Chapter 10

Bio-based textile coatings and composites

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10.1 Introduction

Generally there is a move toward renewable, natural, green, and environmental friendly products due to the increasing consciousness of consumers, the influence of environmental organizations (e.g., Greenpeace), and the impact of legislation (e.g., REACH). Furthermore, current global municipal waste in 2016 amounted to approximately 2.01 billion tonnes and is expected to increase to 3.4 billion tonnes by 2050 (World Bank, 2019). About 45.5% of waste were landfilled and 37.8% were recycled in the EU in 2016 (EUROSTAT, 2019). The European Coatings supply chain is increasing its efforts to ensure that a much higher proportion of its products are derived from renewable sources. The stimulus is the climate change. The European Union has set a target of 30% of existing petrochemical-derived chemicals and materials being replaced by bio-based and biodegradable alternatives by 2030. This objective is in line with the long-term aim of the European Union of establishing low-carbon, circular economies with substantial reductions in CO_2 emissions and greater reliance on its own raw materials with much more recycling and reuse of materials to achieve zero waste.

At the same time there is a widespread desire to move away from fossil fuels to reduce air pollution. There is also, however, a gradually urgent need for action to deal with frequent deficiencies of petrochemical-derived raw materials (Coatings World, 2018). The textile market covers a broad range of materials. Consequently, the textile industry has a significant impact on the environment. Therefore, extensive research in the field of bio-based, biodegradable, or even recyclable textiles is being done to reduce the environmental impact of textiles. CO_2-neutral renewable materials are being developed due to the depletion of fossil fuels and the impact of CO_2-emission on the global climate. Some fabrics are already made from renewable resources (e.g., cotton,

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flax, etc.) but others are synthetic and oil-derived, such as polyester and polyamide. One response to this need has been the development of synthetic bio-based fibers from renewable raw materials. Many bio-based polymers have been developed, including polyethylene terephthalate (PET), polyethylene (PE), polylactic acid (PLA), starch blends, biodegradable polyesters such as polybutylene succinate (PBS) and poly(butylene adipate-co-terephthalate) (PBAT) and cellulose acetate. The development and production of bio-based fibers for textiles is widely reported and will not be discussed in this chapter. Textile fabrics can be used as reinforcement in composites or can be finished or coated to introduce new functionalities (e.g., flame retardancy, antimicrobial activity, etc.). The elaboration of novel bio-based finishing and coating formulations remains a challenge.

The use of textiles as reinforcement in bio-based composites and the development of bio-based coatings for textiles will be further discussed in the following paragraphs. In the following paragraphs an overview of some work done at Centexbel and other institutes in the area of bio-based textiles is presented as well as bio-based products commercially available for the textile industry (renewable textile-based composites and bio-based coating and finishing formulations).

10.2 Bio-based composites

Composite materials offer outstanding properties, such as lightweight, high specific strength, and corrosion resistance, which make them excellent for applications in aerospace, automotive, wind energy, sporting, transport, and construction sector. They are composed of reinforcing fibers (mostly glass, carbon, or aramid) and a bed matrix. The matrix can be thermosetting polymer (e.g., epoxy, vinyl ester, polyester) or thermoplastic (e.g., PP, PA, PEEK).

Bio-based composites cover composites that are made entirely or largely of biomass. As this section is part of the bio-based textiles chapter we will only focus on composites which contain bio-based textile reinforcements and bio-based matrices.

The market of fiber reinforced polymers are still dominated by nonnatural fibers (i.e., glass, carbon, aramid), but there is a growing interest in bio-based fiber reinforced materials. The main reason for this interest is the lower carbon footprint of these materials compared to the traditional composites made from glass and carbon fibers. Other interesting features are the low weight, interesting weight/performance balance, the special looks, and touch (Good market developments for bio-based composites—Bio-based News, 2018).

10.2.1 Bio-based fibers

Bio-based fibers can be derived from plants and animals of which the plant-based fibers are the most interesting one for composite applications because

they have in general a higher stiffness and strength compared to animal fibers. Furthermore, from an economic and ecological point of view plant fibers can grow in many countries, are a renewable resource, and are considered as CO_2 neutral. To be competitive with synthetic fibers the bio-based fibers should have comparable mechanical properties.

A comprehensive overview of the mechanical properties of natural and synthetic fibers was prepared by Pickering et al. and is shown in Table 10.1 (Pickering et al., 2016).

From the table, it can be seen that the highest strength and stiffness are obtained for the cellulose-based fibers ramie, flax, and hemp. When compared to the e-glass fiber, which is the most used fiber in composites, it can be observed that glass fibers have still a higher strength in absolute values, but when looking at the specific tensile strength comparable values can be obtained with natural fibers and the specific young's moduli can even be higher.

