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Biocomposites. Current state of development

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Abstract

Biocomposites are deeply infiltrated in every aspect of our life – from packaging, through furniture and variety of consumers' goods to construction. These materials gather tremendous interest due to their sustainability, durability and environmental efficiency and have the potential to replace a big part of conventional materials in many sectors. Because of the depletion of many natural resources (including petroleum), new policies and their renewable nature biocomposite advanced materials are under extensive R&D work in order to address the increased need for alternative. Many fibers like hemp, flax, juta, kenaf, etc. have been investigated but the opportunity to use waste as a source for biocomposite production makes them even more appealing. The composite materials may be a step towards solving some environmental challenges following the principles of circular economy.

Keywords: *Advanced materials, Biocomposites, Application, Environment*

1. Introduction

In an era of depletion of many resources, mining and production industries which constantly generate significant amounts of waste, the science and society are now looking for sustainable alternatives. Many efforts are focused on the development of advanced materials which has features and characteristics to be used in different fields form packaging and transport to construction and building of variety of structures (1). The main criteria in the development of such materials are related to their low environmental footprint both in terms of production and recycling.

In this context economic, environmental and social sustainability is the biggest challenge for the advanced materials (2). The correlation between advanced materials and high value manufacturing is a preposition to a huge opportunity for innovation and sustainable growth (1). This is in line with the concept for sustainable development created in the late 80's of the previous century in response to the concerns about the ability of the environment to meet current and future technological development needs (3). As we already know, sustainability needs innovation of all kinds and practice shows a positive and significant correlation between sustainability and innovation (4). Furthermore, eco-innovation activities towards sustainability actually contribute to enhancing national competitiveness (5).

Material innovation can prompt the progress of areas like sustainability and materials security; materials for energy; and high value markets. These three areas are interconnected because the advanced materials ensure product security and better resources usage which can also boost high value marketing. This also corresponds with circular economy principles for materials to remain in the value chain for as long as possible by applying less energy consuming material technologies or reuse them to recover energy. To cover the needs and sustainable growth of these three areas new material science and technology have to be developed in order to support the circular economy.

Biocomposites are one of the demanded materials in terms of many environmental challenges we are already facing – from climate change to water and soil pollution. The opportunity to produce biocomposites form waste makes this particular technology an important step toward the transition to circular economy. In this review we will follow the main knowledge accumulated so far on this topic.

2. Biocomposites

The term biocomposite is often referred to polymer materials composed of bio-based or natural fibers and/or matrix (6, 7). The reinforcement leads to improvement of their physical properties and high biological resistance (8, 9). Natural fibers are very attractive because it is accepted that their application has better environmental impact including all stage of their life cycle - reduced CO_2 emissions for production, lower energy consumption for recycling or even incineration for energy recovery (6). Besides, natural fibers have good strength, stiffness, they are lightweight and low cost.

2.1 Fibers

There is a wide range of fibers. They are generally classified in three major groups – natural, mineral and synthetic fibers (fig. 1). Natural fibers are not only the most diverse among all but also they are the one which attracts the most of the interest as reinforcement component for biocomposite materials (6). The bast, leaf and wood fibers are among the most used natural fiber because of their longest length and highest strength and stiffness. The biggest advantages of plant based fibers are their biodegradability, recycling and the fact that they are "carbon positive" (absorb more CO_2 than they release) (6, 11).

2.2 Composition

Plant fibers are mostly composed of cellulose, hemicellulose and lignin (or combination). The fiber cellulose is the major presented compound among all. It is hydrophilic with degree of polymerization about 1000 and crystalline structure which define its physical properties. The hemicelluloses have more complex structure and include different simple sugars as monomers. This natural polymer is hydrophilic with non-crystalline structure and its polymerization ranges from 50 to 300 monomers. The hemicellulose acts as a matrix for the most of the plant microfibrils (10). Unlike the others, lignin is hydrophobic, with amorphous structure. In combined materials, lignin gives the stiffness to structures.

2.3 Growing, harvesting and processing

Every stage of fiber production is important for the final product quality and properties. The growing stage affects the fiber quality and consistency, even the weather conditions influence significantly crop quality from year to year. Some plants, like hemp and flax for instance, are used to harvest both fiber and oil (6).

