



Bio-composite materials: a short review of recent trends, mechanical and chemical properties, and applications

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Abstract

Recently, the attraction on the bio-composite (known as green composites) materials has significantly increased due to the potential of being substitute to conventional materials used in manufacturing industries. Bio-composite materials are produced with natural fibers or natural resins instead of synthesized fibres (carbon, glass, etc fibers) or resins (poly vinyl alcohol, epoxy, etc resins). The bio-based fibers such as jute, sisal, flax, hemp, bamboo, hair, wool, silk etc., are obtained from plants or animals. Also, natural matrix materials such as natural rubber, polyester, etc., are produced from plants. The advantages of bio-composites such as the ease of disposal and being able to composted characteristics of bio-composites after the expiration date which is not generally possible with conventional synthetic materials, being renewable, sustainable have attracted many researcher. Furthermore, the comparable mechanical properties of bio-composites make feasible for application to many different products. This study reviews the, recent trends, mechanical and chemical properties, and application of bio-composites in recent years.

Keywords: Composites, Bio-composites, Natural fibers, Review

1. INTRODUCTION

Bio-based composites are promising materials for future applications of automotive industry. The challenge of making automotive products lighter, safer and cheaper leads to investigate advanced materials with desired properties. Also, awareness of environmental issues forces the researchers and manufacturers to spend effort on composite and bio-composite materials field.

Composite material is a combination of two different materials with discrete properties and generally, is produced with the reinforcement of a matrix structure. The most common matrix materials are thermoset or thermoplastic resins such as polyester, epoxy and vinyl ester. And, the most common reinforcement agents are carbon, aramid and glass fibers. Composite materials also may contain additives, core materials or fillers, and have different properties than conventional materials that are used to manufacture. The main difference is the being anisotropic which means properties change with direction of the applied load. The main advantage of the composite materials is the allowance to modify the properties according to design requirements. Composite materials can be produced lighter and safer compared to its traditional counterparts.

Composite materials are generally produced with fiber reinforcements and the most common reinforcement agent is carbon. Recently, many researchers focused on the natural fibers in order to produce sustainable materials for manufacturing industry. Many researchers investigated the mechanical chemical properties of the materials which are produced with natural fibers such as kenaf, abaca, grass, hemp, flax, bamboo, sisal, etc.

Recently, the all world faced with environmental concerns and issues such as sustainability and cost. Thus, researches in the field of manufacturing have focused on biomaterial technology which has promising opportunities. The ease of disposal and being able to composted characteristics of bio-composites after the expiration date which is not generally possible with conventional synthetic materials have attracted many researcher. Also, the advantages of natural fibers such as low weight, corrosion resistance, and high strength compared to synthetic counterparts make bio-fibers more attractive. But also, the bio-fibers have some drawbacks such as being anisotropic and extra moisture absorption.

The final characteristics of the composite materials are

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determined by many factors such as matrix material, fibre, fibre direction, fibre application type, production method, and etc. Matrix material is an important parameter for mechanical and chemical features of the composite material product and most of the matrix materials are petro-chemical based materials. Depletion of fossil sources is a critical issue for composites. Therefore, some researchers are studying on the natural resins which are obtained from plants in order to synthesize matrix material for composite-materials.

The increasing attraction and importance of the bio-composites increased the number of publications on that particular subject with a variety of different perspectives. The publications including books, articles and reviews show the importance of the subject. John and Thomas (2008), Faruk et al. (2012), Hassan et al. (2010), Shinoja et al. (2011), Venkateshwaran and Elayaperumal (2010), reviewed bio-composite materials produced with natural fiber and matrices [1-5]. This paper includes the recent studies on the subject of bio-composites, focusing on the sources for natural fibers excluding animal (hair, silk, wool, etc) based fibers and matrices, production methods, mechanical and chemical properties of bio-composites and application of the bio-composite materials.

2. FIBERS

Fibers are the reinforcing agents of the composite materials and main part of the composite system that carries structural loads. Composite materials are mostly produced with synthetic reinforcing agents. Generally, carbon, aramid and glass fibers are used for composite material production. But, the sustainability and environmental issues need effective solutions for the mankind. The efforts on producing renewable and biodegradable materials for manufacturing industry are widening all around world.

