 3. Mechanical properties of different natural fibers.

Fiber	Density (g/cm^3)	Diameter (μm)	Micro-Fibrillar Angle (°)	Moisture Content (%)	Tensile Strength (MPa)	Elongation at Break (%)	References
Abaca	1.5	10–30	20–25	5–10	400–980	3–10	[23,75,154,155]
Areca	0.7–0.8	-	-	-	147–322	10.2–13.15	[156,157]
Bagasse	1.25	10–34	-	-	222–290	1.1	[23,75,158]
Bamboo	0.6–1.11	240–330	-	9.16	140–800	1.40	[23,72,159–161]
Banana	1.35	50–250	11–12	10.71	529–914	3	[80,161–163]
Coir	1.2–1.5	100–450	30–49	8–11.36	175–180	30	[18,40,74,75,159,164]
Cotton	1.5–1.6	12–35	-	7.85–8.5	287–597	7–8	[72,163–167]
Curaua	1.4	170	-	-	500–1150	3.7–4.3	[23,161]
Flax	1.5	5–38	5–10	1.2–8	345–1035	2.7–3.2	[23,161,167–169]
Hemp	1.48	-	2–6.2	6.2–12	690	1.6	[23,161,163,164,169]
Henequen	1.2	-	-	-	430–570	3.7–5.9	[71,72]
Isora	1.2–1.3	-	-	-	500–600	5–6	[71,170]
Jute	1.3–1.5	20–200	8	12.5–13.7	200–773	1.5–1.8	[23,75,164,168,171]
Kenaf	1.4	70–250	2–6.2	6.2–12	930	1.5	[23,163,165,165]
Nettle	1.51	20–80	-	11–17	650	1.7	[75,155,167]
Oil Palm	0.7–1.55	150–500	42–46	-	80–248	3.2	[23,75,165,172]
Palf	0.8–1.6	20–80	14	11.8	180–1627	1.6–14.5	[74,75,112]
Piassava	1.4	-	-	-	134–143	7.8–21.9	[74,75,173]
Pineapple	0.8–1.6	8–41	-	10–13	170–1627	2.4	[23,162,167,174]
Ramie	1.5	50	69–83		220–938	2–3.8	[23,163,164]
Sisal	1.5	50–300	-	11	511–635	3–7	[23,163,164]

4. Biodegradable Matrix Materials

Biodegradable matrices are environmental and eco-friendly. Disposal and the environmental problems of composites can be solved using renewable and biodegradable matrices and fibers [168]. These biodegradable composites have given rise to new markets [169]. Biodegradable polymer matrices are categorized according to the source. Biodegradable polymers are created through agricultural products, byproducts, microbial actions, and chemical methods [26,170]. Bio-composites are fabricated by combining natural fibers in a matrix material. The matrix material can be biodegradable, non-biodegradable, or synthetic. Synthetic matrix materials, along with natural fibers, are used to form hybrid bio-composites [18]. Polymers can also be fabricated by combining or blending two biopoly-

mers. The biodegradability of the polymer depends on factors such as the origin of the polymer, the polymer structure, and the conditions around the polymer during degradation [171]. During biodegradation, the biopolymer is decomposed by microbial actions with the release of CO_2, various compounds, and biomass [161]. Biodegradable polymer matrix materials have poor properties, but the introduction of natural fibers increases mechanical properties [172]. Conventional polymers such as polyethylene, polyester, polypropylene, and epoxy have been through the cycle of development and commercialization [173–175]. Years of research and development have resulted in high performance and better mechanical properties. However, recycling and environmental issues have shifted attention to bio-polymers [176]. As of 2020, a total of more than nine billion metric tons of synthetic polymers has been produced from petroleum products [177,178]. Only about 25% of total produced synthetic polymers are recycled or incinerated; most of it ends up in landfill sites or the natural environment [179]. Low mechanical properties, lack of manufacturing processes, high production cost, low melting temperatures, and a narrow processing temperature range are limitations of biopolymers. Several methods have been employed to produce higher molecular weight polymers [180,181]. Bio-based polymers can replace synthetic polymers in key sectors such as the construction, automobile, and packaging industries.

Some of the examples of bio-based polymer matrices are polybutylene succinate (PBS), polylactic acid (PLA), poly hydroxyalkanotes (PHA), and poly(ε-caprolactone) (PCL) [9,37–39].

4.1. Polybutylene Succinate (PBS)

Polybutylene succinate (PBS) is fabricated from succinic acid and 1,4-butanediol (BDO). PBS is a biodegradable polymer with excellent mechanical and thermal properties [182]. PBS belongs to the aliphatic polyester family. Due to ever-increasing environmental concerns, monomers from renewable sources are encouraged for use [183]. Succinic acid is produced from maleic anhydride hydrogenization: maleic anhydride is converted into succinic anhydride; and highly pure succinic acid is produced via the electrolysis route. Highly pure succinic acid is required in the pharmaceutical and food industries [184]. Succinic acid is also produced through the fermentation of agricultural carbohydrates and byproducts [185]. Microbial organisms are responsible for fermentation. Different bacterial cultures are used in fermentation processes, such as *Actinobacillus succinogenes* and *Anaerobiospirillum succiniciproducens* [186]. The U.S.A. Department of Energy recognized succinic acid as a replacement for petroleum-based products. Succinic acid is used in the preparation of different chemical compounds [187]. BDO is produced mainly from petroleum products [184]. Various processes such as the Reppe process, Mitsubishi 1,3-butadiene acetoxylation technology, the LyondellBasell propylene oxide route, and Davy Process Technology are used in industries [183,188]. PBS is synthesized through two-step polycondensation. The first step involves esterification and transesterification of succinic acid and BDO [189]. Oligomers are produced by esterification, and the next step involves removing BDO via polycondensation to form higher molecular weight PBS. In this process, the reactor must have a mechanical stirrer, oil bath, and nitrogen gas [190], along with various catalysts [190].

PBS is a highly crystalline polyester with a melting temperature of around 115 °C, critical for high-temperature applications [191]. Tensile yield strength and Young's modulus reach up to 35 MPa and 500 MPa, respectively. Both properties are highly dependent on the degree of crystallinity for PBS [183,192,193]. Physical properties of PBS are altered by copolymerization with different comonomers, such as ethylene glycol and adipic acid [192–194]. Aliphatic structure and the presence of ester bonds makes PBS biodegradable in lipase mixtures, soil, moisture content, and sludge [41,182]. Biodegradation of PBS depends on chemical structure, the degree of crystallinity, specimen size, and conditions around the specimen. The rate of aliphatic polyester is slowed down with an increase in aromatic content, while it increases with the addition of comonomers [193–195]. The degradation rate is controlled by PBS copolymerization. Processability of PBS is strongly dependent

on melt strength, the viscosity of the melt, thermal stability, the degree of crystallization, and water resistance. Extrusion and injection molding are suitable for PBS fabrication for molecular weight under 100,000, while blowing and casting mechanisms require higher molecular weight PBS for easy processing [183]. Mechanical properties of PBS are improved significantly by blending with other bio-based polymers such as starch, PLA, carbohydrates, and its copolymers [194]. Tensile, elastic modulus and impact properties of PBS are enhanced with polylactic acid (PLA). With some limitations at the molecular level, PBS and PLA are compatible [196]. PBS is replacing conventional polymers in packaging, bottles, molds, fibers, flushable hygiene, shopping bags [41,197], etc.

4.2. Polylactic Acid (PLA)

Polylactic acid is an eco-friendly, bio-degradable polymer and is made up of lactic acid produced from renewable agricultural products and byproducts such as starch extracted from potatoes, corn grain, sugar cane, etc. Hydrolytic or thermal degradation of PLA results in low toxicity byproducts [198–201]. Lactic acid is categorized into two optically active isomers, L and D type enantiomers [202,203]: L type lactic acid rotates the polarized light in a clockwise plane; D types rotate anticlockwise. Isomer type dictates PLA classification in a family of three polymers: poly-D-lactic acid (PDLA), poly-L-lactic acid (PLLA), and poly-L-D-lactic acid (PDLLA) [201,204]. PLA is fabricated through three routes, which are polymerization through the formation of lactide, direct condensation polymerization, and azeotropic dehydration condensation [205–207]. Ring-opening polymerization (ROP) is one of the most widely used methods to fabricate PLA [208,209]. A cyclic dimer of lactic acid is used in ROP, and the process involves ring-opening of the cyclic dimer in lactic acid.

Catalysts are used to control the molecular weight of PLA [210]. The L:D ratio in lactic acid is controlled through factors such as temperature, residence time, type, and concentration of catalyst [203]. ROP is performed in bulk, melt, or even in solution form through different mechanisms such as cationic, anionic, and coordination insertion [211]. The direct or polycondensation route is the least expensive PLA process—it involves solution and melts polycondensation with different solvents under high vacuum and temperature [200,202]. Limitations in the production of solvent-free high molecular weight PLA are associated with these routes [212]. Condensation polymerization yields low molecular weight PLA, making it unfit for many applications. A low molecular weight in PLA is due to polymer melt viscosity, low concentration of reactive end groups, moisture presence, and impurities. Coupling agents or esterification promotors increase molecular weight but with the addition of increased complexity and cost. Mechanical properties and molecular weight are improved by removing solvents, moisture, and impurities from the melt. Azeotropic dehydration condensation is used to obtain high molecular weight PLA without any use of coupling agents or esterification promotors. Water is removed to produce high molecular weight PLA [200,209,212]. This process involves the distillation of lactic acid for 2 to 3 h at a temperature around 130–140 °C with the use of a catalyst. Catalysts can cause impurities and an increase in production costs. Catalyst impurities are removed with the addition of various acids. Enzymatic polymerization is another method to produce PLA with mild processing conditions [200,208,213].

Research studies are trying to reduce the shortcoming and limitations of PLA [213]. PLA requires an estimated 25–50% less energy in fabrication than conventional polymers, contributing to cost reduction in the process [214]. PLA has high strength, processability, and mechanical properties. PLA exhibits better tensile properties than polystyrene PS and polyethylene terephthalate (PET) [215]. PLA is the better choice for tensile and flexural modulus properties among PET, PP, and HDPE. Impact strength values and elongation at break are lower than PET, PP, and HDPE [216]. PLA is crystallized in three structural forms: α, β, and γ. α form is developed from a melt or cold crystallization, and mechanical stretching and deformation in the formation of the β form. PLA has a high crystallization rate due to fast-growing semi-crystalline regions [217,218]. Crystallinity influences properties such as tensile strength, melting temperature, hardness, stiffness, etc. PLA is brittle with low

toughness. Low toughness values limit the use of PLA in high-stress level applications. The inertness of PLA causes troubles in surface modifications for various applications [201,207]. Thermally unstable PLA loses molecular weight during thermal treatments and processing temperatures. Degradation of ester linkages, even at a temperature lower than melting temperature, causes this thermal instability. Degradation increases by many folds after melting temperature. Several methods are used to overcome this issue, such as hydrolysis, oxidative degradation, esterification reactions, and depolymerization. Thermal degradation is dependent on factors such as moisture content, size of the particles, lactic acid concentration, the molecular weight of PLA, impurities, and the catalyst used [207,219,220]. PLA is degradable by hydrolysis when PLA is exposed to moisture for longer periods. Degradation has two main steps. The first step involves the degradation of ester groups and the lowering of PLA molecular weight. The second step involves yielding CO_2 and water through microbial action to degrade low molecular weight oligomers [212,219]. PLA is blended with other polymers to overcome limitations and improve mechanical properties, degradation, and thermal instability [203]. PLA is used in various household applications, such as plastic bags, sanitary products, cups, bottles, plates, etc. [198]. PLA applications range from textile products, to the pharmaceutical, medical, and packaging industries. In biomedical applications, PLA eliminates the need to remove medical implants due to biological degradation with time. PLA has good compatibility with human tissues and organs and has low production costs and excellent mechanical properties. PLA is used for surgical sutures in tissues, skin, and closing wounds. PLA is additionally used in drug delivery systems for the continuous release of drugs [207,208,220,221]. The non-toxic degradability of PLA is very effective for implants and supports in the human body. PLA may take four months to four years to degrade completely, dependent on chemical composition, crystallinity, polymer porosity, and the degradation environment around the implant. PLA is used for bone fixation devices, replacing metallic fixation devices. PLA is readily used to make screws, pins, and wires for bone fixation [220,221]. PLA provides polymeric support in tissue engineering and is used in tissue or organ construction. PLA is used to develop filaments to reconstruct nerves for paralyzed persons. Schwann cells are grown on PLA polymeric supports. Schwann cells are grown in damaged nerves to join them artificially. Over time, polymeric support degrades, forming nerve connections. Adhesion of Schwann cells on PLA support is limited and can be increased by various plasma techniques [222–224]. Surface properties of polymers play vital roles in biomedical applications. Various techniques have been utilized to improve surface properties. These techniques include different physical and chemical methods, along with plasma and radiation treatments. PLA is also used to produce agricultural equipment and disposable materials, in the automobile industry, and textile industry [198–200].