The so called technical fibers are used for composite reinforcement fiber. Usually, they are fibers with diameter of 50-100 µm and length of 100-300 mm. Aggressive mechanical processing could damage these fine structures which will implicate negatively the fiber quality of the composites in terms of strength.

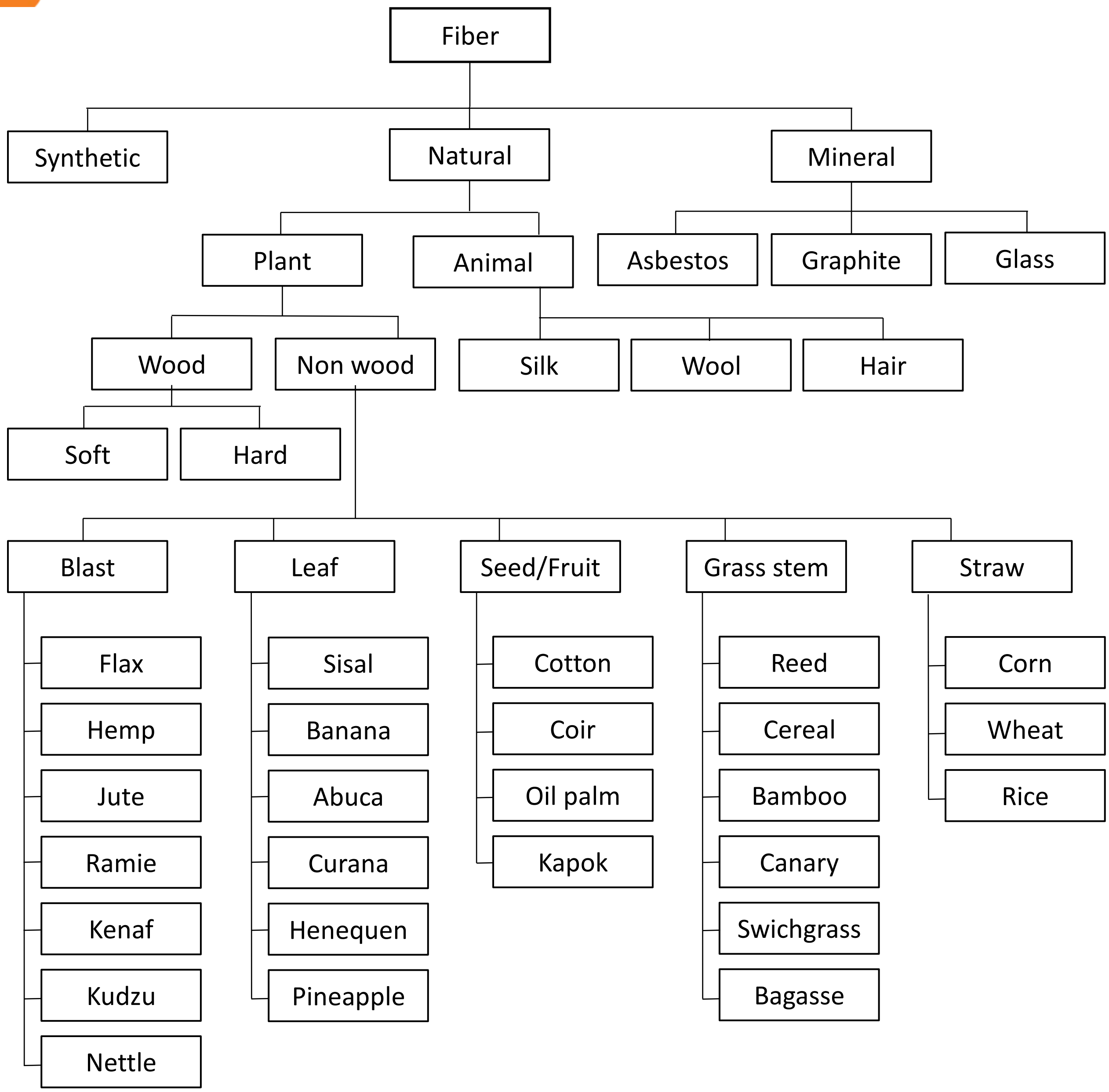

Fig. 1 Fiber classification (6, 7, 10)

2.4 Properties

The characteristics and properties of the natural fibers such as density, tensile strength, moisture absorption etc. can significantly vary depending on their source and composition (Tabl.1).