Further, there is also a huge variation in mechanical properties within one fiber family. One reason is that it is a natural fiber, making it difficult to obtain always the same properties (Eve et al., 2009). The SEM image of flax fibers (Fig. 10.1) clearly shows that the fibers differ in diameter, have kink bands, and some of them are damaged.

On the other hand, the SEM image of glass fibers (Fig. 10.2) reveals that the fibers are uniform and very smooth making it possible to obtain always the same mechanical properties.

Other reasons for the huge variation in mechanical properties are that fibers were damaged during processing; different characterization methods were used such as testing single fibers instead of fiber bundles; some misalignment of fibers; or different testing conditions are applied such as difference in speed, gauge length, moisture content, or temperature (Pickering et al., 2016).

In Europe flax is one of the most used natural fiber for composite applications because the climatology conditions are beneficial to grow flax especially in the countries of France, Belgium, and the Netherlands (about 85% −90% of the worldwide flax production). Also, flax is a crop that requires less fertilizers and crop protection; no irrigation is necessary and it is a zero waste plant making it a very sustainable fiber source (Gardetti and Muthu, 2015). All parts of the plant can be used: long fibers for textile and composites; short fibers for textiles, insulation, car components, and paper industry; linseed for nutrition, animal feed, health care, and industrial use; shives for litter, boards, and building industry (ABV-Algemeen Belgisch Vlasverbond, 2019).

In order to find the best mechanical properties of flax fibers, the influence of several parameters was investigated by many research groups. Martin et al. (2013) investigated the influence of the degree of retting of flax fibers on the tensile properties. Retting is a process to remove pectin and thus releasing the fiber material. From an economic point of view most of the flax is dew retted on the field and is thus dependent on the weather conditions. The researchers collected samples with retting times of 1, 5, 9, 14, 16, and 19 days. They found

TABLE 10.1 Mechanical properties of natural and glass fibers (Pickering et al., 2016).

Fiber	Density (g/cm^3)	Length (mm)	Failure strain (%)	Tensile strength (MPa)	Young's modulus (GPa)	Specific tensile strength ($MPa/g\ cm^3$)	Specific Young's modulus ($GPa/g\ cm^3$)
Ramie	1.5	900–1200	2.0–3.8	400–938	44–128	270–620	29–85
Flax	1.5	5–900	1.2–3.2	345–1830	27–80	230–1220	18–53
Hemp	1.5	5–55	1.6	550–1110	58–70	370–740	39–47
Jute	1.3–1.5	1.5-120	1.5-1.8	393–800	10–55	300–610	7.1–39
Harakeke	1.3	4–5	4.2–5.8	440–990	14–33	338–761	11–25
Sisal	1.3–1.5	900	2.0–2.5	507–855	9.4-28	362–610	6.7–20
Alfa	1.4	350	1.5–2.4	188–308	18–25	134–220	13–18
Cotton	1.5–1.6	10–60	3.0–10	287–800	5.5-1.3	190–530	3.7–8.4
Coir	1.2	20–150	15–30	131–220	4–6	110–180	3.3–5
Silk	1.3	Continuous	15–60	100–1500	5–25	100–1500	4–20
Feather	0.9	10–30	6.9	100–203	3–10	112–226	3.3-11
Wool	1.3	38–152	13.2–35	50–315	2.3-5	38–242	1.8–3.8
E-glass	2.5	Continuous	2.5	2000–3000	70	800–1400	29

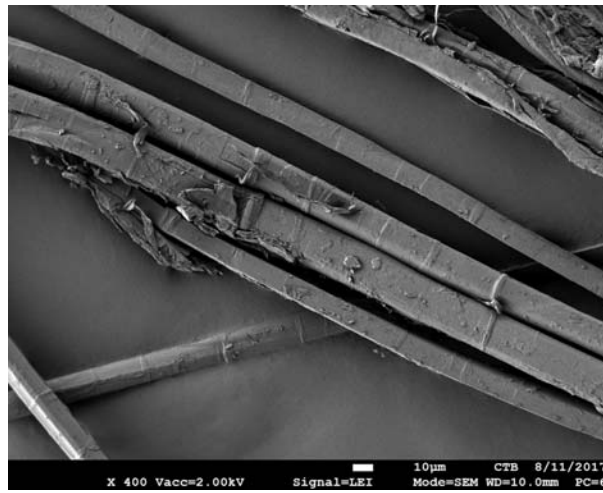

FIGURE 10.1 SEM image of flax fibers.