4.3. Poly Hydroxyalkanote (PHA)

PHA belongs to a group of *R*-hydroxyalkanoic acids. PHA is an eco-friendly and renewable polymer [225]. Only a few among 150 hydroxy acids monomers actively produce PHA under normal conditions. The short-chain PHA has three to five carbon atoms, which improve stiffness, brittleness, and crystallinity. Middle chain polymers have six to fourteen carbon atoms and have a low degree of crystallinity [226,227]. PHA is dependent on plants and bacteria for mass production [228]. Carbon accumulation in cells influences PHA microstructure and properties [229]. PHA is also produced using Gram-positive and Gram-negative bacteria, with over 75 different types, such as *Pseudomonas*, *Bacillus*, and *Ralstonia* [227]. Bacterial PHA has a high molecular weight, varying between 200,000 to 30,00,000 Da due to different bacteria types and growth conditions [230]. Carbon accumulation in a cell is the source of PHA [231], which only happens under stressed conditions with a limited supply of nitrogen, oxygen, and phosphorus nutrients. Large-scale microbial fermentation is used for the mass production of PHA. Mass production is dependent on factors such as bacteria type, cell density, growth rate of bacterial strain, total process time, substrate, and purification methods [231]. Sugar, fatty acids, sucrose,

starch, molasses, wheat, corn, methane, and activated sludge effluent substrates are used in PHA production [232–235]. PHA is commercially produced through glucose and sucrose substrates [236]. High production costs, processing constraints, and poor mechanical and physical properties are some of the factors limiting PHA applications [237]. High output is achieved through batch or continuous fermentation processes. PHA is produced in two-step continuous fermentation. In the first step, biomass is provided with the full amount of nutrients, while limited nutrients are provided in the second step. Some bacteria are efficient in limited nutrient supply, and vice versa. A well-balanced cell growth rate of bacteria is essential to avoid the premature ending of the fermentation process [230,238–241]. PHA is stored in cells that have to be extracted; however, extraction methods have cost limitations [242]. Solvent extraction is the simplest method for PHA extraction, where a cell is ruptured to access PHA. PHA dissolves in selective solvents and is precipitated by non-solvents. Chlorine solvents are used to dissolve PHA, while ethanol and methanol are used for precipitation [243]. A floating method in solvents is employed to recover highly pure PHA [244]. The digestion method is an alternate solvent extraction method that involves chemical or enzymatic digestion mechanisms. Chemical methods degrade polymers and have harmful byproducts, thus, reducing the overall extraction efficiency [245]. Enzymatic digestion methods are target-specific and are highly efficient in PHA extraction [243]. Modern technology supercritical fluid extraction methods are environmentally safe and cost-effective. Diffusion rates are enhanced due to the low viscosity of supercritical fluids having negligible surface tension [246]. CO_2, methanol, and ammonia are used as supercritical fluids [247]. Parameters such as temperature, pressure, and impurities determine the supercritical fluids' efficiency. The aqueous two-phase method consists of two different and unique phases and extracts high purity PHA [248].

PHA is a degradable polymer, and the degradation rate is dependent on the surrounding environment, pH level, water content, chemical composition, crystallinity, and surface area of PHA [230]. Micro-organisms degrade biopolymers with the release of hydroxy acids, which are carbon sources. PHA degradation releases CO_2, water, and methane. PHA is degradable up to 60 °C [229] and used in bone and tissue engineering [226,249]. PHA is used in the development of heart valves to replace metallic valves [250], and also in drug delivery systems; PHA acts as a carrier for drugs to transport bio-active compounds to the target area [251]. PHA shows promising results in nerve grafting to repair damaged nerves [252]. Thus, with enhanced compatibility and adhesion with natural fibers, PHA is used as a polymer matrix in bio-composites [253].

5. Processing Techniques of Bio-Composites

Bio-composites are gaining momentum in various industries and research studies. The demand for bio-composites has been tremendously increased in domestic and industrial sectors due to a surge in environmental pollution concerns and increased environmental regulations by local and international bodies. For desired properties to achieve and make bio-composites cost-effective, different modified chemical treatments and efficient process techniques are needed [64]. Bio-composites are currently fabricated through conventional methods such as compression molding, hand lay-up, injection, extrusion, and pultrusion [254]. These manufacturing techniques are the result of years of research and development. Research studies focus on developing and modifying existing techniques to increase the quality of bio-composites and make them cost-effective. With a few modifications in existing techniques, bio-composites can be readily fabricated [23]. Fabrication techniques are selected based on the requirements for fiber dispersion, orientation, and aspect ratio in desired applications [255]. Factors such as production cost, final design, shape, size, raw material properties, and process constraints are taken into account in selecting any process and technique. Fiber/matrix adhesion, uniform dispersion of fibers, and a high aspect ratio enhance the mechanical properties of bio-composites. Some of the factors affecting manufacturing techniques and properties are fiber length, content, type, orientation, and moisture content. Proper drying of fibers is necessary because moisture

can alter properties and process parameters. Moisture in fibers increases void content and porosity in bio-composites, which affects the final mechanical properties [256,257].

Various modification methods are employed to overcome the moisture issue in fibers [23]. The presence of compounds such as silica and the chemical structure differences among fibers affects manufacturing processes and properties in bio-composites [258,259]. Natural fibers degrade at a high temperature, which gives a narrow temperature range in composite manufacturing [260]. Bio-composites must have a good shelf life and structural integrity while in service [26]. Due to their non-abrasive nature, natural fibers cause less wear and damage to tools and machines used in manufacturing [261]. Induced stresses solidify melt prematurely, and end products can be shrunk by up to 8% [262]. Excess fibers bundle up to form agglomerates and adversely affect bio-composites' final properties [260]. Premature solidification and loss in the strength of final products are also caused by high viscosity of the melt, while homogeneity of final products is affected by fiber length [263].

The addition of various additives solves processing issues, but the overall cost increases and can cause new issues.

5.1. Compression Molding

Compression molding is a reliable method due to the high production rate and low processing time. Compression and flow compression molding is employed in this process. These two techniques are differentiated based on the final products. Glass fibers are manufactured through compression molding, and similar molding techniques can be applied in natural fiber composites. Bio-composites fabricated through this process have adequate mechanical properties for different applications [264]. Compression molding is used for bulk production, such as in automobile parts production [265]. Compression molding decreases fiber strength due to the dependency on initial fiber length and various process parameters such as melt viscosity and screw speed and design. The incompatibility of natural fibers with matrices also reduces fiber strength and the strength of bio-composite [266]. In compression molding, fibers are placed between matrix layers.

Furthermore, load and heat are applied in the process [267]. Compression molding is categorized into hot pressing and auto-clave methods. Sheet and bulk molding materials are starting materials used to cover around 30–70% mold cavity. The mold is closed correctly along with the application of pressure and heat. Natural fibers may break due to high pressure and temperature. Sometimes, short fibers are mixed prior to compression molding to reduce shrinkage and increase the strength of final products [268].

5.2. Extrusion

The plastic industry mostly uses extrusion. Single screw extruders or double screw extruders are used, and screws are rotated clockwise or counterclockwise depending upon the final products. For the limited mixing of melt, a single screw is used. In contrast, a twin-screw extruder is used for the vigorous mixing of melt. Natural fibers are dispersed uniformly in the melt by a twin-screw extruder. Extrusion is a hot-melt technique used for the continuous production of bio-composites [62]. Single and twin extruder have a different processing temperature range, process parameters, and screw designs. Process parameters influence mechanical and thermal properties [269]. Process parameters such as high pressure and high temperature damage natural fibers, albeit resulting in a better aspect ratio but at the cost of mechanical properties such as high porosity [270]. Hang et al. [269] studied the mechanical properties of composites made up of flax fiber using a twin-screw extruder. Chaitanya et al. [271] studied the processing of PLA/sisal bio-composites using extrusion injection molding. The final composite had a 30% weight fraction of fibers. Extrusion injection molding is suitable for processing short and long length fiber, but breakages were observed for long fibers. Extrusion exhibited uniform fiber dispersion for homogenous bio-composites with better mechanical properties. Ranganathan et al. [272] studied the structural properties of jute and viscose fiber hybrid composites. The effect of fiber length and fiber content on fracture toughness and fatigue properties were studied.

Polypropylene was used as the matrix material in twin-screw extrusion. Jute fibers were dried at 60 °C for 48 h, and viscose fibers were dried at the same temperature for about two hours. Samples of 30 wt.% jute fiber with the polypropylene matrix and various weight percentages of viscose fibers were prepared. The composite with 30 wt.% jute fiber showed unstable crack growth with lower fracture toughness. The addition of 10 wt.% of viscose fiber stabilized crack growth. The fatigue life of the composite with 10 wt.% of viscose was three times higher than that of jute fiber composite. The addition of viscose fiber increased fracture energy. Awal et al. [273] analyzed PLA and cellulose fiber composites for thermal and mechanical properties. Bio-composite was fabricated using extrusion molding. Wood cellulosic fibers were used after drying fibers at 80 °C for 24 h. Thermo-gravimetric analysis exhibited an upper limit for processing temperature. The heat distortion temperature was slightly improved for the high-temperature life cycle for PLA and wood fibers composite. The addition of 1.3 wt.% BioAdimide significantly improved the tensile strength and impact strength of the composite. Bio-additives improved the interactions between the fiber and the matrix for better mechanical properties and processability of bio-composites. Tensile modulus for the PLA/wood/adimide composite improved by 26% from the PLA/wood fiber composite.

6. Applications of Bio-Composites

A small number of bio-composites are commercialized and developed. Most of the bio-composites are still under research and development. New processing techniques and technologies are being developed to produce bio-composites at a lower cost. Mostly, bio-composites are used in non-structural and non-load-bearing applications. Developing countries are abundant in natural fibers, but the lack of resources prevents using these fibers in composites and developing new processing techniques, while developed countries in Europe and Asia are ahead in the development of bio-composites [274]. Despite the benefits of these bio-composites, some challenges such as cost reduction, reliable performance, and inferior mechanical properties are still to be addressed for mass production [26]. Despite these challenges, bio-composites still have great potential to be used in various applications. Research has shown promising results, but more research and developments are required to commercialize bio-composites successfully [67]. Focus is being paid to achieve properties comparable with synthetic composites. Bio-composites are biodegradable, renewable, and natural composites with minimum impact on the environment and considerably lower carbon emissions [275]. Growing awareness among people and new laws for environmental protection will promote meaningful improvements for bio-composites. Additionally, developments in agricultural sciences will help to harvest fibers with more favorable properties for these bio-composites. In the near future, bio-composites may completely eradicate the dependence on synthetic products [276]. The energy required for the production of bio-composite is much less than that of synthetic fiber. The production of synthetic composites is energy extensive, while bio-composites save energy [7]. Different governments are encouraging industries to use bio-degradable materials to overcome waste and pollution-related issues [277]. One of the main drawbacks in the use of bio-composites is the variation of mechanical properties in plant fibers. Change in the region, climate, and even fiber from another planet of the same type will likely be different in properties [278]. These shortcomings are balanced through different processing and chemical treatments. The automobile, construction, textile, and packaging industries are the primary industries to employ bio-composites.

6.1. Automobile Industry

Conventional composites have glass and carbon fiber reinforcements that have so far dominated the automobile industry. Renewable alternatives are required to address environmental concerns and reduce petroleum-based composites' carbon footprints [279]. Several candidates have been studied, exhibiting promising results, while others are in the development phase. Various natural fibers such as flax, hemp, kenaf, jute, coir, and

sisal are used to produce bio-composites for automobiles. Bio-composites are also used in automobiles to reduce overall weight, cut down production costs, and improve fuel efficiency. Bio-composites are used to produce different components, such as bumpers, door panels, seat pads, cup holders, trunk covers, armrests, headrests, and seat pads. Furthermore, bio-composites are known to reduce vibrations and noise through damping [264]. Ford uses soy foam seats, bio-based cushions, and hemp fiber composites in the front grills in various vehicle models [280]. Similarly, Mercedes-Benz use jute-based bio-composites for interior panels, flax fiber composites for shelves and trunk covers, and sisal-based composites for rear panel shelves [281]. The use of bio-composites led to a reduced weight of roughly up to 10%, and energy consumption up to 80%, compared to synthetic composites. Toyota use kenaf fibers in tire covers, soy foams for vehicle seats, and PP/PLA-based bio-composites inside trims, toolbox areas, and package trays [282]. Similarly, Volkswagen use bio-composites to make door panels, flap linings, door inserts, and package trays.

6.2. Construction and Textile Industry

In the construction industry, bio-composites are used to manufacture windows, doors, window frames, ceilings, floor mating, and roof tiles. Load-bearing applications include the manufacturing of floor slabs, beams, pipes, and tanks. Furthermore, bio-composites are employed in the repairing and rehabilitation of various structural components. Due to better thermal and acoustic properties, natural fiber composites are used as insulating and soundproofing materials [283]. Hemp/lime/concrete composites have exhibited better sound absorption ability than any other binders [284]. Life cycle assessment, durability properties, and ecological aspects are taken into account before selecting any bio-composite as a construction material. Low weight and comparable mechanical properties with synthetic composites are crucial for construction applications. Similarly, natural fiber composites have enormous potential to be used in the textile industry to manufacture ropes, sacks, bags, and clothes. Moreover, many countries are adopting bio-composite materials to address environmental issues. Many industries are investing in bio-composites due to future demand.