Table 1. Characteristics of natural and glass fibers (6)

Fiber	**Density (g/cm^3)**	**Tensile modulus (GPa)**	**Specific modulus (GPa/g/ cm^3)**	**Tensile strength (MPa)**	**Elongation to failure (%)**	**Moisture absorbtion (%)**
Flax	1.4	60-80	43-57	500-900	1.2-1.5	7
Hemp	1.48	30-70	20-47	300-800	1.6	8

Jute	1.46	20-55	14-38	200-800	1.8	12
Ramie	1.5	44	29	500	2	12-17
Coir	1.25	6	5	220	15-25	10
Sisal	1.33	9-38	7-29	100-800	2-3	11
Cotton	1.51	6-12	4-8	300-600	3-10	8-25
Glass	**2.55**	**73**	**29**	**2400**	**3**	**-**

Despite the glass fibers, the natural polymer fibers expose very high moisture absorption and lower density. Flax and hemp are examples in this regard (good density/moisture uptake ratio) and they are of great interest for composite materials engineering and it is estimated that replacing glass fibers with natural ones can reduce the composite weight by up to 40%. Low weight materials could be efficient alternative in many sectors, particularly in automotive and logistic where they contribute to the fuel economy (6, 12-22). Except for their increased efficiency natural fibers are also usually safer and easier to handle and process.

Still, natural fibers have some drawbacks, as well. They have poor polymers bonding, limited thermal stability and high moisture uptake resulting in swelling, rotting and reduced mechanical properties. Different fiber treatments techniques could help. Physical treatments including plasma and corona discharge and hydrothermal treatment could improve the fiber surface, thermal durability and the wettability of wood fibers. Chemical treatments are also applied and some of the most used methods are alkali treatment, acetylation, coupling agents. Usually, this treatment aims to improve the moisture resistance without harming the strength and stiffness of natural fiber and to avoid microbial colonization and degradation of the materials produces.

2.5 Fully bio-based composites

There are also entirely bio-based composites (have both fiber and matrix all natural) and there is great interest to these materials from the research and the market. Recently, there is some progress in the development of completely bio-based composite materials for application in injection molding and extrusion. There is a plenty of examples based on wood, flax and hemp fibers as well as PLA, starch and lignin matrices (23).

University of Delaware (USA) have developed a natural fiber thermoset bio resin material combining soybean resin derivatives with flax, hemp and jute fibers for biocomposites production (6). These materials are suitable for production of chairs, hurricane-resistant homes and cars body panel (24). University of Warwick (UK) also have developed a natural fiber composite (NFC) from vegetable oil from which they produced the body panels of the Eco One and World F3rst sustainable racing cars models (25) (fig. 2). There is another collaboration of several companies including Eden Project, Homeblown, Sustainable Composites and Laminations which developed a NFC surfboard skins with a biofiber core (6).

Fig. 2. Formula 3 racing car built from renewable materials powered by waste derivative fuel.

3. Application

The interest in advanced and natural materials is increasing rapidly according to company's desire to switch to more sustainable materials. This action also expands the potential application of these materials from small particles and composites to large almost semi structural scale. The stage of advanced material development is a reflection of the usage levels of different natural materials. At this point they are applied mainly in sectors like automotive industry, construction, sports/leisure and consumer's goods (6, 7, 9, 26, 27).

Fig. 3 Biocomposite body panels and components of E-class Mercedes (28)

The most used advanced materials in cars are wood plastic composites (WPC), short natural fiber injection moulding composites and non-woven natural fibers mats. Application of nature fibers in cars is not new since even Henry Ford in the 1940's experimented with hemp-reinforces soy resin panel (6, 9). In 2012 the EU automotive industry used 90 000 tons of NFC and 60 000 tons of WPC (29). Except for wood, recycled cotton, flax, kenaf, hemp and other fibers (in a variable ratio) are applied. On average, every new car in Europe contains 4 up to 30 kg of natural fibers (6). Almost all internal components of E-class Mercedes (fig. 3) are made from NFC (7, 3014). Toyota Raum even claims to be the first 100% natural automotive product in the world (26). Some claim 25% weight saving (6).