Fibers can be divided into two main categories as natural and synthetic. Synthetic fibers are generally petro-chemical products. Natural fibers are obtained from plants or animals. Plant based fibers are composed of cellulose and animal fibers includes proteins (hair, silk, wool, etc.). Plant fibers consist of leaf, seed, bast, fruit, wood, grass, and stalk. In this study, plant fiber sources were reviewed and the results were given in following sections.

2.1 Plant Fibers (Lignocellulosic Fibers)

Plant fibers are promising reinforcement agents mainly composed of cellulose and, with the concerns of sustainability and renewability these fibers are getting more attention by the researchers and the industry.

Lignocellulosic fibers are formed basically from three chemical substances. These substances are cellulose (α -cellulose), hemicelluloses and lignin. Also, lignocellulosic fibers may contain other different substances depending on the plant, region, species, etc., such as waxes, pectin, inorganics, starch, protein, etc. Table 1 shows the chemical composition

of the plant based natural fibers. Even though the all plant fibers are basically polymers of sugar, the chemical composition varies with many parameters such as climate, soil type, environmental factors, etc.

Table 1. Chemical compositions of some natural fiber types

Type	Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Reference
GRASS	Bagasse	44,1	31,8	22,3	[6]
	Bamboo	22,8-56,7	17,2-43,8	1,1-26,6	[7]
	Canary	37,2-41,7	19-22,9	-	[8]
	Corn	41,7	46	7,4	[9]
WOOD	Hard Wood	31-64	25-40	14-34	[10]
	Soft Wood	30-60	20-30	21-37	[10]
FRUIT	Coir	36-43	0,15-0,25	41-45	[11]
	Kapok	35	22	21,5	[12]
	Oil palm	47,91	19,06	24,45	[13]
BAST (STEM)	Jute	61-71,5	13,6-20,4	12-13	[11]
	Flax	74,93	10,37	2,62	[14]
	Hemp	75	15	3	[15]
	Kenaf	31-57	21,5-23	15-19	[16]
	Kudzu	33	11,3	14	[17]
	Nettle	79-83,6	6,5-12,5	3,5-4,4	[18]
	Ramie	61,85-73,21	5,27-7,58	4,6-,9,06	[19]
	Roselle	70,20	7,21	14,91	[20]
LEAF	Abaca	60,4	20,8	12,4	[21], [22]
	Banana	63-64	10-24	5	[23]
	Henequen	70-77,6	4--20	8-13,1	[22], [24]
	Pineapple	70-82	18	5-12	[25]
	Sisal	26	38,2	26	[26]
SEED	Cotton	82,7-92	5,7-6	0	[22]
	Kapok	64	13	23	[27]
STALK	Wheat	33-38	26-32	17-19	[25]
	Rice	28-36	23-28	12-14	[25]

Cellulose

Cellulose is the main structural components of the natural fibers which consist of D-glucopyranose units joined each other with 1,4-b-D-glycosidic bonds (C1 and C4). Cellulose is hydrophilic and has around 10000 degree of polymerization which varies with fiber type. The hydrogen bonds provided by hydroxyl (OH) in the structure and also van der Waals forces makes cellulose molecules to be crystalline packed. This mainly determines the physical properties of celluloses. Besides these highly ordered regions, cellulose has less ordered amorphous regions. In the nature, two types of cellulose which are cellulose I_α and I_β exist [1, 22]. Cellulose can be degraded with chemical applications, but also is resistant to oxidising and alkali agents and hydrolysis relatively.