7. Conclusions

The potential of bio-composites to be used as eco-friendly, renewable, and sustainable substitutes is the main driving force for research, development, and commercialization. The use of bio-composites in various applications has opened avenues for research studies and industries to explore further. Early on, the lack of fabrication methods and higher production costs restricted bio-composites' growth, but environmental issues have removed these hurdles. Bio-composites are regarded as the best replacement for synthetic composites because of their comparable mechanical properties and eco-friendly nature. Synthetic composites cause pollution, emit toxic byproducts, use excessive energy, and have recyclability issues and high carbon footprints. The sustainability of synthetic composites comes into question due to the depletion of finite petroleum resources. The use of synthetic composites must be limited to protect the environment. In this review, bio-composites were analyzed to provide an overview of the contemporary developments.

The structure, morphology, content, and mechanical properties of natural fibers were discussed in detail, along with natural fiber constituents. Micro-fibrils, lumen, and different bonding structures play important roles in determining the mechanical properties and low density of fibers. Different modification techniques to improve shortcomings such as the fiber/matrix adhesion, hydrophilicity, and flammability of natural fibers were employed. Modification techniques enhance fiber/matrix interlocking, as well as moisture and thermal resistance. Some of the degradable polymer matrices are polybutylene succinate (PBS), polylactic acid (PLA), poly hydroxyalkanotes (PHA), and poly(ε-caprolactone) (PCL). During biodegradation, biopolymers are decomposed through microbial actions with the release of CO_2, various compounds, and biomass. The addition of natural fibers to these

bio-degradable matrix materials enhances strength and other properties. Bio-composites are manufactured through conventional methods such as compression molding, hand lay-up, injection, extrusion, and pultrusion. Some of these manufacturing techniques and research studies are focusing on the development and modifications of existing techniques to increase the quality of bio-composites. Bio-composites were analyzed in terms of production cost, final design, shape and size, raw material properties, and process constraints. Various applications of bio-composites include construction, automobile, and textile industries. With the ever-increasing demand for bio-composites, numerous new potential applications for bio-composites will be developed in the near future.

References

1. Ojha, S.; Raghavendra, G.; Acharya, S.K. A Comparative Investigation of Bio Waste Filler (Wood Apple-Coconut) Reinforced Polymer Composites. *Polym. Compos.* **2014**, *35*, 180–185. [CrossRef]
2. Molaba, T.P.; Chapple, S.; John, M.J. Aging Studies on Flame Retardant Treated Lignocellulosic Fibers. *J. Appl. Polym. Sci.* **2016**, *133*. [CrossRef]
3. Liu, W.; Drzal, L.T.; Mohanty, A.K.; Misra, M. Influence of Processing Methods and Fiber Length on Physical Properties of Kenaf Fiber Reinforced Soy Based Biocomposites. *Compos. Part B Eng.* **2007**, *38*, 352–359. [CrossRef]
4. Wiley: Lignocellulosic Polymer Composites: Processing, Characterization, and Properties—Vijay Kumar Thakur. Available online: http://www.wiley.com/WileyCDA/WileyTitle/productCd-1118773578.html (accessed on 7 December 2017).
5. Book Review: An Inconvenient Truth. Available online: http://www.webofcreation.org/religious-education/179-book-review-an-inconvenient-truth (accessed on 8 December 2017).
6. Guna, V.; Ilangovan, M.; Ananthaprasad, M.G.; Reddy, N. Hybrid Biocomposites. *Polym. Compos.* **2018**. [CrossRef]
7. Banik, N.; Dey, V.; Sastry, G.R.K. An Overview of Lignin & Hemicellulose Effect upon Biodegradable Bamboo Fiber Composites Due to Moisture. *Mater. Today Proc.* **2017**, *4*, 3222–3232. [CrossRef]
8. A Statistical Approach to Develop Biocomposites from Epoxy Resin, Poly(Furfuryl Alcohol), Poly(Propylene Carbonate), and Biochar—Mashouf Roudsari—2017—Journal of Applied Polymer Science—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/app.45307/full (accessed on 7 December 2017).
9. Biocomposites Based on Polylactic Acid and Olive Solid Waste Fillers: Effect of Two Compatibilization Approaches on the Physicochemical, Rheological and Mechanical Properties—Khemakhem—2016—Polymer Composites—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/pc.24094/full (accessed on 7 December 2017).
10. A Study of the Thermal and Water Diffusivity Properties of Cellulose Nanofibril Reinforced Starch/PVA Bionanocomposite Films—Das—2015—Advances in Polymer Technology—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/adv.21552/full (accessed on 7 December 2017).
11. A Sustainable and Resilient Approach through Biochar Addition in Wood Polymer Composites—ScienceDirect. Available online: http://www.sciencedirect.com/science/article/pii/S0048969715000789 (accessed on 8 December 2017).
12. Adam, J.; Korneliusz, B.A.; Agnieszka, M. Dynamic Mechanical Thermal Analysis of Biocomposites Based on PLA and PHBV—A Comparative Study to PP Counterparts. *J. Appl. Polym. Sci.* **2013**, *130*, 3175–3183. [CrossRef]
13. Effect of Nanoclay and Silica on Mechanical and Morphological Properties of Jute Cellulose Polyethylene Biocomposites—Rahman—2016—Journal of Vinyl and Additive Technology—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/vnl.21554/full (accessed on 8 December 2017).
14. Integration of Biobased Functionalized Feedstock and Plastisol in Epoxy Resin Matrix toward Developing Structural Jute Biocomposites with Enhanced Impact Strength and Moisture Resistance Properties—Bhosale—2014—Polymer Composites—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/pc.23192/full (accessed on 8 December 2017).
15. Ramzy, A.; Beermann, D.; Steuernagel, L.; Meiners, D.; Ziegmann, G. Developing a New Generation of Sisal Composite Fibres for Use in Industrial Applications. *Compos. Part B Eng.* **2014**, *66*, 287–298. [CrossRef]
16. Biocomposites Market Research Report by Material Type, by Fiber Type, by Application—Global Forecast to 2025—Cumulative Impact of COVID-19. Available online: https://www.reportlinker.com/p05913586/Biocomposites-Market-Research-Report-by-

Material-Type-by-Fiber-Type-by-Application-Global-Forecast-to-Cumulative-Impact-of-COVID-19.html?utm_source=GNW (accessed on 9 October 2020).

17. An Investigation of Sound Absorption Coefficient on Sisal Fiber Poly Lactic Acid Bio-Composites—Jayamani—2015—Journal of Applied Polymer Science—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/app.42470/full (accessed on 7 December 2017).

18. A Review: Natural Fiber Composites Selection in View of Mechanical, Light Weight, and Economic Properties—Ahmad—2014—Macromolecular Materials and Engineering—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/mame.201400089/full (accessed on 7 December 2017).

19. Jatropha Deoiled Cake Filler-Reinforced Medium-Density Polyethylene Biocomposites: Effect of Filler Loading and Coupling Agent on the Mechanical, Dynamic Mechanical and Morphological Properties—Elshaarani—2013—Polymer Composites—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/pc.22479/full (accessed on 8 December 2017).

20. Jawaid, M.; Abdul Khalil, H.P.S. Cellulosic/Synthetic Fibre Reinforced Polymer Hybrid Composites: A Review. *Carbohydr. Polym.* **2011**, *86*, 1–18. [CrossRef]

21. Soykeabkaew, N.; Arimoto, N.; Nishino, T.; Peijs, T. All-Cellulose Composites by Surface Selective Dissolution of Aligned Ligno-Cellulosic Fibres. *Compos. Sci. Technol.* **2008**, *68*, 2201–2207. [CrossRef]

22. Darder, M.; Aranda, P.; Ruiz-Hitzky, E. Bionanocomposites: A New Concept of Ecological, Bioinspired, and Functional Hybrid Materials. *Adv. Mater.* **2007**, *19*, 1309–1319. [CrossRef]

23. Faruk, O.; Bledzki, A.K.; Fink, H.-P.; Sain, M. Biocomposites Reinforced with Natural Fibers: 2000–2010. *Prog. Polym. Sci.* **2012**, *37*, 1552–1596. [CrossRef]

24. Sharma, A.K.; Bhandari, R.; Aherwar, A.; Rimašauskienė, R. Matrix Materials Used in Composites: A Comprehensive Study. *Mater. Today Proc.* **2020**, *21*, 1559–1562. [CrossRef]

25. Microfibrillated Cellulose—Its Barrier Properties and Applications in Cellulosic Materials: A Review—ScienceDirect. Available online: http://www.sciencedirect.com/science/article/pii/S014486171200447X (accessed on 8 December 2017).

26. Satyanarayana, K.G.; Arizaga, G.G.; Wypych, F. Biodegradable Composites Based on Lignocellulosic Fibers—An Overview. *Prog. Polym. Sci.* **2009**, *34*, 982–1021. [CrossRef]

27. Norgren, M.; Edlund, H. Lignin: Recent Advances and Emerging Applications. *Curr. Opin. Colloid Interface Sci.* **2014**, *19*, 409–416. [CrossRef]

28. Kumar, S.; Mohanty, A.K.; Erickson, L.; Misra, M. Lignin and Its Applications with Polymers. *J. Biobased Mater. Bioenergy* **2009**, *3*, 1–24. [CrossRef]

29. Li, S.; Xiao, M.; Zheng, A.; Xiao, H. Cellulose Microfibrils Grafted with PBA via Surface-Initiated Atom Transfer Radical Polymerization for Biocomposite Reinforcement. *Biomacromolecules* **2011**, *12*, 3305–3312. [CrossRef]

30. Sajith, S.; Arumugam, V.; Dhakal, H.N. Comparison on Mechanical Properties of Lignocellulosic Flour Epoxy Composites Prepared by Using Coconut Shell, Rice Husk and Teakwood as Fillers. *Polym. Test.* **2017**, *58*, 60–69. [CrossRef]

31. Reddy, N.; Yang, Y. Biofibers from Agricultural Byproducts for Industrial Applications. *Trends Biotechnol.* **2005**, *23*, 22–27. [CrossRef]

32. Célino, A.; Freour, S.; Jacquemin, F.; Casari, P. The Hygroscopic Behavior of Plant Fibers: A Review. *Front. Chem.* **2014**, *1*. [CrossRef]

33. Biocomposites from Abaca Strands and Polypropylene. Part I: Evaluation of the Tensile Properties—ScienceDirect. Available online: http://www.sciencedirect.com/science/article/pii/S0960852409009638 (accessed on 9 December 2017).

34. Biocomposites Containing Cellulose Fibers Treated with Nanosized Elastomeric Latex for Enhancing Impact Strength—ScienceDirect. Available online: http://www.sciencedirect.com/science/article/pii/S0266353813000328 (accessed on 9 December 2017).

35. Signori, F.; Pelagaggi, M.; Bronco, S.; Righetti, M.C. Amorphous/Crystal and Polymer/Filler Interphases in Biocomposites from Poly (Butylene Succinate). *Thermochim. Acta* **2012**, *543*, 74–81. [CrossRef]

36. Biocomposites from Wheat Proteins and Fibers: Structure/Mechanical Properties Relationships—ScienceDirect. Available online: http://www.sciencedirect.com/science/article/pii/S0926669012004438 (accessed on 9 December 2017).

37. Kellersztein, I.; Amir, E.; Dotan, A. Grafting of Wheat Straw Fibers with Poly (ε-Caprolactone) via Ring-Opening Polymerization for Poly(Lactic Acid) Reinforcement. *Polym. Adv. Technol.* **2016**, *27*, 657–664. [CrossRef]

38. Cunha, M.; Berthet, M.-A.; Pereira, R.; Covas, J.A.; Vicente, A.A.; Hilliou, L. Development of Polyhydroxyalkanoate/Beer Spent Grain Fibers Composites for Film Blowing Applications. *Polym. Compos.* **2015**, *36*, 1859–1865. [CrossRef]

39. García, A.V.; Santonja, M.R.; Sanahuja, A.B.; Selva, M.D.C.G. Characterization and Degradation Characteristics of Poly(ε-Caprolactone)-Based Composites Reinforced with Almond Skin Residues. *Polym. Degrad. Stab.* **2014**, *108*, 269–279. [CrossRef]

40. Ku, H.; Wang, H.; Pattarachaiyakoop, N.; Trada, M. A Review on the Tensile Properties of Natural Fiber Reinforced Polymer Composites. *Compos. Part B Eng.* **2011**, *42*, 856–873. [CrossRef]

41. Biocomposites Based on Poly(Butylene Succinate) and Curaua: Mechanical and Morphological Properties—ScienceDirect. Available online: https://www.sciencedirect.com/science/article/pii/S0142941815001415 (accessed on 11 December 2017).

42. Synthesis, Characterization and Properties of Novel Linear Poly(Butylene Fumarate) Bearing Reactive Double Bonds—Documents. Available online: https://docslide.net/documents/synthesis-characterization-and-properties-of-novel-linear-polybutylene-fumarate.html (accessed on 11 December 2017).

43. Zhao, Q.; Tao, J.; Yam, R.C.M.; Mok, A.C.K.; Li, R.K.Y.; Song, C. Biodegradation Behavior of Polycaprolactone/Rice Husk Ecocomposites in Simulated Soil Medium. *Polym. Degrad. Stab.* **2008**, *93*, 1571–1576. [CrossRef]

44. All-Cellulose and All-Wood Composites by Partial Dissolution of Cotton Fabric and Wood in Ionic Liquid—ScienceDirect. Available online: http://www.sciencedirect.com/science/article/pii/S0144861713007480 (accessed on 11 December 2017).