Manufacture and application of biocomposite panels in construction is entirely feasible but it faces the challenge to achieve the durability needed for outdoor use (6). Anyway, wide variety of natural fibers are used in construction nowadays. The largest share is hold by WPC. Flax fiber based materials show almost the same performance as the glass fiber reinforced composites (7). Flax fiber composites are also used as low cost structural components for load bearing application (31). These materials are also used as partial wood substitute in house roofing (32, 33). Another advanced material based on recycled waste paper has found application for construction of roofs, as well (34). The composite consists of soy oil–based resin and recycled paper fibers. By application of retardant treatment, the materials could be easily used in the interior or insulation board (35).

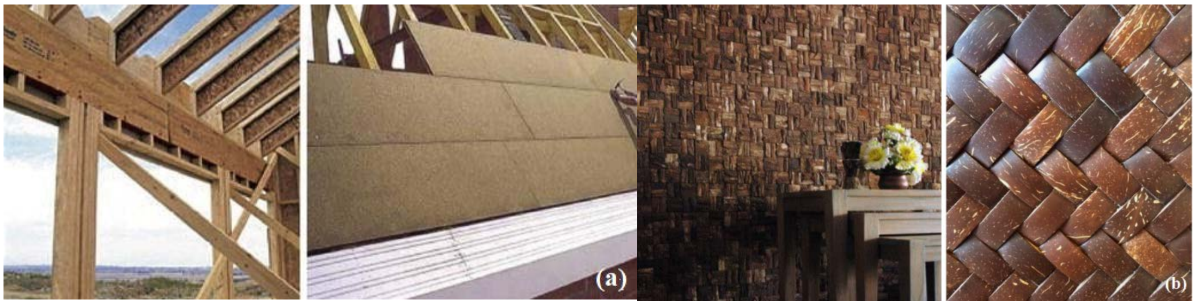

Fig. 4 NFC in (a) construction (36) and (b) interior - coconut tiles (www.cocomosaic.co.za)

Jute fiber is also one of the commonly used. Materials reinforced with jute fiber are used in trenchless restoration of underground pipes (37), acoustic wall coverage and floor mats (38) (fig 5). Hemp mats applied in curved pipe construction together with glass fiber reduce the cost with about 20% and the weight with 23% (39).

Fig. 5 Construction pipes: (a) Pipes without jute fiber reinforcement, (b) pipes with untreated jute fiber reinforcement, (c) pipes with chemically modified jute fiber reinforcement (27)

Advanced materials find extent application in consumer's products, some of which are presented in fig 6. Furniture, tableware, carpets, doors, loudspeakers, musical instruments, handles, shelves, boxes, electrical goods, rigid packaging, plants pots, window frames, partition boards, even mobile phones and many more are currently produced by application of NFCs (6, 7 36, 40).

Fig. 6 Consumer's products built from biocomposites: chair: www.designboom.com, hemp computer bag: www.thehempshop.co.uk

Sports and leisure is another sector where biocomposite materials are successfully applied. Different equipment like snowboards, surfboards, canoes, bike frames and even ice-hockey equipment is produced by variety of NFCs (6) (fig. 7). The last trends in the industry are to find new and more specific fields of application of the biocomposites such as the medicine and healthcare. In orthopedics for instance, there are efforts to replace the conventional materials like titanium, cobalt, chrome, stainless steel, zirconium, plastics and gypsum plaster with advanced materials (7, 41).

Fig 7. Sports and leisure equipment skateboard: www.kickstarter.com, biodoard: www.xboards.com

4. Environmental impact

All the industry is usually affected and have to deal with health and safety issues. Composite materials engineering and production is no exception. The increasing need of answering these problems led to creation of new technologies for natural materials production.

From all the aspects of application benefits, the biocomposite materials are most important for their environmental properties. They reduce energy and emissions during products, they save fuel by reducing weight during legists and they have better environmental fate after the end of the life cycle. In addition, for production of biocomposites, waste materials form other sectors are often used. The end product themselves are also with better recycling characteristic comparing to conventional polymers. With that reason, even taking into account the less desirable and competitive characteristics of natural fiber composite compared to the conventional carbon based equivalents (this applies in full force for automotive industry) the industry and society are increasing their attention to the biocomposites. (6, 42).

