Bio-Composites

Subjects: Materials Science, Biomaterials

Contributor: Mohammed Zwawi

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. 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 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.

Bio-Composites natural fibers

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][47][48][49][50][51][52][53][54][55][56][57][58][59][60][61].

2. 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 [62]. 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 [63]. 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 [64]. 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 [65]. 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 [66]. 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.

2.1. 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 [67]. 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 [68]. Ford uses soy foam seats, bio-based cushions, and hemp fiber composites in the front grills in various vehicle models [69]. 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 [70]. 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 [71]. Similarly, Volkswagen use bio-composites to make door panels, flap linings, door inserts, and package trays.

2.2. 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 [72]. Hemp/lime/concrete composites have exhibited better sound absorption ability than any other binders [73]. 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.

3. 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.
2. Molaba, T.P.; Chapple, S.; John, M.J. Aging Studies on Flame Retardant Treated Lignocellulosic Fibers. J. Appl. Polym. Sci. 2016, 133.
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.
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.
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.
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.
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.

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

28. Kumar, S.; Mohanty, A.K.; Erickson, L.; Misra, M. Lignin and Its Applications with Polymers. J. Biobased Mater. Bioenergy 2009, 3, 1–24.
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.
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.
31. Reddy, N.; Yang, Y. Biofibers from Agricultural Byproducts for Industrial Applications. Trends Biotechnol. 2005, 23, 22–27.
32. Célino, A.; Freour, S.; Jacquemin, F.; Casari, P. The Hygroscopic Behavior of Plant Fibers: A Review. Front. Chem. 2014, 1.
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.
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.
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.
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.

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.
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.
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.
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.
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.
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.
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.

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.
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.
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.
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.
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.
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.
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.
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. 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.
63. 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.
64. 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.
65. 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.
66. 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.
67. Mooney, B.P. The Second Green Revolution? Production of Plant-Based Biodegradable Plastics. Biochem. J. 2009, 418, 219–232.
68. 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.
69. 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.
70. La Mantia, F.P.; Morreale, M. Green Composites: A Brief Review. Compos. Part Appl. Sci. Manuf. 2011, 42, 579–588.
71. Toyota Green Innovations. Available online: http://www.toyota.com (accessed on 5 January 2021).
72. Mosallam, A.S.; Bayraktar, A.; Elmikawi, M.; Pul, S.; Adanur, S. Polymer Composites in Construction: An Overview; UC Irvine: Irvine, CA, USA, 2015.
73. Kinnane, O.; Reilly, A.; Grimes, J.; Pavia, S.; Walker, R. Acoustic Absorption of Hemp-Lime Construction. Constr. Build. Mater. 2016, 122, 674–682.

Retrieved from https://encyclopedia.pub/entry/history/show/16557