45. Cocca, M.; Avolio, R.; Gentile, G.; Di Pace, E.; Errico, M.E.; Avella, M. Amorphized Cellulose as Filler in Biocomposites Based on Poly(ε-Caprolactone). *Carbohydr. Polym.* **2015**, *118*, 170–182. [CrossRef]

46. Mastali, M.; Abdollahnejad, Z.; Pacheco-Torgal, F. Carbon Dioxide Sequestration of Fly Ash Alkaline-Based Mortars Containing Recycled Aggregates and Reinforced by Hemp Fibres. *Constr. Build. Mater.* **2018**, *160*, 48–56. [CrossRef]

47. Mechanical and Thermal Properties of Polypropylene Reinforced with Doum Fiber: Impact of Fibrillization | SpringerLink. Available online: https://link.springer.com/chapter/10.1007/978-3-319-46610-1_11 (accessed on 9 December 2017).

48. Thomas, S.; Woh, Y.-K.; Wang, R.; Goh, K.L. Probing the Hydrophilicity of Coir Fibres: Analysis of the Mechanical Properties of Single Coir Fibres. *Procedia Eng.* **2017**, *200*, 206–212. [CrossRef]

49. Arfaoui, M.A.; Dolez, P.I.; Dubé, M.; David, É. Development and Characterization of a Hydrophobic Treatment for Jute Fibres Based on Zinc Oxide Nanoparticles and a Fatty Acid. *Appl. Surf. Sci.* **2017**, *397*, 19–29. [CrossRef]

50. Quiles-Carrillo, L.; Montanes, N.; Sammon, C.; Balart, R.; Torres-Giner, S. Compatibilization of Highly Sustainable Polylactide/Almond Shell Flour Composites by Reactive Extrusion with Maleinized Linseed Oil. *Ind. Crops Prod.* **2017**. [CrossRef]

51. de Oliveira, J.P.; Bruni, G.P.; Lima, K.O.; Halal, S.L.M.E.; da Rosa, G.S.; Dias, A.R.G.; Zavareze, E.D.R. Cellulose Fibers Extracted from Rice and Oat Husks and Their Application in Hydrogel. *Food Chem.* **2017**, *221*, 153–160. [CrossRef] [PubMed]

52. Montaño-Leyva, B.; Gontard, N.; Angellier-Coussy, H. Poly (3-Hydroxybutyrate-Co-Hydroxyvalerate) and Wheat Straw Fibers Biocomposites Produced by Co-Grinding: Processing and Mechanical Behavior. *J. Compos. Mater.* **2017**, *51*, 985–996. [CrossRef]

53. Biocomposites From Switchgrass and Lignin Hybrid and Poly(Butylene Succinate) Bioplastic: Studies on Reactive Compatibilization and Performance Evaluation—Sahoo—2013—Macromolecular Materials and Engineering—Wiley Online Library. Available online: http://onlinelibrary.wiley.com/doi/10.1002/mame.201300038/abstract (accessed on 9 December 2017).

54. Spinacé, M.A.; De Paoli, M.-A. Biocomposite of a Multilayer Film Scrap and Curauá Fibers: Preparation and Environmental Degradation. *J. Thermoplast. Compos. Mater.* **2017**, *30*, 225–240. [CrossRef]

55. Hashim, M.Y.; Amin, A.M.; Marwah, O.M.F.; Othman, M.H.; Yunus, M.R.M.; Huat, N.C. The Effect of Alkali Treatment under Various Conditions on Physical Properties of Kenaf Fiber. *J. Phys. Conf. Ser.* **2017**, *914*, 012030. [CrossRef]

56. Pereira, G.B.; Pereira, G.C.; Lima, M.; Jesus, B.; Silva, E.D.A.; Benini, K.C.C.; Bandeira, C.; Montoro, S.R. Featuring High Impact Polystyrene Composites Strengthened with Green Coconut Fiber Developed for Automotive Industry Application. *J. Res. Updat. Polym. Sci.* **2017**, *6*, 17–20.

57. Inoue, K.; Bigeard, A.; Hirogaki, T.; Aoyama, E.; Ogawa, K.; Nobe, H. Fabrication of Complex-Shape Products From a Binder-Free Green Composite Using Bamboo Fibers and Powders Extracted with a Machining Center. *Am. Soc. Mech. Eng.* **2017**, *58165*, V004T05A023. [CrossRef]

58. Mohammadkazemi, F.; Aguiar, R.; Cordeiro, N. Improvement of Bagasse Fiber–Cement Composites by Addition of Bacterial Nanocellulose: An Inverse Gas Chromatography Study. *Cellulose* **2017**, *24*, 1803–1814. [CrossRef]

59. KOH Activated Carbon Derived from Biomass-Banana Fibers as an Efficient Negative Electrode in High Performance Asymmetric Supercapacitor—ScienceDirect. Available online: http://www.sciencedirect.com/science/article/pii/S2095495616300961 (accessed on 9 December 2017).

60. Patil, N.V.; Rahman, M.M.; Netravali, A.N. "Green" Composites Using Bioresins from Agro-Wastes and Modified Sisal Fibers. *Polym. Compos.* **2019**. [CrossRef]

61. Low-Density Polyethylene/Sugarcane Fiber Composites from Recycled Polymer and Treated Fiber by Steam Explosion: Journal of Natural Fibers. Available online: http://www.tandfonline.com/doi/abs/10.1080/15440478.2017.1379044 (accessed on 9 December 2017).

62. Gallos, A.; Paës, G.; Allais, F.; Beaugrand, J. Lignocellulosic Fibers: A Critical Review of the Extrusion Process for Enhancement of the Properties of Natural Fiber Composites. *RSC Adv.* **2017**, *7*, 34638–34654. [CrossRef]

63. Fengel, D.; Wegener, G. *Wood—Chemistry, Ultrastructure, Reactions*; Walter de Gruyter: Berlin, Germany; New York, NY, USA, 1984; Volume 613, Available online: http://onlinelibrary.wiley.com/doi/10.1002/pol.1985.130231112/abstract (accessed on 15 December 2017).

64. John, M.J.; Thomas, S. Biofibres and Biocomposites. *Carbohydr. Polym.* **2008**, *71*, 343–364. [CrossRef]

65. Abdul Khalil, H.P.S.; Davoudpour, Y.; Islam, M.d.N.; Mustapha, A.; Sudesh, K.; Dungani, R.; Jawaid, M. Production and Modification of Nanofibrillated Cellulose Using Various Mechanical Processes: A Review. *Carbohydr. Polym.* **2014**, *99*, 649–665. [CrossRef] [PubMed]

66. Kalia, S.; Dufresne, A.; Cherian, B.M.; Kaith, B.S.; Avérous, L.; Njuguna, J.; Nassiopoulos, E. Cellulose-Based Bio- and Nanocomposites: A Review. Available online: https://www.hindawi.com/journals/ijps/2011/837875/ (accessed on 15 December 2017).

67. Khalil, H.A.; Bhat, A.H.; Yusra, A.I. Green Composites from Sustainable Cellulose Nanofibrils: A Review. *Carbohydr. Polym.* **2012**, *87*, 963–979. [CrossRef]

68. Dufresne, A. Nanocellulose: A New Ageless Bionanomaterial. *Mater. Today* **2013**, *16*, 220–227. [CrossRef]

69. Hansen, C.M.; Björkman, A. The Ultrastructure of Wood from a Solubility Parameter Point of View. *Holzforsch. Int. J. Biol. Chem. Phys. Technol. Wood* **2009**, *52*, 335–344. [CrossRef]

70. Rowell, R.M.; Han, J.S.; Rowell, J.S. Characterization and Factors Effecting Fiber Properties. In *Natural Polymers and Agrofibers Based Composites*; Embrapa Instrumentacao Agropecu: Sao Carlos, Brazil, 2000; pp. 115–134.

71. Yan, L.; Kasal, B.; Huang, L. A Review of Recent Research on the Use of Cellulosic Fibres, Their Fibre Fabric Reinforced Cementitious, Geo-Polymer and Polymer Composites in Civil Engineering. *Compos. Part B Eng.* **2016**, *92*, 94–132. [CrossRef]

72. Dittenber, D.B.; GangaRao, H.V. Critical Review of Recent Publications on Use of Natural Composites in Infrastructure. *Compos. Part Appl. Sci. Manuf.* **2012**, *43*, 1419–1429. [CrossRef]

73. John, M.J.; Anandjiwala, R.D. Recent Developments in Chemical Modification and Characterization of Natural Fiber-Reinforced Composites. *Polym. Compos.* **2008**, *29*, 187–207. [CrossRef]

74. Feughelman, M. *Mechanical Properties and Structure of Alpha-Keratin Fibres: Wool, Human Hair and Related Fibres*; UNSW Press: Sydney, Australia, 1997.

75. Fakirov, S.; Bhattacharyya, D. *Handbook of Engineering Biopolymers: 'Homopolymers, Blends, and Composites*; Bhattacharya, D., Ed.; Hanser Publications: Munich, Germany; Cincinnati, OH, USA, 2007; ISBN 978-1-56990-405-3.

76. Badrinath, R.; Senthilvelan, T. Comparative Investigation on Mechanical Properties of Banana and Sisal Reinforced Polymer Based Composites. *Procedia Mater. Sci.* **2014**, *5*, 2263–2272. [CrossRef]

77. Cherian, B.M.; Leão, A.L.; de Souza, S.F.; Thomas, S.; Pothan, L.A.; Kottaisamy, M. Isolation of Nanocellulose from Pineapple Leaf Fibres by Steam Explosion. *Carbohydr. Polym.* **2010**, *81*, 720–725. [CrossRef]

78. Ramesh, M.; Palanikumar, K.; Reddy, K.H. Plant Fibre Based Bio-Composites: Sustainable and Renewable Green Materials. *Renew. Sustain. Energy Rev.* **2017**, *79*, 558–584. [CrossRef]

79. Ramakrishna, G.; Sundararajan, T. Impact Strength of a Few Natural Fibre Reinforced Cement Mortar Slabs: A Comparative Study. *Cem. Concr. Compos.* **2005**, *27*, 547–553. [CrossRef]

80. Naidu, A.L.; Raghuveer, D.; Suman, P. Studies on Characterization and Mechanical Behavior of Banana Peel Reinforced Epoxy Composites. *Int. J. Sci. Eng. Res.* **2013**, *4*, 844.

81. Athijayamani, A.; Thiruchitrambalam, M.; Natarajan, U.; Pazhanivel, B. Effect of Moisture Absorption on the Mechanical Properties of Randomly Oriented Natural Fibers/Polyester Hybrid Composite. *Mater. Sci. Eng. A* **2009**, *517*, 344–353. [CrossRef]

82. Kozłowski, R.; Władyka-Przybylak, M. Flammability and Fire Resistance of Composites Reinforced by Natural Fibers. *Polym. Adv. Technol.* **2008**, *19*, 446–453. [CrossRef]

83. Manikandan, N.; Morshed, M.N.; Karthik, R.; Al Azad, S.; Deb, H.; Rumi, T.M.; Ahmed, M.R. Improvement of Mechanical Properties of Natural Fiber Reinforced Jute/Polyester Epoxy Composite through Meticulous Alkali Treatment. *Am. J. Curr. Org. Chem.* **2017**, *3*, 9–18.

84. Joseph, S.; Oommen, Z.; Thomas, S. Environmental Durability of Banana-Fiber-Reinforced Phenol Formaldehyde Composites. *J. Appl. Polym. Sci.* **2006**, *100*, 2521–2531. [CrossRef]

85. Popelka, A.; Novák, I.; Al-Maadeed, M.A.S.; Ouederni, M.; Krupa, I. Effect of Corona Treatment on Adhesion Enhancement of LLDPE. *Surf. Coat. Technol.* **2017**, *335*, 118–125. [CrossRef]

86. Ragoubi, M.; Bienaimé, D.; Molina, S.; George, B.; Merlin, A. Impact of Corona Treated Hemp Fibres onto Mechanical Properties of Polypropylene Composites Made Thereof. *Ind. Crops Prod.* **2010**, *31*, 344–349. [CrossRef]

87. Marais, S.; Gouanvé, F.; Bonnesoeur, A.; Grenet, J.; Poncin-Epaillard, F.; Morvan, C.; Métayer, M. Unsaturated Polyester Composites Reinforced with Flax Fibers: Effect of Cold Plasma and Autoclave Treatments on Mechanical and Permeation Properties. *Compos. Part Appl. Sci. Manuf.* **2005**, *36*, 975–986. [CrossRef]

88. Seki, Y.; Sever, K.; Sarikanat, M.; Güleç, H.A.; Tavman, I.H. The Influence of Oxygen Plasma Treatment of Jute Fibers on Mechanical Properties of Jute Fiber Reinforced Thermoplastic Composites. In Proceedings of the 5th International Advanced Technologies Symposium (IATS'09), Karabuk, Turkey, 13–15 May 2009.