Evaluation of the biocomposite materials in terms of their environmental benefits is still a work in progress. Different methodologies are applied but among them the Life Cycle Assessment (LCA) is considered as most relevant. This is an approach for assessment of the potential environmental impact of a product or service on the surrounding world during its entire life cycle (production, distribution, use and end-of-life) including upstream and downstream processes. LCA validates the impact by taking into account also social and economic factors. There are two types of assessments – cradle-to-gate and cradle-to-grave. The first one assesses all the primary and preliminary work of extraction of the precursors to the resin and fiber as well as the manufacturing itself. Cradle-to-gate methodology stops by the gate of the factory. Cradle-to-grave type of assessment explores not only all stages of manufacture but also all stages through the product life (use, reuse, repair, recycle, end-of-life and disposal options). The LCA models consider impacts like human toxicity, eutrophication, carbon sequestration, ozone depletion and acidification (6). For every factor is establish its specific weighting depending on its actual impact. The row data concerning the modeled process is normalized to the specific weighting and then eco print rating and functional units are assigned in order to enable direct comparison.

The environmental impact of natural fibers varies depending of the fiber crops and retting processes (43). The factor with most influence over magnitude of environmental benefits is the kind of application of the advanced composite material (6). The prevalent advantage is actually a side effect like weight saving, rather than the fiber origin or growing. Still, due to the fiber crops moderate requirement for fertilizers, water and energy, their production is found to have limited environmental impact (44). During the post-harvest stages of fiber extraction is possible to be consumed fossil energy and water leading to generation of biomass waste and water contamination. If there are respective measures this could be not only easily prevented, but also could present an opportunity for energy or other added value products recovery. This will additionally improve the environmental impact of fiber crops. Generally, comparison between production of fiber crops and other synthetic products define fiber crops as environmentally beneficial in terms of reduced greenhouse gas emissions and low consumption of fossil fuels (6). These conclusions are valid for the bio-based polymers, as well.

There are two important factor which are source of the feedstock and application, as environmentally and LCA preferably is feedstock to be from waste (6). There are different concerns in the terms of environmental impact of bio-based polymers including aquatic eutrophication and nitrate emissions from corn growing (in the case of PLA). A critical review conducted by University of Cambridge (45) reported that choice of environmental impact aspect affects the results from the LCA. If we consider energy and global warming potential bio-based polymers was found to have advantage, but if the case is focused on other categories, the results are not so favorable. This issue shows the need of future optimization in terms of efficiency. Usage of waste biomass from agriculture, food or animal waste as a resin is completely feasible and really beneficial in terms of energy and greenhouse gasses emissions (46).

As we said above, when we discus natural fibers the environmental impact of crops growing is considered relatively low. The processing method and the application field of composite materials are more important for the final assessment. Interdependency of fiber, matrix and treatment process worth mentioning because often it is not possible to choose both fiber and matrix with good environmental score (6).

Advanced materials have many beneficial characteristics but their key quality during a long term usage is the durability. The concerns in this sense are related to the moisture uptake and material degradation and rotting. Anyway, there are many reports proving that the materials could be significantly improved by treatment techniques. When such a treatment is applied, it is important to keep the environmental properties of the materials. They have to be still safe for all the end-of-life options such as recycling, biodegradation, composting or even burned for energy recovery. Incineration could be considered good option for energy recovery. The amount and type of combustible materials define energy benefit. The net benefit form incineration of natural materials is about 3 times lower than polypropylene for instance, but natural composite materials do not use petrochemical sources so they don’t release additional CO_2. In some specific cases, the biodegradable materials could be also utilized by microorganisms closing the CO_2 cycle.

Reference

[1] Enabling technologies strategy 2012-2015, Technology Strategy Board, November 2012.
[2] A European strategy for Key Enabling Technologies (KETs) – A bridge to growth and jobs. European Commission. Jun 2012.