Hemicellulose

Hemicellulose is the second major structural component of the fibers. It is not a type of cellulose and has more complex structure than natural cellulose. Hemicelluloses are composed of different sugar units, very hydrophilic, non-crystalline, and acts as the matrix for cellulose microfibrils. Hemi-

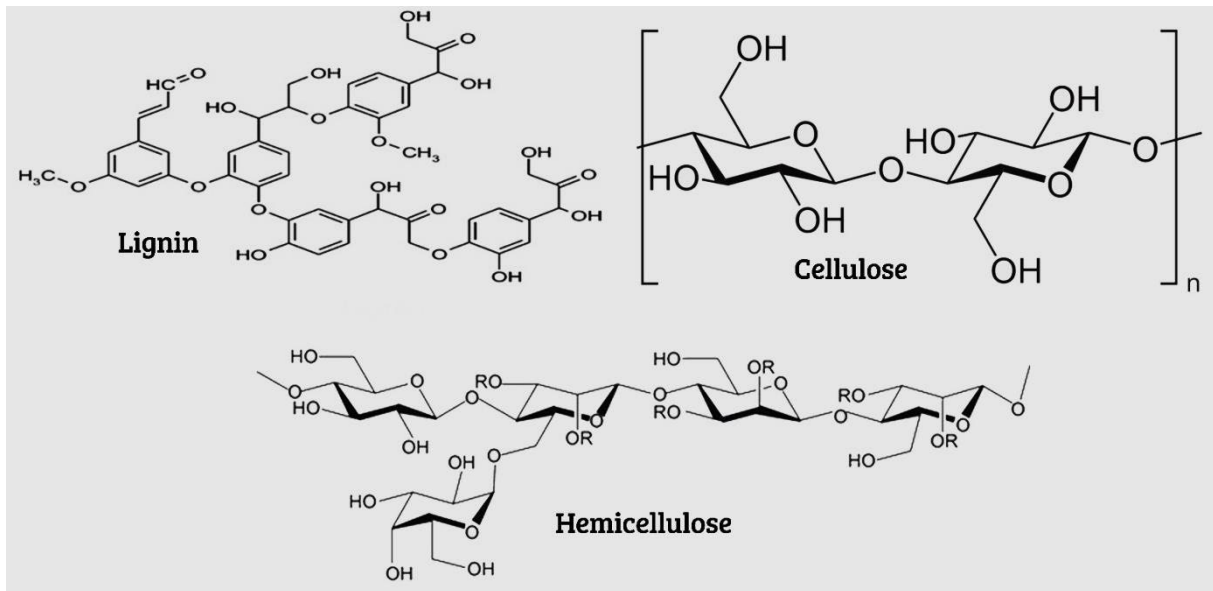


Figure 1. Structure of cellulose, hemicellulose and lignin.

celluloses have a degree of polymerization around 50-300. Hemicelluloses can be soluted in alkali and hydrolyzed in acids [28].

Lignin

Lignin is the hydrophobic, insoluble in the water, amorphous aromatic polymer resulting from the oxidative combinatorial coupling of 4-hydroxyphenylpropanoids which has strong intramolecular bonds. Lignin is especially presented in vascular plants and acts as filler between cellulose hemicellulose and pectin structures. Lignin provides stiffness to cellulose and hemicellulose structures. Figure 1 depicts the chemical structure of the cellulose, hemicellulose and lignin molecules [1, 22, 28].

Some of the most important fiber sources and the recent studies were reviewed and the important mechanical properties such as tensile strength, elastic modulus, and elongation at break were given in Table 2.

2.1.1 Grass

Bagasse

Bagasse also known as sugarcane bagasse is the waste (by-product) of sugar production. While paper is produced from bagasse in some Latin American countries, also bagasse can be used to produce animal feed, furfural, and biodegradable composite materials [29].

Bamboo

Bamboo which is mostly grown in Asia is a member of grass family and there are above 1400 types. Bamboo stem is hard and woody. The bamboo fibers are produced from pulp of bamboo plants. It has wide application area such as food, paper, textile, furniture, construction, and in most of the woody goods. Bamboo fibers can provide fine mechanical strength, stiffness, low density and high modulus [30, 31].

Corn

Corn is one of the major plants used in food industry all

around the world. The high amounts of corn production and processing ends up with different by-products such as corn husk and corncob. The fibrous structure of these by-products makes corn promising candidate for bio-composite production [32].