89. Bilba, K.; Arsene, M.-A. Silane Treatment of Bagasse Fiber for Reinforcement of Cementitious Composites. *Compos. Part Appl. Sci. Manuf.* **2008**, *39*, 1488–1495. [CrossRef]

90. Law, T.T.; Ishak, Z.A. Water Absorption and Dimensional Stability of Short Kenaf Fiber-Filled Polypropylene Composites Treated with Maleated Polypropylene. *J. Appl. Polym. Sci.* **2011**, *120*, 563–572. [CrossRef]

91. Pommet, M.; Juntaro, J.; Heng, J.Y.; Mantalaris, A.; Lee, A.F.; Wilson, K.; Kalinka, G.; Shaffer, M.S.; Bismarck, A. Surface Modification of Natural Fibers Using Bacteria: Depositing Bacterial Cellulose onto Natural Fibers to Create Hierarchical Fiber Reinforced Nanocomposites. *Biomacromolecules* **2008**, *9*, 1643–1651. [CrossRef] [PubMed]

92. Joseph, K.; Mattoso, L.H.C.; Toledo, R.D.; Thomas, S.; De Carvalho, L.H.; Pothen, L.; Kala, S.; James, B. Natural Fiber Reinforced Thermoplastic Composites. *Nat. Polym. Agrofibers Compos.* **2000**, *159*, 159–201.

93. Mohanty, A.K.; Misra, M.; Drzal, L.T. Surface Modifications of Natural Fibers and Performance of the Resulting Biocomposites: An Overview. *Compos. Interfaces* **2001**, *8*, 313–343. [CrossRef]

94. Valadez-Gonzalez, A.; Cervantes-Uc, J.M.; Olayo, R.; Herrera-Franco, P.J. Chemical Modification of Henequen Fibers with an Organosilane Coupling Agent. *Compos. Part B Eng.* **1999**, *30*, 321–331. [CrossRef]

95. Valadez-Gonzalez, A.; Cervantes-Uc, J.M.; Olayo, R.; Herrera-Franco, P.J. Effect of Fiber Surface Treatment on the Fiber–Matrix Bond Strength of Natural Fiber Reinforced Composites. *Compos. Part B Eng.* **1999**, *30*, 309–320. [CrossRef]

96. Mishra, S.; Mohanty, A.K.; Drzal, L.T.; Misra, M.; Parija, S.; Nayak, S.K.; Tripathy, S.S. Studies on Mechanical Performance of Biofibre/Glass Reinforced Polyester Hybrid Composites. *Compos. Sci. Technol.* **2003**, *63*, 1377–1385. [CrossRef]

97. Kabir, M.M.; Wang, H.; Lau, K.T.; Cardona, F. Chemical Treatments on Plant-Based Natural Fibre Reinforced Polymer Composites: An Overview. *Compos. Part B Eng.* **2012**, *43*, 2883–2892. [CrossRef]

98. Wang, B.; Panigrahi, S.; Crerar, W.; Tabil, L. Application of Pre-Treated Flax Fibers in Composites. In Proceedings of the CSAE SCGR, Montréal, QC, Canada, 6–9 July 2003.

99. Kohli, D.; Garg, S.; Jana, A.K.; Maiti, M. Synthesis of Graft Copolymers for Green Composite Films and Optimization of Reaction Parameters Using Taguchi (L16) Orthogonal Array. *Indian Chem. Eng.* **2017**, *59*, 136–158. [CrossRef]

100. Beyaz, K.; Charton, M.; Rouilly, A.; Vedrenne, E.; Vaca-Garcia, C.; Benaboura, A.; Thiebaud-Roux, S. Synthesis of Graft-Copolymers from Palm Cellulose and Solketal Acrylate and Their Characterization. *Ind. Crops Prod.* **2017**, *97*, 32–40. [CrossRef]

101. Rahman, M.M.; Mallik, A.K.; Khan, M.A. Influences of Various Surface Pretreatments on the Mechanical and Degradable Properties of Photografted Oil Palm Fibers. *J. Appl. Polym. Sci.* **2007**, *105*, 3077–3086. [CrossRef]

102. Kalia, S.; Kaith, B.S.; Kaur, I. Pretreatments of Natural Fibers and Their Application as Reinforcing Material in Polymer Composites—A Review. *Polym. Eng. Sci.* **2009**, *49*, 1253–1272. [CrossRef]

103. Methacanon, P.; Weerawatsophon, U.; Sumransin, N.; Prahsarn, C.; Bergado, D.T. Properties and Potential Application of the Selected Natural Fibers as Limited Life Geotextiles. *Carbohydr. Polym.* **2010**, *82*, 1090–1096. [CrossRef]

104. Zakaria, S.; Kok Poh, L. Polystyrene-Benzoylated EFB Reinforced Composites. *Polym.-Plast. Technol. Eng.* **2002**, *41*, 951–962. [CrossRef]

105. Sgriccia, N.; Hawley, M.C.; Misra, M. Characterization of Natural Fiber Surfaces and Natural Fiber Composites. *Compos. Part Appl. Sci. Manuf.* **2008**, *39*, 1632–1637. [CrossRef]

106. Hosseinaei, O.; Wang, S.; Enayati, A.A.; Rials, T.G. Effects of Hemicellulose Extraction on Properties of Wood Flour and Wood–Plastic Composites. *Compos. Part Appl. Sci. Manuf.* **2012**, *43*, 686–694. [CrossRef]

107. Espert, A.; Vilaplana, F.; Karlsson, S. Comparison of Water Absorption in Natural Cellulosic Fibres from Wood and One-Year Crops in Polypropylene Composites and Its Influence on Their Mechanical Properties. *Compos. Part Appl. Sci. Manuf.* **2004**, *35*, 1267–1276. [CrossRef]

108. Wang, Y.; Wei, Q.; Wang, S.; Chai, W.; Zhang, Y. Structural and Water Diffusion of Poly (Acryl Amide)/Poly (Vinyl Alcohol) Blend Films: Experiment and Molecular Dynamics Simulations. *J. Mol. Graph. Model.* **2017**, *71*, 40–49. [CrossRef] [PubMed]

109. Wang, W.; Sain, M.; Cooper, P.A. Study of Moisture Absorption in Natural Fiber Plastic Composites. *Compos. Sci. Technol.* **2006**, *66*, 379–386. [CrossRef]

110. Benard, P.; Kroener, E.; Vontobel, P.; Kaestner, A.; Carminati, A. Water Percolation through the Root-Soil Interface. *Adv. Water Resour.* **2016**, *95*, 190–198. [CrossRef]

111. Gupta, A. Synthesis, Chemical Resistance, and Water Absorption of Bamboo Fiber Reinforced Epoxy Composites. *Polym. Compos.* **2016**, *37*, 141–145. [CrossRef]

112. Dhakal, H.N.; Zhang, Z.Y.; Richardson, M.O.W. Effect of Water Absorption on the Mechanical Properties of Hemp Fibre Reinforced Unsaturated Polyester Composites. *Compos. Sci. Technol.* **2007**, *67*, 1674–1683. [CrossRef]

113. Baltazar-y-Jimenez, A.; Awal, A.; Sain, M. Natural Composites: Fiber Modification. In *Wiley Encyclopedia of Composites*; John Wiley & Sons: Hoboken, NJ, USA, 2012.

114. Pott, G.T.; Hueting, D.J.; Van Deursen, J.H. Reduction of Moisture Sensitivity in Wood and Natural Fibers for Polymer Composites. In Proceedings of the 3rd International Wood and Natural Fiber Composites Symposium, Kassel, Germany, 19–20 September 2000.

115. Li, X.; Tabil, L.G.; Panigrahi, S. Chemical Treatments of Natural Fiber for Use in Natural Fiber-Reinforced Composites: A Review. *J. Polym. Environ.* **2007**, *15*, 25–33. [CrossRef]

116. Lepetit, A.; Drolet, R.; Tolnai, B.; Zerrouki, R.; Montplaisir, D. Effect of Acetylation on the Properties of Microfibrillated Cellulose-LDPE Composites. *J. Appl. Polym. Sci.* **2017**, *134*, 44933. [CrossRef]

117. Tserki, V.; Zafeiropoulos, N.E.; Simon, F.; Panayiotou, C. A Study of the Effect of Acetylation and Propionylation Surface Treatments on Natural Fibres. *Compos. Part Appl. Sci. Manuf.* **2005**, *36*, 1110–1118. [CrossRef]

118. Khalil, H.A.; Ismail, H. Effect of Acetylation and Coupling Agent Treatments upon Biological Degradation of Plant Fibre Reinforced Polyester Composites. *Polym. Test.* **2000**, *20*, 65–75. [CrossRef]

119. Kumar, D.R.; Mohanraj, P. Review on Natural Fiber in Various Pretreatment Conditions for Preparing Perfect Fiber. *Asian J. Appl. Sci. Technol. AJAST* **2017**, *1*, 66–78.

120. Islam, M.N.; Ahmed, N.; Hossain, M.Y.; Rahman, A.; Sultana, A. Effect of PH on the Adsorption Kinetics of Cr (VI) on Sodium Chlorite Treated Coconut Coir. *Bangladesh J. Sci. Ind. Res.* **2016**, *51*, 95–100. [CrossRef]

121. Rambabu, N.; Panthapulakkal, S.; Sain, M.; Dalai, A.K. Production of Nanocellulose Fibers from Pinecone Biomass: Evaluation and Optimization of Chemical and Mechanical Treatment Conditions on Mechanical Properties of Nanocellulose Films. *Ind. Crops Prod.* **2016**, *83*, 746–754. [CrossRef]

122. Kalaprasad, G.; Francis, B.; Thomas, S.; Kumar, C.R.; Pavithran, C.; Groeninckx, G.; Thomas, S. Effect of Fibre Length and Chemical Modifications on the Tensile Properties of Intimately Mixed Short Sisal/Glass Hybrid Fibre Reinforced Low Density Polyethylene Composites. *Polym. Int.* **2004**, *53*, 1624–1638. [CrossRef]

123. Rajesh, M.; Pitchaimani, J. Mechanical Characterization of Natural Fiber Intra-Ply Fabric Polymer Composites: Influence of Chemical Modifications. *J. Reinf. Plast. Compos.* **2017**, *36*, 1651–1664. [CrossRef]

124. Mengeloglu, F.; Karakus, K. Thermal Degradation, Mechanical Properties and Morphology of Wheat Straw Flour Filled Recycled Thermoplastic Composites. *Sensors* **2008**, *8*, 500–519. [CrossRef] [PubMed]

125. Pandey, J.K.; Ahn, S.H.; Lee, C.S.; Mohanty, A.K.; Misra, M. Recent Advances in the Application of Natural Fiber Based Composites. *Macromol. Mater. Eng.* **2010**, *295*, 975–989. [CrossRef]

126. Corrales, F.; Vilaseca, F.; Llop, M.; Girones, J.; Mendez, J.A.; Mutje, P. Chemical Modification of Jute Fibers for the Production of Green-Composites. *J. Hazard. Mater.* **2007**, *144*, 730–735. [CrossRef] [PubMed]

127. Gulati, D.; Sain, M. Fungal-Modification of Natural Fibers: A Novel Method of Treating Natural Fibers for Composite Reinforcement. *J. Polym. Environ.* **2006**, *14*, 347–352. [CrossRef]

128. Wang, W.; Sain, M.; Cooper, P.A. Hygrothermal Weathering of Rice Hull/HDPE Composites under Extreme Climatic Conditions. *Polym. Degrad. Stab.* **2005**, *90*, 540–545. [CrossRef]

129. Hollaway, L.C. A Review of the Present and Future Utilisation of FRP Composites in the Civil Infrastructure with Reference to Their Important In-Service Properties. *Constr. Build. Mater.* **2010**, *24*, 2419–2445. [CrossRef]

130. Stark, N.M.; White, R.H.; Mueller, S.A.; Osswald, T.A. Evaluation of Various Fire Retardants for Use in Wood Flour–Polyethylene Composites. *Polym. Degrad. Stab.* **2010**, *95*, 1903–1910. [CrossRef]

131. Ngo, T.D.; Ton-That, M.T.; Hu, W. Innovative and Sustainable Approaches to Enhance Fire Resistance of Cellulosic Fibers for Green Polymer Composites. *SAMPE J.* **2013**, *49*, 31–37.

132. Manfredi, L.B.; Rodríguez, E.; Wladyka-Przybylak, M.; Vazquez, A. Thermal Properties and Fire Resistance of Jute-Reinforced Composites. *Compos. Interfaces* **2010**, *17*, 663–675. [CrossRef]

133. Azwa, Z.N.; Yousif, B.F. Characteristics of Kenaf Fibre/Epoxy Composites Subjected to Thermal Degradation. *Polym. Degrad. Stab.* **2013**, *98*, 2752–2759. [CrossRef]

134. Azwa, Z.N.; Yousif, B.F.; Manalo, A.C.; Karunasena, W. A Review on the Degradability of Polymeric Composites Based on Natural Fibres. *Mater. Des.* **2013**, *47*, 424–442. [CrossRef]

135. Manfredi, L.B.; Rodríguez, E.S.; Wladyka-Przybylak, M.; Vázquez, A. Thermal Degradation and Fire Resistance of Unsaturated Polyester, Modified Acrylic Resins and Their Composites with Natural Fibres. *Polym. Degrad. Stab.* **2006**, *91*, 255–261. [CrossRef]

136. Suardana, N.P.G.; Ku, M.S.; Lim, J.K. Effects of Diammonium Phosphate on the Flammability and Mechanical Properties of Bio-Composites. *Mater. Des.* **2011**, *32*, 1990–1999. [CrossRef]

137. Kozlowski, R.; Helwig, M. Progress in Fire Retardants for Lignocellulosic Materials. In Proceedings of the 6th Arab International Conference on Materials Science, Materials & Fire, Alexandria, Egypt, 22–25 March 1998; pp. 1–11.