[3] World Commission on Environment and Development (WCED). Report of the World Commision on Environement and Development: Our Common Future. 1987.
[4] S. Behnam, and R. Cagliano, “Be sustainable to be innovative: An analysis of their mutual reinforcement”, Sustainability, Vol 9, 2017, pp. 17-34.
[5] L. M. Fonseca, and V. M. Lima, “Countries three wise men: Sustainability, Innovation, and Competitiveness”, Journal of Industrial Engineering and Management, Vol 8, 2015, pp. 1288-1302.
[6] Knowledge Transfer Network, “Biocomposites: Technology overview”, march 2014.
[7] K. N. Bharath, and S. Basavarajappa, “Application of biocomposite materials based on natural fibers from renewable resources: a review”, Science and Engineering of Composite Materials, Vol 23, No 2, 2016, pp. 123–133.
[8] M. Nagalakshmaiah, S. Afrin, R. P. Malladi, S. Elkoun, M. Robert, M. A. Ansari, A. Svedberg, Z. Karim, “Biocomposites: present trends and challenges for the future” in Green composites for automotive applications, Woodhead publishing 2019
[9] N. Ramli, N. Mazlan, Y. Ando, Z. Leman, K. Abdan, A. A. Aziz, and N. A. Sairy, “Natural fiber for green technology in automotive industry: A brief review”, in IOP Conf. Series: Materials Science and Engineering 2018, Vol. 368, 012012
[10] S. Yıldızhan, A. Calık, M. Ozcanlı, H. Serin, “Bio-composite materials: a short review of recent trends, mechanical and chemical properties, and applications”. European Mechanical Science, Vol. 2, No. 3, 2018, pp. 83-91
[11] J. McDonald, “BIOCOMP Innovation Review”, BIOCOMP project internal report, February 2006
[12] A. Stark, “Thermoplastic bio-polymer resins”, Bio-Composites - The Next Generation of Composites, Smithers Rapra, Shawbury, UK, 25 September 2008
[13] S. Goutianos, and T. Peijs, “The optimization of flax fibre yarns for the development of highperformance natural fibre composites”, Advanced Composites Letters, Vol. 12, No. 6, 2003, pp. 237-241
[14] “Comingled Biomaterials From Nature (COMBINE)”, UK collaborative project part-funded by Technology Strategy Board, www.combineproject.org.uk, 2007-2009
[15] “Natural Aligned Fibres and Textiles for Use in Structural Composite Applications (NATEX)”, European collaborative project supported by the European Commission’s 7th Framework Programme, www.natex.eu, 2008-2012
[16] “Stimulating the UK supply chain for BioComposites (UK-BIOCOMP)”, UK collaborative project part funded by the Composites Innovation Cluster, http://the-cic.org.uk/uk-biocomp, 2013-2016
[17] “Fire-retardant, environmentally sustainable composites using natural fibres and biopolymers (FRBioComp)”, UK collaborative project part funded by the Technology Strategy Board, http://www.frbiocomp.org.uk, 2011-2014
[18] “Tailor -made materials from environmentally friendly production routes using materials based on a polyhydroxybutyrate (PHB) biopolymer matrix and lignocellulosic nanofibres (Bugworkers)”, European collaborative project supported by the European Commission’s 7th Framework Programme, http://www.bugworkersproject.eu/, 2010-2014
[19] “Biocomposites for high-performance, low environmental impact, economical building products (BioBuild)”, European collaborative project supported by the European Commission’s 7th Framework Programme, http://www.biobuildproject.eu/, 20112015
[20] DeHondt NATTEX UD roving http://www.dehondt-lin.com/default.asp?file=pg28-2_fr
[21] G. Marsh, “Next Step for Automotive Materials”, Materials Today, Vol. 6, No. 4, 2003, pp. 36-43.
[22] J. Nickel, and U. Riedel, “Activities in Biocomposites”, Materials Today, Vol. 6, 2003, pp. 44-48.
[23] “New Classes of Engineering CompositeMaterials from Renewable Resources (BIOCOMP)”, European collaborative project supported by theEuropean Commission’s 6th Framework Programme, www.biocomp.eu.com, 2008-2012
[24] R. P. Wool, and X. S. Sun, “Bio-Based Polymers and Composites”, Elsevier Academic Pres, 2005
[25] B. Suddell, “Developments in the Innovative Use of Natural Fibres for Industrial Applications”, in JEC Biomaterials Forum, 2009.