2.1.2 Wood

Woods are categorized according to their botanical properties. The angiosperm woods are called hard and gymnosperm woods are soft. The main anatomical difference is the enclosement of the seeds in the ovary of the flower. Both hardwoods and softwoods can be used as reinforcement material or filler [22, 33].

Hard Wood

Hardwoods contain vessels and are porous and most of the tropical woods are hardwoods. Alder red Ash, Oregon, Aspen, Birch, paper Cottonwood, Oak, Beech, and Maple are the examples of the hardwoods.

Soft Wood

Softwoods do not contain vessels and are non-porous. Cedar, Western Red, Cedar, Larch, and Pine are the examples of softwoods.

2.1.3 Fruit

Coir

Coir is a by-product of different coconut products. Coir contains a high amount of lignin (41-45 %) compared to other natural fibers [11]. The lignin is generally extracted with a chemical or organic solvent. Annually, over 50 billion coconuts are harvested and a very small amount of coconut husk is recycled (around 15%) [34]. Thus, coir husk fibers have a great potential for bio-composite reinforcement material production.

Kapok

Kapok fibers are produced from natively tropical tree kapok

which can grow up to 50 meters. Kapok products have different applications like pillow filling from kapok cotton and oil extraction from its seeds. The high amounts of kapok harvesting produce a potential for recycling the wastes and by-products of the kapok [35, 36].

Oil Palm

Oil palm is an important crop mostly harvested in Malaysia and Indonesia and generally used for palm oil extraction and paper production. The great amount of oil palm production also ends up with a high amount of biomass including empty fruit bunches, fronds and trunks [37].

2.1.4 Bast (Stem)

Jute

Jute which has highest production volume for fibers after cotton all around the world is mostly cultivated for its fiber. It mainly grows in India and Bangladesh [38]. Also, China, Nepal, Brazil and Thailand are the some other countries that cultivate jute fiber. Despite the disadvantages of the jute fiber such as being highly brittle and relatively lower tensile strength it has a broad range of application due to fine texture and heat resistance [39].

Flax

Flax is one of the known oldest textile raw material and cultivated for centuries. Linen fabric is produced from flax plant and due to its high strength has a wide application area. Flax fibers are used for production of tents, canvas, towel, sails furnishing fabrics, household textiles etc [40].

Hemp

Hemp is another important crop used in fiber reinforcement and the history of hemp usage is very old. Even though the bad reputation about the hemp (narcotic issues), industrial hemp can't be used as narcotic since it produces 9- tetrahydrocannabinol (THC) less than 0.2% [41]. Hemp is an annual crop which has significant growth rate and suitable for temperature climates [2].

Kenaf

Kenaf has a high potential to be the reinforcement material for bio-composite production due to its growth rate, and similar structure to jute and cotton which are the mostly used crop for fiber production [42]. Kenaf is an annual crop and its origin is Africa. It is cultivated mostly in Africa, Bangladesh, India, China and Malaysia [43].

Kudzu

Kudzu is an invasive crop native to southern regions of Japan and China. It is mostly used for erosion control. It is used for clothing and basketry for centuries. It has a similar morphology to flax and hemp [17] and thus it has potential to be the reinforcement material for bio-composite production.

Nettle

Nettle also known as stinging nettle is a perennial crop which has similar properties to flax. There are several species of the nettle crop.

Ramie

Ramie also known as Chinese nettle is a perennial crop that grows in warm climates. The treatment of ramie fibers is expensive due to gummy resins in the structure. Ramie is generally used for clothing but recently it has been started to use in automotive industry. Ramie fibers have long length and lower density than glass fibers [44].

Roselle

Roselle is a crop that is cultivated for its jute-like fibers mostly in tropical regions. Its origin is assumed as Africa. It is an annual crop and can grow up to 2.5 m [45].

2.1.5 Leaf

Abaca

Abaca is one of the most important leaf fibers. Abaca is mostly cultivated in where its origin is Philippines. It is related with banana family. Abaca fibers have good mechanical properties like high strength and flexibility [46].

Banana

Banana is a tropical plant mostly cultivated for its nutritious fruit. Its tree bark have good mechanical properties which can be used as reinforcement agent instead of synthetic ones [47].