138. Garcia, M.; Hidalgo, J.; Garmendia, I.; García-Jaca, J. Wood–Plastics Composites with Better Fire Retardancy and Durability Performance. *Compos. Part Appl. Sci. Manuf.* **2009**, *40*, 1772–1776. [CrossRef]

139. Hamid, M.R.Y.; Ab Ghani, M.H.; Ahmad, S. Effect of Antioxidants and Fire Retardants as Mineral Fillers on the Physical and Mechanical Properties of High Loading Hybrid Biocomposites Reinforced with Rice Husks and Sawdust. *Ind. Crops Prod.* **2012**, *40*, 96–102. [CrossRef]

140. Vinod, B.; Anandajothi, M. Mechanical and Tribological Properties of Abaca-Roselle/Cardanol Formaldehyde Hybrid Composites. *Mater. Res. Express* **2020**, *6*, 125363. [CrossRef]

141. Kencanawati, C.; Suardana, N.P.G.; Sugita, I.K.G.; Suyasa, I.W.B. Characteristics of Fiber Treatments on Tensile and Impact Strengths of Pine Resin/Areca Husk Fiber Biocomposites. *Int. J. Civ. Eng. Technol.* **2020**, *11*, 86–93.

142. Sajna, V.P.; Mohanty, S.; Nayak, S.K. Influence of Nanoclay and Graft Copolymer on the Thermal and Flammability Properties of Poly (Lactic Acid)/Banana Fiber Biocomposites. *J. Vinyl Addit. Technol.* **2017**, *23*, E81–E91. [CrossRef]

143. Fiore, V.; Scalici, T.; Valenza, A. Effect of Sodium Bicarbonate Treatment on Mechanical Properties of Flax-Reinforced Epoxy Composite Materials. *J. Compos. Mater.* **2018**, *52*, 1061–1072. [CrossRef]

144. Dhakal, H.N.; Ismail, S.O.; Zhang, Z.; Barber, A.; Welsh, E.; Maigret, J.-E.; Beaugrand, J. Development of Sustainable Biodegradable Lignocellulosic Hemp Fiber/Polycaprolactone Biocomposites for Light Weight Applications. *Compos. Part Appl. Sci. Manuf.* **2018**, *113*, 350–358. [CrossRef]

145. Lakshmanan, A.; Ghosh, R.K.; Dasgupta, S.; Chakraborty, S.; Ganguly, P.K. Optimization of Alkali Treatment Condition on Jute Fabric for the Development of Rigid Biocomposite. *J. Ind. Text.* **2018**, *47*, 640–655. [CrossRef]

146. Abdellaoui, H.; Bensalah, H.; Raji, M.; Rodrigue, D.; Bouhfid, R. Laminated Epoxy Biocomposites Based on Clay and Jute Fibers. *J. Bionic Eng.* **2017**, *14*, 379–389. [CrossRef]

147. Prakash, V.A.; Viswanthan, R. Fabrication and Characterization of Echinoidea Spike Particles and Kenaf Natural Fibre-Reinforced Azadirachta-Indica Blended Epoxy Multi-Hybrid Bio Composite. *Compos. Part Appl. Sci. Manuf.* **2019**, *118*, 317–326. [CrossRef]

148. Debeli, D.K.; Qin, Z.; Guo, J. Study on the Pre-Treatment, Physical and Chemical Properties of Ramie Fibers Reinforced Poly (Lactic Acid)(PLA) Biocomposite. *J. Nat. Fibers* **2018**, *15*, 596–610. [CrossRef]

149. Xie, Q.; Li, F.; Li, J.; Wang, L.; Li, Y.; Zhang, C.; Xu, J.; Chen, S. A New Biodegradable Sisal Fiber–Starch Packing Composite with Nest Structure. *Carbohydr. Polym.* **2018**, *189*, 56–64. [CrossRef]

150. Rowell, R.M. *Properties and Performance of Natural-Fibre Composites*; Elsevier: Amsterdam, The Netherlands, 2008; pp. 4–36.

151. Juarez, C.; Duran, A.; Valdez, P.; Fajardo, G. Performance of "Agave Lecheguilla" Natural Fiber in Portland Cement Composites Exposed to Severe Environment Conditions. *Build. Environ.* **2007**, *42*, 1151–1157. [CrossRef]

152. Shalwan, A.; Yousif, B.F. In State of Art: Mechanical and Tribological Behaviour of Polymeric Composites Based on Natural Fibres. *Mater. Des.* **2013**, *48*, 14–24. [CrossRef]

153. Saheb, D.N.; Jog, J.P. Natural Fiber Polymer Composites: A Review. *Adv. Polym. Technol.* **1999**, *18*, 351–363. [CrossRef]

154. Sampathkumar, D.; Punyamurthy, R.; Bennehalli, B.; Venkateshappa, S.C. Effect of Esterification on Moisture Absorption of Single Areca Fiber. *Int. J. Agric. Sci.* **2012**, *4*, 227.

155. Binoj, J.S.; Raj, R.E.; Sreenivasan, V.S.; Thusnavis, G.R. Morphological, Physical, Mechanical, Chemical and Thermal Characterization of Sustainable Indian Areca Fruit Husk Fibers (*Areca catechu* L.) as Potential Alternate for Hazardous Synthetic Fibers. *J. Bionic Eng.* **2016**, *13*, 156–165. [CrossRef]

156. Stokke, D.D.; Wu, Q.; Han, G. *Introduction to Wood and Natural Fiber Composites*; John Wiley & Sons: Hoboken, NJ, USA, 2013.

157. Yu, Y.; Wang, H.; Lu, F.; Tian, G.; Lin, J. Bamboo Fibers for Composite Applications: A Mechanical and Morphological Investigation. *J. Mater. Sci.* **2014**, *49*, 2559–2566. [CrossRef]

158. Huda, M.S.; Drzal, L.T.; Mohanty, A.K.; Misra, M. Chopped Glass and Recycled Newspaper as Reinforcement Fibers in Injection Molded Poly (Lactic Acid)(PLA) Composites: A Comparative Study. *Compos. Sci. Technol.* **2006**, *66*, 1813–1824. [CrossRef]

159. Zahn, H.; Föhles, J.; Nlenhaus, M.; Schwan, A.; Spel, M. Wool as a Biological Composite Structure. *Ind. Eng. Chem. Prod. Res. Dev.* **1980**, *19*, 496–501. [CrossRef]

160. Kumar, R.; Obrai, S.; Sharma, A. Chemical Modifications of Natural Fiber for Composite Material. *Chem. Sin.* **2011**, *2*, 219–228.

161. Mohanty, A.K.; Misra, M.; Hinrichsen, G. Biofibers, Biodegradable Polymers and Biocomposites: An Overview. *Macromol. Mater. Eng.* **2000**, *276*, 1–24. [CrossRef]

162. Akil, H.; Omar, M.F.; Mazuki, A.A.M.; Safiee, S.; Ishak, Z.M.; Bakar, A.A. Kenaf Fiber Reinforced Composites: A Review. *Mater. Des.* **2011**, *32*, 4107–4121. [CrossRef]

163. Wambua, P.; Ivens, J.; Verpoest, I. Natural Fibres: Can They Replace Glass in Fibre Reinforced Plastics? *Compos. Sci. Technol.* **2003**, *63*, 1259–1264. [CrossRef]

164. Gurunathan, T.; Mohanty, S.; Nayak, S.K. A Review of the Recent Developments in Biocomposites Based on Natural Fibres and Their Application Perspectives. *Compos. Part Appl. Sci. Manuf.* **2015**, *77*, 1–25. [CrossRef]

165. Summerscales, J.; Dissanayake, N.; Virk, A.; Hall, W. A Review of Bast Fibres and Their Composites. Part 2–Composites. *Compos. Part Appl. Sci. Manuf.* **2010**, *41*, 1336–1344. [CrossRef]

166. Rowell, R.M.; Sanadi, A.R.; Caulfield, D.F.; Jacobson, R.E. Utilization of Natural Fibers in Plastic Composites: Problems and Opportunities. *Lignocellul.-Plast. Compos.* **1997**, *13*, 23–51.

167. Joshy, M.K.; Mathew, L.; Joseph, R. Influence of Fiber Surface Modification on the Mechanical Performance of Isora-Polyester Composites. *Int. J. Polym. Mater.* **2008**, *58*, 2–20. [CrossRef]

168. Narayan, R. Biobased and Biodegradable Polymer Materials: Principles, Concepts and Technology Exemplars. In Proceedings of the World Polymer Congress and 41st International Symposium on Macromolecules, MACRO-2006, Rio de Janeiro, Brazil, 16–21 July 2006.

169. Netravali, A.N.; Chabba, S. Composites Get Greener. *Mater. Today* **2003**, *6*, 22–29. [CrossRef]

170. Saad, G.R.; Seliger, H. Biodegradable Copolymers Based on Bacterial Poly ((R)-3-Hydroxybutyrate): Thermal and Mechanical Properties and Biodegradation Behaviour. *Polym. Degrad. Stab.* **2004**, *83*, 101–110. [CrossRef]

171. Mohanty, A.K.; Misra, M.; Drzal, L.T. Sustainable Bio-Composites from Renewable Resources: Opportunities and Challenges in the Green Materials World. *J. Polym. Environ.* **2002**, *10*, 19–26. [CrossRef]

172. Van de Velde, K.; Kiekens, P. Biopolymers: Overview of Several Properties and Consequences on Their Applications. *Polym. Test.* **2002**, *21*, 433–442. [CrossRef]

173. Alavudeen, A.; Rajini, N.; Karthikeyan, S.; Thiruchitrambalam, M.; Venkateshwaren, N. Mechanical Properties of Banana/Kenaf Fiber-Reinforced Hybrid Polyester Composites: Effect of Woven Fabric and Random Orientation. *Mater. Des. 1980–2015* **2015**, *66*, 246–257. [CrossRef]

174. Eagan, J.M.; Xu, J.; Di Girolamo, R.; Thurber, C.M.; Macosko, C.W.; LaPointe, A.M.; Bates, F.S.; Coates, G.W. Combining Polyethylene and Polypropylene: Enhanced Performance with PE/IPP Multiblock Polymers. *Science* **2017**, *355*, 814–816. [CrossRef]

175. Carrillo-Escalante, H.J.; Alvarez-Castillo, A.; Valadez-Gonzalez, A.; Herrera-Franco, P.J. Effect of Fiber-Matrix Adhesion on the Fracture Behavior of a Carbon Fiber Reinforced Thermoplastic-Modified Epoxy Matrix. *Carbon Lett.* **2016**, *19*, 47–56. [CrossRef]

176. Isikgor, F.H.; Becer, C.R. Lignocellulosic Biomass: A Sustainable Platform for the Production of Bio-Based Chemicals and Polymers. *Polym. Chem.* **2015**, *6*, 4497–4559. [CrossRef]

177. Jawaid, M.; Paridah, M.T.; Saba, N. *1.1 Biomass, Source and Its Compositions*; Universiti Putra Malaysia: Serdang, Malaysia, 2017.

178. Miller, S.A.; Landis, A.E.; Theis, T.L. *Feature: Environmental Trade-Offs of Biobased Production*; ACS Publications: Washington, DC, USA, 2007.

179. Geyer, R. Chapter 2—Production, use, and fate of synthetic polymers. In *Plastic Waste and Recycling*; Letcher, T.M., Ed.; Academic Press: Cambridge, MA, USA, 2020; pp. 13–32. ISBN 978-0-12-817880-5.

180. Xu, Y.; Xu, J.; Liu, D.; Guo, B.; Xie, X. Synthesis and Characterization of Biodegradable Poly (Butylene Succinate-Co-Propylene Succinate) s. *J. Appl. Polym. Sci.* **2008**, *109*, 1881–1889. [CrossRef]

181. Hottle, T.A.; Bilec, M.M.; Landis, A.E. Sustainability Assessments of Bio-Based Polymers. *Polym. Degrad. Stab.* **2013**, *98*, 1898–1907. [CrossRef]

182. Xu, J.; Guo, B.-H. Microbial succinic acid, its polymer poly (butylene succinate), and applications. In *Plastics from Bacteria*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 347–388.

183. Xu, J.; Guo, B.-H. Poly (Butylene Succinate) and Its Copolymers: Research, Development and Industrialization. *Biotechnol. J.* **2010**, *5*, 1149–1163. [CrossRef] [PubMed]

184. Cukalovic, A.; Stevens, C.V. Feasibility of Production Methods for Succinic Acid Derivatives: A Marriage of Renewable Resources and Chemical Technology. *Biofuels Bioprod. Biorefining* **2008**, *2*, 505–529. [CrossRef]

185. Zeikus, J.G.; Jain, M.K.; Elankovan, P. Biotechnology of Succinic Acid Production and Markets for Derived Industrial Products. *Appl. Microbiol. Biotechnol.* **1999**, *51*, 545–552. [CrossRef]

186. Lee, P.C.; Lee, W.G.; Lee, S.Y.; Chang, H.N. Succinic Acid Production with Reduced By-Product Formation in the Fermentation of Anaerobiospirillum Succiniciproducens Using Glycerol as a Carbon Source. *Biotechnol. Bioeng.* **2001**, *72*, 41–48. [CrossRef]

187. Biosuccinic Acid Ready for Take Off? Available online: https://www.chemistryworld.com/news/biosuccinic-acid-ready-for-take-off/3000559.article (accessed on 28 December 2017).