[26] T. Nishimura, "Development of car components using kenaf and a new evolution in biomaterials", in SusCompNet 7, University of Bath, 2004
[27] Development of jute fiber reinforced cement concrete composites. Project No: JMDC/JTM/MM-IV/7.1/2008, 2008
[28] O. Akampumuza, P. M. Wambua, A. Ahmed, W. Li, X. Qin. "Review of the applications of biocomposites in the automotive industry", Polymer composites, Vol. 38, No. 11, 2017, pp. 2553-2569
[29] Biocomposites: 350,000 t production of wood and natural fibre composites in the European Union in 2012, Nova-Institut GmbH, press release, 26 November 2013
[30] A. Sindhuphak, "Bioproducts of automotive accessories: Rethinking design materials through cornstarch, sugarcane and hemp", KMITL Science and Technology Journal, Vol. 7, No. S2, 2007, pp. 160–170.
[31] R. Burgueño, M. J. Quagliata, A. K. Mohanty, G. Mehta, L. T. Drzal, M. Misra, "Load-bearing natural fiber composite cellular beams and panels", Composites Part A: Applied Science and Manufacturing, Vol. 35, No. 6, 2004, pp. 645–656.
[32] A. N. Papadopoulos, and J. R. B. Hague, "The potential for using flax (Linum usitatissimum L.) shiv as a lignocellulosic raw material for particleboard", Industrial Crops and Products, Vol. 17, No. 2, 2003, pp. 143–147.
[33] M. A. Dweib, B. Hu, A. O'Donnell, H. W. Shenton, R. P. Wool, "All natural composite sandwich beams for structural applications", Composite Structures, Vol. 63, No. 2, 2004, pp. 147–157.
[34] M. A. Dweib, B. Hu, H. W. Shenton, "Bio-based composite roof structure: Manufacturing and processing issues", Composite Structures, Vol. 74, No. 4, 2006, pp. 379–388.
[35] H-S. Yang, D-J. Kim, H-J. Kim, "Combustion and Mechanical Properties of Fire Retardant Treated Waste Paper Board for Interior Finishing Material", Journal of Fire Sciences, Vol. 20, 2002, pp. 505–517.
[36] M. Fam, and F. Fu, "Introduction: a perspective natural fibre composites in construction" in Advanced high strength natural fibre composites in construction, Woodhead publishing series, 2017
[37] H.N. Yu, S. S. Kim, I.U. Hwang, D. G. Lee, "Application of natural fiber reinforced composites to trenchless rehabilitation of underground pipes", Composite Structures, Vol. 86, 2008, pp. 285–290.
[38] G. Thilagavathi, E. Pradeep, T. Kannaian, L. Sasikala, "Development of natural fiber nonwovens for application as car interiors for noise control", Journal of Industrial Textiles, Vol. 39, No. 3, 2010, pp. 267–278.
[39] G. Cicala, G. Cristaldi, G. Recca, G. Ziegmannb, A. El-Sabbaghb, M. Dickert, Materials & Design, Vol. 30, No. 7, 2009, pp. 2538–2542.
[40] S. C. Mishra, "Low cost polymer composites with rural resources", Journal of Reinforced Plastics and Composites, Vol. 28, No. 18, 2009, pp. 2183–2188.
[41] D. Chandramohan, and K. Marimuthu, "Natural fiber particle reinforced composite material for bone implant", European Journal of Scientific Research, Vol. 54, 2011, pp. 384–406.
[42] C. Arnold, "Life Cycle Assessment of Composite Materials", Composites and the Environment, Welsh Composites Consortium, University of Wales, Bangor, UK, 5 June 2008
[43] H. M. G van der Werf, and L. Turunen L, "The environmental impacts of the production of hemp and flax textile yarn", Industrial Crops and Products, Vol. 27, No. 1, 2008, pp. 1-10.
[44] J. E. G. Van Dam, and H. L. Bos, "Consultation on natural fibres: the environmental impact of hard fibres and jute in non-textile industrial applications", ESCFibres Consultation no 04/4, Rome, 15-16 December 2004.
[45] M. Yates, and C. Barlow, "Life cycle assessments of biodegradable, commercial biopolymers - A critical review", Resources, Conservation and Recycling, Vol. 78, 2013, pp. 54–66.
[46] A. Kendall, "A life cycle assessment of biopolymer production from material recovery facility residuals", Resources, Conservation and Recycling, Vol. 61, 2012, pp. 69-74.