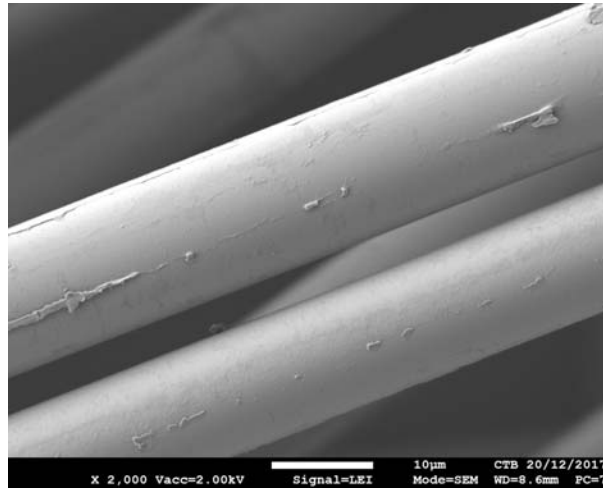

FIGURE 10.2 SEM image of glass fibers.

that the water uptake is higher for low retted fibers, which is unfavorable for composite applications. Also, the tensile properties of single fiber increased with the degree of retting. Another factor that influences the fiber property is the growing condition (year effect). It was found that composites from the flax grown in 2013 had higher stiffness than those with flax grown in 2012 (Haag et al., 2017). The same research group also identified flax varieties which are showing higher or lower mechanical properties in composites. In the Interreg project Biocompal it is also found that the flax variety can have an influence on

the mechanical properties of flax (Pisupati et al., 2019). The tensile strength and modulus of the fibers were determined by the impregnated fiber bundle test (based on ISO 10618) instead of testing the individual fibers. This in situ behavior testing of the technical fiber is much more realistic and relevant for composite applications than its behavior when tested as an individual technical fiber (Bensadoun et al., 2017).

The results of the tensile modulus (Fig. 10.3) and strength (Fig. 10.4) of different flax varieties from 1 test field and 1 year were compared with a commercially available flax type. The results show that almost all the tested varieties possess higher mechanical properties than the reference. An explanation for this could be that the reference fibers were more damaged due to processing (hackling) than the fibers that were only scutched and combed (Bos et al., 2002). Methods to minimize the degradation of the fibers during processing are treating them with ammonia instead of retting or skipping the hackling step during preform manufacturing (Zeng et al., 2015).

Although natural fibers have intrinsic good mechanical properties and are considered as durable, they are most of time incinerated after use. For recycling applications thermoplastic bio-based fibers are an interesting approach. Although mostly known as a bio-based matrix system (see bio-based matrices), poly(lactic acid) (PLA) fibers possess interesting properties to be utilized as reinforcement in composites. PLA is not only made from 100% renewable sources such as corn, but is also compostable. It is a linear aliphatic thermoplastic polyester which has mechanical properties similar to conventional PET, but with lower melting and softening temperatures. The density of the fibers is 1.25 g/cm^3 which is lower than natural fibers and they have a low moisture regain (Farrington et al., 2005). The Young's modulus of PLA fibers derived by melt-spinning ranges from 5.2 to 9.2 GPA and the strength varies from 280 to 870 MPA depending on the initial weight and process parameters (draw ratio and temperature) (Goutianos et al., 2019).

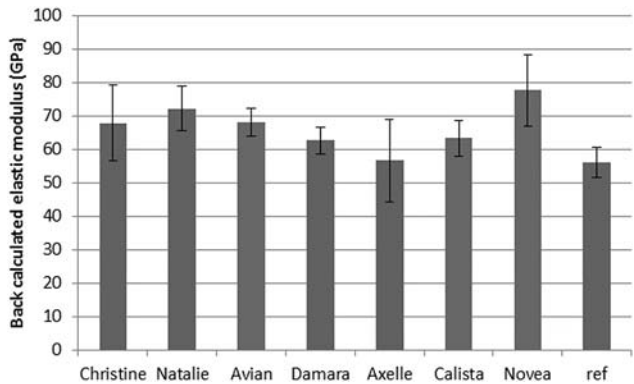

FIGURE 10.3 Tensile modulus of different flax varieties and a commercially available reference sample determined by the impregnated fiber bundle test.

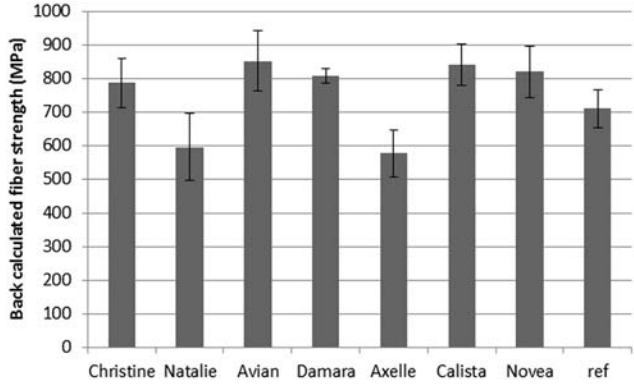

FIGURE 10.4 Tensile strength of different flax varieties and a commercially available reference sample determined by the impregnated fiber bundle test.