188. Haas, T.; Jaeger, B.; Weber, R.; Mitchell, S.F.; King, C.F. New Diol Processes: 1,3-Propanediol and 1,4-Butanediol. *Appl. Catal. Gen.* **2005**, *280*, 83–88. [CrossRef]

189. Tserki, V.; Matzinos, P.; Pavlidou, E.; Vachliotis, D.; Panayiotou, C. Biodegradable Aliphatic Polyesters. Part I. Properties and Biodegradation of Poly (Butylene Succinate-Co-Butylene Adipate). *Polym. Degrad. Stab.* **2006**, *91*, 367–376. [CrossRef]

190. Takahashi, H.; Hayakawa, T.; Ueda, M. Convenient Synthesis of Poly (Butylene Succinate) Catalyzed by Distannoxane. *Chem. Lett.* **2000**, *29*, 684–685. [CrossRef]

191. Papageorgiou, G.Z.; Bikiaris, D.N. Crystallization and Melting Behavior of Three Biodegradable Poly (Alkylene Succinates). A Comparative Study. *Polymer* **2005**, *46*, 12081–12092. [CrossRef]

192. Deng, L.-M.; Wang, Y.-Z.; Yang, K.-K.; Wang, X.-L.; Zhou, Q.; Ding, S.-D. A New Biodegradable Copolyester Poly (Butylene Succinate-Co-Ethylene Succinate-Co-Ethylene Terephthalate). *Acta Mater.* **2004**, *52*, 5871–5878. [CrossRef]

193. Nikolic, M.S.; Djonlagic, J. Synthesis and Characterization of Biodegradable Poly (Butylene Succinate-Co-Butylene Adipate) s. *Polym. Degrad. Stab.* **2001**, *74*, 263–270. [CrossRef]

194. Han, Y.-K.; Kim, S.-R.; Kim, J. Preparation and Characterization of High Molecular Weight Poly (Butylene Succinate). *Macromol. Res.* **2002**, *10*, 108–114. [CrossRef]

195. Li, F.; Xu, X.; Yu, J.; Cao, A. The Morphological Effects upon Enzymatic Degradation of Poly (Butylene Succinate-Co-Butylene Terephthalate) s (PBST). *Polym. Degrad. Stab.* **2007**, *92*, 1053–1060. [CrossRef]

196. Bhatia, A.; Gupta, R.; Bhattacharya, S.; Choi, H. Compatibility of Biodegradable Poly (Lactic Acid)(PLA) and Poly (Butylene Succinate)(PBS) Blends for Packaging Application. *Korea-Aust. Rheol. J.* **2007**, *19*, 125–131.

197. Cao, A.; Okamura, T.; Nakayama, K.; Inoue, Y.; Masuda, T. Studies on Syntheses and Physical Properties of Biodegradable Aliphatic Poly (Butylene Succinate-Co-Ethylene Succinate) s and Poly (Butylene Succinate-Co-Diethylene Glycol Succinate) s. *Polym. Degrad. Stab.* **2002**, *78*, 107–117. [CrossRef]

198. Mathew, A.P.; Oksman, K.; Sain, M. Mechanical Properties of Biodegradable Composites from Poly Lactic Acid (PLA) and Microcrystalline Cellulose (MCC). *J. Appl. Polym. Sci.* **2005**, *97*, 2014–2025. [CrossRef]

199. Tsuji, H. Poly (Lactic Acid). *Bio-Based Plast. Mater. Appl.* **2013**, 171–239.

200. Garlotta, D. A Literature Review of Poly (Lactic Acid). *J. Polym. Environ.* **2001**, *9*, 63–84. [CrossRef]

201. Rasal, R.M.; Janorkar, A.V.; Hirt, D.E. Poly (Lactic Acid) Modifications. *Prog. Polym. Sci.* **2010**, *35*, 338–356. [CrossRef]

202. Lunt, J.; Shafer, A.L. Polyactic Acid Polymers from Corn-Applications in the Textiles Industry; Cargill Dow Polymers LLC: Minnetonka, MN, USA. Available online: http://www.jimluntllc.com/pdfs/PolylacticAcidPolymersFromCorn.pdf (accessed on 1 December 2020).

203. Gupta, B.; Revagade, N.; Hilborn, J. Poly (Lactic Acid) Fiber: An Overview. *Prog. Polym. Sci.* **2007**, *32*, 455–482. [CrossRef]

204. Griffith, L.G. Polymeric Biomaterials. *Acta Mater.* **2000**, *48*, 263–277. [CrossRef]

205. Linnemann, B.; Sri Harwoko, M.; Gries, T. FIBER TABLE-Fiber Table Polylactide Fibers (PLA). *Chem. Fibers Int.* **2003**, *53*, 426–433.

206. Tsuji, H. *Polyesters 3 (Biopolymers, Vol. 4)*; Wiley-VCH GmbH: Weinheim, Germany, 2002; pp. 129–177.

207. Jamshidian, M.; Tehrany, E.A.; Imran, M.; Jacquot, M.; Desobry, S. Poly-Lactic Acid: Production, Applications, Nanocomposites, and Release Studies. *Compr. Rev. Food Sci. Food Saf.* **2010**, *9*, 552–571. [CrossRef]

208. Lasprilla, A.J.; Martinez, G.A.; Lunelli, B.H.; Jardini, A.L.; Maciel Filho, R. Poly-Lactic Acid Synthesis for Application in Biomedical Devices—A Review. *Biotechnol. Adv.* **2012**, *30*, 321–328. [CrossRef]

209. Richard, F.G.; Nwabunma, D. *Poly (Lactic Acid) Synthesis, Structures, Properties, Processing, and Application*; Wiley Series on Polymer Engineering and Technology; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2010.

210. Kim, E.; Shin, E.W.; Yoo, I.-K.; Chung, J.S. Characteristics of Heterogeneous Titanium Alkoxide Catalysts for Ring-Opening Polymerization of Lactide to Produce Polylactide. *J. Mol. Catal. Chem.* **2009**, *298*, 36–39. [CrossRef]

211. Löfgren, A.; Albertsson, A.-C.; Dubois, P.; Jérôme, R. Recent Advances in Ring-Opening Polymerization of Lactones and Related Compounds. *J. Macromol. Sci. Part C Polym. Rev.* **1995**, *35*, 379–418. [CrossRef]

212. Auras, R.; Harte, B.; Selke, S. An Overview of Polylactides as Packaging Materials. *Macromol. Biosci.* **2004**, *4*, 835–864. [CrossRef]

213. Malmgren, T.; Mays, J.; Pyda, M. Characterization of Poly (Lactic Acid) by Size Exclusion Chromatography, Differential Refractometry, Light Scattering and Thermal Analysis. *J. Therm. Anal. Calorim.* **2006**, *83*, 35–40. [CrossRef]

214. Vink, E.T.; Rabago, K.R.; Glassner, D.A.; Gruber, P.R. Applications of Life Cycle Assessment to NatureWorks[TM] Polylactide (PLA) Production. *Polym. Degrad. Stab.* **2003**, *80*, 403–419. [CrossRef]

215. Auras, R.A.; Harte, B.; Selke, S.; Hernandez, R. Mechanical, Physical, and Barrier Properties of Poly (Lactide) Films. *J. Plast. Film Sheeting* **2003**, *19*, 123–135. [CrossRef]

216. Dorgan, J.R.; Lehermeier, H.; Mang, M. Thermal and Rheological Properties of Commercial-Grade Poly (Lactic Acid) s. *J. Polym. Environ.* **2000**, *8*, 1–9. [CrossRef]

217. Lim, L.-T.; Auras, R.; Rubino, M. Processing Technologies for Poly (Lactic Acid). *Prog. Polym. Sci.* **2008**, *33*, 820–852. [CrossRef]

218. Di Lorenzo, M.L. Crystallization Behavior of Poly (L-Lactic Acid). *Eur. Polym. J.* **2005**, *41*, 569–575. [CrossRef]

219. Oyama, H.T.; Tanaka, Y.; Kadosaka, A. Rapid Controlled Hydrolytic Degradation of Poly (l-Lactic Acid) by Blending with Poly (Aspartic Acid-Co-l-Lactide). *Polym. Degrad. Stab.* **2009**, *94*, 1419–1426. [CrossRef]

220. Gollwitzer, H.; Thomas, P.; Diehl, P.; Steinhauser, E.; Summer, B.; Barnstorf, S.; Gerdesmeyer, L.; Mittelmeier, W.; Stemberger, A. Biomechanical and Allergological Characteristics of a Biodegradable Poly (D, L-Lactic Acid) Coating for Orthopaedic Implants. *J. Orthop. Res.* **2005**, *23*, 802–809. [CrossRef] [PubMed]

221. Edwards, R.C.; Kiely, K.D.; Eppley, B.L. The Fate of Resorbable Poly-L-Lactic/Polyglycolic Acid (LactoSorb) Bone Fixation Devices in Orthognathic Surgery. *J. Oral Maxillofac. Surg.* **2001**, *59*, 19–25. [CrossRef] [PubMed]

222. Steuer, H.; Fadale, R.; Müller, E.; Müller, H.-W.; Planck, H.; Schlosshauer, B. Biohybride Nerve Guide for Regeneration: Degradable Polylactide Fibers Coated with Rat Schwann Cells. *Neurosci. Lett.* **1999**, *277*, 165–168. [CrossRef]

223. Yang, F.; Murugan, R.; Wang, S.; Ramakrishna, S. Electrospinning of Nano/Micro Scale Poly (L-Lactic Acid) Aligned Fibers and Their Potential in Neural Tissue Engineering. *Biomaterials* **2005**, *26*, 2603–2610. [CrossRef]

224. Kumbar, S.G.; Nukavarapu, S.P.; James, R.; Nair, L.S.; Laurencin, C.T. Electrospun Poly (Lactic Acid-Co-Glycolic Acid) Scaffolds for Skin Tissue Engineering. *Biomaterials* **2008**, *29*, 4100–4107. [CrossRef]

225. Chen, G.-Q. A Microbial Polyhydroxyalkanoates (PHA) Based Bio-and Materials Industry. *Chem. Soc. Rev.* **2009**, *38*, 2434–2446. [CrossRef] [PubMed]

226. Reddy, C.S.K.; Ghai, R.; Kalia, V. Polyhydroxyalkanoates: An Overview. *Bioresour. Technol.* **2003**, *87*, 137–146. [CrossRef]

227. Philip, S.; Keshavarz, T.; Roy, I. Polyhydroxyalkanoates: Biodegradable Polymers with a Range of Applications. *J. Chem. Technol. Biotechnol.* **2007**, *82*, 233–247. [CrossRef]

228. Verlinden, R.A.; Hill, D.J.; Kenward, M.A.; Williams, C.D.; Radecka, I. Bacterial Synthesis of Biodegradable Polyhydroxyalkanoates. *J. Appl. Microbiol.* **2007**, *102*, 1437–1449. [CrossRef]

229. Chen, G.-Q.; Hajnal, I.; Wu, H.; Lv, L.; Ye, J. Engineering Biosynthesis Mechanisms for Diversifying Polyhydroxyalkanoates. *Trends Biotechnol.* **2015**, *33*, 565–574. [CrossRef]

230. Khanna, S.; Srivastava, A.K. Recent Advances in Microbial Polyhydroxyalkanoates. *Process Biochem.* **2005**, *40*, 607–619. [CrossRef]

231. Urtuvia, V.; Villegas, P.; González, M.; Seeger, M. Bacterial Production of the Biodegradable Plastics Polyhydroxyalkanoates. *Int. J. Biol. Macromol.* **2014**, *70*, 208–213. [CrossRef]

232. Le Meur, S.; Zinn, M.; Egli, T.; Thöny-Meyer, L.; Ren, Q. Production of Medium-Chain-Length Polyhydroxyalkanoates by Sequential Feeding of Xylose and Octanoic Acid in Engineered Pseudomonas Putida KT2440. *BMC Biotechnol.* **2012**, *12*, 53. [CrossRef]

233. Rocha, R.C.; da Silva, L.F.; Taciro, M.K.; Pradella, J.G. Production of Poly (3-Hydroxybutyrate-Co-3-Hydroxyvalerate) P (3HB-Co-3HV) with a Broad Range of 3HV Content at High Yields by Burkholderia Sacchari IPT 189. *World J. Microbiol. Biotechnol.* **2008**, *24*, 427–431. [CrossRef]

234. Loo, C.-Y.; Lee, W.-H.; Tsuge, T.; Doi, Y.; Sudesh, K. Biosynthesis and Characterization of Poly (3-Hydroxybutyrate-Co-3-Hydroxyhexanoate) from Palm Oil Products in a Wautersia Eutropha Mutant. *Biotechnol. Lett.* **2005**, *27*, 1405–1410. [CrossRef]

235. López-Cuellar, M.R.; Alba-Flores, J.; Rodríguez, J.G.; Pérez-Guevara, F. Production of Polyhydroxyalkanoates (PHAs) with Canola Oil as Carbon Source. *Int. J. Biol. Macromol.* **2011**, *48*, 74–80. [CrossRef] [PubMed]