Henequen

Henequen plant natively grows in Guatemala and Mexico. It is cultivated for its fibers in order to made ropes mostly. It has similar properties to sisal and also called Cuban or Yucatan sisal [48].

Pineapple

The pineapple which origin is Brazil now spreaded to all tropical regions. It has a very high amount of production and thus it provides a great potential for fiber production as by-product.

Sisal

Sisal is native to Mexico and mostly cultivated in Brazil. It has wide range of application area. The sisal fibers possess good mechanical properties and thus it is used in bio-composite material production [49].

2.1.6 Seed

Cotton

Cotton is one of the most important crops that used all over the world. It has variety of uses. But due to its relatively low mechanical properties it rarely used as reinforcement agent. It is generally used as secondary fiber in green hybrid-composites.

Table 2. Mechanical properties of some natural fiber types

Type	Fiber	Density (g/cm ³)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)
GRASS	Bagasse	1.2-1.25	20-290	17-27.1	1.1
	Bamboo	0.6-1.1	140-230	11-17	-
WOOD	Hard Wood	0.3-0.88	51-210.7	5.2-15.6	-
	Soft Wood	0.3-1.5	45.5-1000	3.6-40.0	4.4
FRUIT	Coir	1.15-1.45	106-593	1.27-6.0	15.0-59.9
	Oil palm	0.7-1.55	100-400	1.0-9.0	8-25
BAST (STEM)	Jute	1.3-1.46	393-800	10-30	1.5-10.0
	Flax	1.4-1.5	345-1500	27.6-80	1.2-3.2
	Hemp	1.47-1.48	550-900	70	1.6-4.0
	Kenaf	1.2-1.45	295-930	53	1.6-6.9
	Kudzu	-	130-418	-	-
	Nettle	-	650	38	1.7
LEAF	Ramie	1.45-1.5	220-938	24.5-128	1.2-3.8
	Abaca	1.5	400-980	3-12	3-10
	Banana	1.35-	355-500	12-33.8	5.9-53
	Henequen	1.2-1.4	430-580	10.1-16.3	3.0-4.7
	Pineapple	0.8-1.6	170-1672	82	1.0-3.0
SEED	Sisal	1.33-1.5	400-700	9.0-38.0	2.0-14
	Cotton	1.5-1.6	287-597	5.5-12.6	3.0-10.0
	Kapok	0.38	93.3	-	-
SYNTHETIC	Carbon	1.4	4000	23-240	1.4-1.8
	E-glass	2.5	2000-3500	70.0	0.5-3.0
	S-glass	2.5	4570	86.0	2.8
	Aramide	1.4	3000-3150	63-70	2.5-3.7

Kapok

Kapok has similar properties to cotton and mostly cultivated in Malaysia. Kapok husk which is the by-product of the kapok production can be used as the fiber production raw material [36].

Using bio-fibers has some cons as well as pros. The main drawbacks of bio-fibers are the high moisture absorption, relatively lower structural strength and poor adhesion with matrix material. Thus, many researchers studied on morphological properties and the treatments for modifications of bio fibers [6, 14, 16, 24, 44, 46, 50-94]. Also many articles have been published that reviews the treatment methods and the effects of these treatments on mechanical, chemical and morphological properties of bio-fibers and bio-composites [55, 95-97]. The main goal for all treatment types (physical, chemical or physico-chemical) is to improve the adhesion characteristics of the fibers and by this way to improve the mechanical properties of the bio-composites. The most common physical methods are simple mechanical methods (stretching, calendaring, rolling), solvent extraction, electric discharge (corona, plasma, ionized air), thermal treatments. Alkaline, coupling (silane, acylation, graft copolymerization), bleaching (reduction, oxidation), enzyme, peroxide treatments are the chemical methods for modification of the fibers. Also there are some methods that combine the physical and chemical methods and called physico-chemical

Table 3. Mechanical properties of some natural fiber reinforced composite materials

Fiber	Fiber Treatment	Matrix	Fibre/Matrix-Ratio (%-wt – Fiber/Matrix)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)	Production Method	Reference
Bagasse	Untreated	Cardanol-formaldehyde	15	24.4	1.8	-	Compression Moulding	[105]
Bagasse powder	Untreated	Polypropylene	3	35	2.0	-	Injection Molding	[106]
	ChOAc		3	40	2.6			
Bagasse	Untreated	Polyethylene	5	36±5.1	330±8.4	8.7±5.1	Melt Compounding	[107]
	Mechanical			129±1.1	440±6.1	10.6±5.1		
Bamboo	Untreated	Polypropylene	80/20	37	4.34	-	Compression Molding	[108]
	Alkali			40-51	4.38-5.57			
Corn	Untreated	Polylactic Acid	-	46	-	-	Injection Molding	[109]
	Alkali			58-64				
	Alkali+Silane			62-72				
Kapok	Untreated	Cassava Starch	5	3	25	30	Compression Molding	[110]
			10	4	40	20		
			15	4.5	40	19		
Jute	NaOH	Polyethylene	30	10.9±0.1	0.25±0.02	12.8±0.9	Injection Moulding	[111]
	Stearic Acid			12.8±0.3	0.26±0.01	11.8±0.8		
Flax	-	Polypropylene	30	29±1.5	5±0.4	2.7±1.5	Compression Moulding	[112]
			40	29±0.8	7.6±0.9	1.5±0.8		
		Polylactic Acid	30	53±0.2	8.3±0.6	1.0±0.2		
			40	44±0.2	7.3±0.5	0.9±0.2		
Kenaf	-	Polylactic Acid	10	61.1±1.3	3.8±0.1	-	Injection Molding	[113]
			20	74.5±0.9	5.3±0.2			
Sisal	-	Thermoplastic Starch and Polycaprolactone.	5	3.8	0.205	5.3	Twin Screw Extrusion	[114]
			10	3.6	0.255	2.9		
Cotton	Untreated	Epoxy	-	35	-	-	Hand Lay-Up	[115]
	Alkali			45				

methods such as hydrothermal and steam explosion [10, 16, 22, 98-104].

3. BIO-COMPOSITES MECHANICAL PROPERTIES

While the fibers carry the structural loads of the composite parts matrix material keeps the structure in solid phase that forms the shape and the appearance of the product. Today, most of the products produced from composite material include non-renewable matrices of petroleum based chemicals. But, there are numerous studies that investigate the usage of renewable and sustainable matrices for composite material production. The most commonly used thermoplastic composites for bio-composite material production are polystyrene (PS), polyethylene (PE), polypropylene (PP), and polyvinylchloride (PVC). Epoxy, vinyl esters, polyester and phenol formaldehyde are the thermoset resins which are used to produce composite materials reinforced with natural fibers [2]. Mechanical properties of the final material depend on many different parameters. The main parameters are the fiber and matrix material properties and the compatibility of matrix and the fiber bundle. Mechanical properties of different matrices and fibers were studied by many researchers and a brief summary of the studies were given Table 3.

4. CONCLUSIONS

This paper is a brief review study of the recent investigations on mechanical and chemical properties and applications of bio-fibers and bio-composites. The study showed that bio-composites are promising materials for the future applications in many industrial sectors especially in automotive sector which is the leading sector of the industrial and technological development. The remarkable advantages such as the renewability and sustainability and further being bio-degradable characteristics of bio-composite materials make bio-composites the “future materials.” Also studies show that, the issues of bio-composites such as moisture absorption and low adhesion characteristics are need to be solved in order to replace conventional materials or synthetic composites. Reinforcing synthetic matrix with natural fibers could be a temporary solution for the progress. But, it is mandatory to use both natural fibers and natural resins to produce goods from completely recyclable, bio-degradable, “green” materials. The increasing awareness of the people and the legislations will enforce the usage of bio-composite materials instead of conventional materials to ensure the sustainability.

ACKNOWLEDGEMENT

The authors would like to thank the Cukurova University Scientific Research Project Coordination (FBA-2017-9122) for financial support to this project.

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