236. Keshavarz, T.; Roy, I. Polyhydroxyalkanoates: Bioplastics with a Green Agenda. *Curr. Opin. Microbiol.* **2010**, *13*, 321–326. [CrossRef]

237. Singh, M.; Kumar, P.; Ray, S.; Kalia, V.C. Challenges and Opportunities for Customizing Polyhydroxyalkanoates. *Indian J. Microbiol.* **2015**, *55*, 235–249. [CrossRef] [PubMed]

238. Yamane, T.; Fukunaga, M.; Lee, Y.W. Increased PHB Productivity by High-Cell-Density Fed-Batch Culture of Alcaligenes Latus, a Growth-Associated PHB Producer. *Biotechnol. Bioeng.* **1996**, *50*, 197–202. [CrossRef]

239. Pandian, S.R.; Deepak, V.; Kalishwaralal, K.; Rameshkumar, N.; Jeyaraj, M.; Gurunathan, S. Optimization and Fed-Batch Production of PHB Utilizing Dairy Waste and Sea Water as Nutrient Sources by Bacillus Megaterium SRKP-3. *Bioresour. Technol.* **2010**, *101*, 705–711. [CrossRef] [PubMed]

240. Kulpreecha, S.; Boonruangthavorn, A.; Meksiriporn, B.; Thongchul, N. Inexpensive Fed-Batch Cultivation for High Poly (3-Hydroxybutyrate) Production by a New Isolate of Bacillus Megaterium. *J. Biosci. Bioeng.* **2009**, *107*, 240–245. [CrossRef] [PubMed]

241. Shahhosseini, S. Simulation and Optimisation of PHB Production in Fed-Batch Culture of Ralstonia Eutropha. *Process Biochem.* **2004**, *39*, 963–969. [CrossRef]

242. Raza, Z.A.; Abid, S.; Banat, I.M. Polyhydroxyalkanoates: Characteristics, Production, Recent Developments and Applications. *Int. Biodeterior. Biodegrad.* **2018**, *126*, 45–56. [CrossRef]

243. Jacquel, N.; Lo, C.-W.; Wei, Y.-H.; Wu, H.-S.; Wang, S.S. Isolation and Purification of Bacterial Poly (3-Hydroxyalkanoates). *Biochem. Eng. J.* **2008**, *39*, 15–27. [CrossRef]

244. Ibrahim, M.H.; Steinbüchel, A. Poly (3-Hydroxybutyrate) Production from Glycerol by Zobellella Denitrificans MW1 via High-Cell-Density Fed-Batch Fermentation and Simplified Solvent Extraction. *Appl. Environ. Microbiol.* **2009**, *75*, 6222–6231. [CrossRef]

245. Koller, M. *Recent Advances in Biotechnology Volume, 1: Microbial Biopolyester Production, Performance and Processing Microbiology, Feedstocks, and Metabolism*; Bentham Science Publishers: Oak Park, IL, USA, 2016; Volume 1.

246. Hejazi, P.; Vasheghani-Farahani, E.; Yamini, Y. Supercritical Fluid Disruption of Ralstonia Eutropha for Poly (β-Hydroxybutyrate) Recovery. *Biotechnol. Prog.* **2003**, *19*, 1519–1523. [CrossRef]

247. Kunasundari, B.; Sudesh, K. Isolation and Recovery of Microbial Polyhydroxyalkanoates. *Express Polym. Lett.* **2011**, *5*, 620–634. [CrossRef]

248. Divyashree, M.S.; Shamala, T.R.; Rastogi, N.K. Isolation of Polyhydroxyalkanoate from Hydrolyzed Cells of Bacillus Flexus Using Aqueous Two-Phase System Containing Polyethylene Glycol and Phosphate. *Biotechnol. Bioprocess Eng.* **2009**, *14*, 482–489. [CrossRef]

249. Porter, M.M.; Lee, S.; Tanadchangsaeng, N.; Jaremko, M.J.; Yu, J.; Meyers, M.; McKittrick, J. Porous hydroxyapatite-polyhydroxybutyrate composites fabricated by a novel method via centrifugation. In *Mechanics of Biological Systems and Materials*; Springer: Berlin/Heidelberg, Germany, 2013; Volume 5, pp. 63–71.

250. Hong, H.; Dong, N.; Shi, J.; Chen, S.; Guo, C.; Hu, P.; Qi, H. Fabrication of a Novel Hybrid Heart Valve Leaflet for Tissue Engineering: An in Vitro Study. *Artif. Organs* **2009**, *33*, 554–558. [CrossRef]

251. Valappil, S.P.; Boccaccini, A.R.; Bucke, C.; Roy, I. Polyhydroxyalkanoates in Gram-Positive Bacteria: Insights from the Genera Bacillus and Streptomyces. *Antonie Van Leeuwenhoek* **2007**, *91*, 1–17. [CrossRef] [PubMed]

252. Bugnicourt, E.; Cinelli, P.; Lazzeri, A.; Alvarez, V.A. Polyhydroxyalkanoate (PHA): Review of Synthesis, Characteristics, Processing and Potential Applications in Packaging. *Express Polym. Lett.* **2014**, *8*, 791–808. [CrossRef]

253. Abid, S.; Raza, Z.A.; Rehman, A. Synthesis of Poly (3-Hydroxybutyrate) Nanospheres and Deposition Thereof into Porous Thin Film. *Mater. Res. Express* **2016**, *3*, 105042. [CrossRef]

254. Bajpai, P.K.; Ahmad, F.; Chaudhary, V. Processing and Characterization of Bio-Composites. *Handb. Ecomater.* **2017**, 1–18.

255. Le Duc, A.; Vergnes, B.; Budtova, T. Polypropylene/Natural Fibres Composites: Analysis of Fibre Dimensions after Compounding and Observations of Fibre Rupture by Rheo-Optics. *Compos. Part Appl. Sci. Manuf.* **2011**, *42*, 1727–1737. [CrossRef]

256. Faruk, O.; Bledzki, A.K.; Fink, H.-P.; Sain, M. Progress Report on Natural Fiber Reinforced Composites. *Macromol. Mater. Eng.* **2014**, *299*, 9–26. [CrossRef]

257. Bledzki, A.K.; Jaszkiewicz, A.; Murr, M.; Sperber, V.E.; Lützendgrf, R.; Reußmann, T. Processing techniques for natural-and wood-fibre composites. In *Properties and Performance of Natural-Fibre Composites*; Elsevier: Amsterdam, The Netherlands, 2008; pp. 163–192.

258. Bledzki, A.K.; Specht, K.; Cescutti, G.; Müssig, M. Comparison of Different Compounding Processes by an Analysis of Fibres Degradation. In Proceedings of the 3rd International Conference on Eco-Composites, Stockholm, Sweden, 20–21 June 2005; p. B3.

259. Chaudhary, V.; Bajpai, P.K.; Maheshwari, S. Studies on Mechanical and Morphological Characterization of Developed Jute/Hemp/Flax Reinforced Hybrid Composites for Structural Applications. *J. Nat. Fibers* **2018**, *15*, 80–97. [CrossRef]

260. Pickering, K.L.; Efendy, M.A.; Le, T.M. A Review of Recent Developments in Natural Fibre Composites and Their Mechanical Performance. *Compos. Part Appl. Sci. Manuf.* **2016**, *83*, 98–112. [CrossRef]

261. Huda, M.S.; Drzal, L.T.; Ray, D.; Mohanty, A.K.; Mishra, M. Natural-fiber composites in the automotive sector. In *Properties and Performance of Natural-Fibre Composites*; Elsevier: Amsterdam, The Netherlands, 2008; pp. 221–268.

262. Azaman, M.D.; Sapuan, S.M.; Sulaiman, S.; Zainudin, E.S.; Abdan, K. An Investigation of the Processability of Natural Fibre Reinforced Polymer Composites on Shallow and Flat Thin-Walled Parts by Injection Moulding Process. *Mater. Des.* **2013**, *50*, 451–456. [CrossRef]

263. Leong, Y.W.; Thitithanasarn, S.; Yamada, K.; Hamada, H. Compression and injection molding techniques for natural fiber composites. In *Natural Fibre Composites*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 216–232.

264. Akampumuza, O.; Wambua, P.; Ahmed, A.; Li, W.; Qin, X.-H. Review of the Applications of Biocomposites in the Automotive Industry. *Polym. Compos.* **2017**, *38*, 2553–2569. [CrossRef]

265. Alves, C.; Silva, A.J.; Reis, L.G.; Freitas, M.; Rodrigues, L.B.; Alves, D.E. Ecodesign of Automotive Components Making Use of Natural Jute Fiber Composites. *J. Clean. Prod.* **2010**, *18*, 313–327. [CrossRef]

266. Ho, M.; Wang, H.; Lee, J.-H.; Ho, C.; Lau, K.; Leng, J.; Hui, D. Critical Factors on Manufacturing Processes of Natural Fibre Composites. *Compos. Part B Eng.* **2012**, *43*, 3549–3562. [CrossRef]

267. Srinivas, K.; Naidu, A.L.; Raju Bahubalendruni, M. A Review on Chemical and Mechanical Properties of Natural Fiber Reinforced Polymer Composites. *Int. J. Perform. Eng.* **2017**, *13*, 189–200. [CrossRef]

268. Mallick, P.K. *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*; CRC Press: Boca Raton, FL, USA, 2007.

269. Haag, K.; Padovani, J.; Fita, S.; Trouvé, J.-P.; Pineau, C.; Hawkins, S.; De Jong, H.; Deyholos, M.K.; Chabbert, B.; Müssig, J. Influence of Flax Fibre Variety and Year-to-Year Variability on Composite Properties. *Ind. Crops Prod.* **2017**, *98*, 1–9. [CrossRef]

270. Du, Y.; Wu, T.; Yan, N.; Kortschot, M.T.; Farnood, R. Fabrication and Characterization of Fully Biodegradable Natural Fiber-Reinforced Poly (Lactic Acid) Composites. *Compos. Part B Eng.* **2014**, *56*, 717–723. [CrossRef]

271. Chaitanya, S.; Singh, I. Processing of PLA/Sisal Fiber Biocomposites Using Direct-and Extrusion-Injection Molding. *Mater. Manuf. Process.* **2017**, *32*, 468–474. [CrossRef]

272. Ranganathan, N.; Oksman, K.; Nayak, S.K.; Sain, M. Structure Property Relation of Hybrid Biocomposites Based on Jute, Viscose and Polypropylene: The Effect of the Fibre Content and the Length on the Fracture Toughness and the Fatigue Properties. *Compos. Part Appl. Sci. Manuf.* **2016**, *83*, 169–175. [CrossRef]

273. Awal, A.; Rana, M.; Sain, M. Thermorheological and Mechanical Properties of Cellulose Reinforced PLA Bio-Composites. *Mech. Mater.* **2015**, *80*, 87–95. [CrossRef]

274. Evans, W.J.; Isaac, D.H.; Suddell, B.C.; Crosky, A. Natural Fibres and Their Composites: A Global Perspective. In Proceedings of the Risø International Symposium on Materials Science, Roskilde, Denmark, 2–5 September 2002; pp. 1–14.

275. Alkbir, M.F.M.; Sapuan, S.M.; Nuraini, A.A.; Ishak, M.R. Fibre Properties and Crashworthiness Parameters of Natural Fibre-Reinforced Composite Structure: A Literature Review. *Compos. Struct.* **2016**, *148*, 59–73. [CrossRef]

276. Mohanty, A.K.; Seydibeyoglu, M.O.; Sahoo, S.; Misra, M. 4.08-Matching Crops for Selected Bioproducts A2-Moo-Young, Murray. In *Comprehensive Biotechnology*; Academic Press: Burlington, VT, USA, 2011.

277. AL-Oqla, F.M.; Omari, M.A. Sustainable biocomposites: challenges, potential and barriers for development. In *Green Biocomposites*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 13–29.

278. Al-Oqla, F.M.; Sapuan, S.M. Polymer Selection Approach for Commonly and Uncommonly Used Natural Fibers under Uncertainty Environments. *Jom* **2015**, *67*, 2450–2463. [CrossRef]

279. Mooney, B.P. The Second Green Revolution? Production of Plant-Based Biodegradable Plastics. *Biochem. J.* **2009**, *418*, 219–232. [CrossRef] [PubMed]

280. Andresen, C.; Demuth, C.; Lange, A.; Stoick, P.; Pruszko, R. *Biobased Automobile Parts Investigation. A Report Developed for the USDA Office of Energy Policy and New Uses*; Iowa State University: Ames, IA, USA, 2012.

281. La Mantia, F.P.; Morreale, M. Green Composites: A Brief Review. *Compos. Part Appl. Sci. Manuf.* **2011**, *42*, 579–588. [CrossRef]

282. Toyota Green Innovations. Available online: http://www.toyota.com (accessed on 5 January 2021).

283. Mosallam, A.S.; Bayraktar, A.; Elmikawi, M.; Pul, S.; Adanur, S. *Polymer Composites in Construction: An Overview*; UC Irvine: Irvine, CA, USA, 2015.

284. Kinnane, O.; Reilly, A.; Grimes, J.; Pavia, S.; Walker, R. Acoustic Absorption of Hemp-Lime Construction. *Constr. Build. Mater.* **2016**, *122*, 674–682. [CrossRef]