10.2.2 Bio-based matrix

In composite materials, the matrix binds the fibers and transfers the load between the fibers. The concentration of the matrix can vary between 30% and 80%, meaning that a large part of the composite consists of matrix polymers. Therefore, to obtain fully bio-based composites also the matrix should be derived from natural sources.

The most used matrix resins in conventional composites are unsaturated polyester resins, because they have acceptable mechanical, electrical, and chemical properties and are quite cheap. Because they have a high share in the composite market, the replacement of these resins by bio-based resins can have a huge impact on the sustainability of composite materials. Feedstocks for these resins are soybean oil and corn oil. These oils cannot be used as such and other functional groups such as epoxy or acrylate groups have to be introduced to convert these oils into thermoset resins (The matrix: CompositesWorld, 2016).

To replace petroleum-based unsaturated polyester resin acrylated epoxidized soybean oil (AESO) and maleinated epoxidized oil (MAESO) are proposed. However these resins need similar to standard resins styrene as reactive diluent in a concentration of about 35%. Besides that, styrene is non-bio-based, it also has other drawbacks of which one is that it is reported as a potential human carcinogen. So the development of bio-based diluents that can replace styrene are gaining more and more interest. Zhang et al. (2018) determined that methacrylated eugenol is the most promising, sustainable reactive diluent to replace styrene for MAESO resin.

The first commercially available resins are the Envirez resins from Ashland (Ashland, 2019). These resins meet the same performance and processing requirements as 100% petroleum-based unsaturated polyester resins. The biocontent of these resins varies between 10% and 20%. Another

commercially available bio-based resin is ENVIROLITE from Reichhold (Reichhold, 2019). This resin is based on soy oil and has a green content of 25%. The resin can be used as a stand-alone resin or in combination with other unsaturated polyester resins. The resulting laminates have similar mechanical performance compared to laminates with standard resins. AOC resins offer bio-based unsaturated polyester (Eko Tek) resins with a biocontent up to 30% (AOC).

When higher mechanical properties of composite are required, epoxies are selected as matrix material. Epoxies are cured with a harder element, which are in most cases amines or anhydrides. Bio-based alternatives are derived from vegetable oils, lignin, rosin, tannin, sugar, cardanol or itaconic acid (Ramon et al., 2018). Bio-based hardeners can be derived from cashew nut shell liquid (Benega et al., 2017). Companies that already offer bio-based epoxies or hardeners are, for example, Sicomin (Sicomin, 2014), Cardolite (Cardolite, 2017), Anacarda (Anacarda, 2019), and Entropy Resins (Entropy Resins, 2019).

When composites need to be flame retardant, phenolic resins are often used due to their superior fire, smoke, and toxicity properties compared to other polymeric matrices. Good bio-based alternatives are furan resins. They are produced from agriculture waste products such as sugarcane bagasse. Hemicellulose is turned into furfural via steam digestion and dehydration. Next furfuryl alcohol is formed by hydrogenation of furfural which is the precursor to synthesize furan prepolymers. Furan resins possess interesting properties such as a high stiffness, fire resistance, and chemical resistance to organic and inorganic acids. One of the pioneers in furfural chemicals is the company TransFurans Chemicals and has a yearly manufacturing capability of more than 40,000 MT (TransFurans Chemicals, 2019).

For challenging applications benzoxazine resins are interesting resins. They almost do not shrink and do not release volatiles during curing. Other properties of these resins are high stiffness, excellent thermal resistance with glass transition temperatures that can go beyond 200°C, and similar flammability, smoke, and toxicity performance of phenolic resins. Bio-based benzoxazine alternatives can be derived from natural phenolic compounds such as cardanol, vanillin, and eugenol (Trejo-Machin et al., 2018). Further Dumas et al. (2016) synthesized fully bio-based benzoxazines using hydroquinone and resorcinol as phenolic compounds resulting in glass transition temperatures higher than 280°C. The same researchers also reported that adding carbon nanotubes (CNTs) leads to a significant improvement of the thermomechanical behavior (about 50°C) (Dumas et al., 2014).

Besides thermoset matrices, thermoplastic polymers are also used in composite manufacturing mainly because they can be recycled or reshaped by just melting the polymer. One of the most studied bio-based thermoplastic matrices for composites is PLA. PLA was already mentioned as fiber, but it is more investigated as matrix in composite materials. The glass transition temperature of PLA is around 55–60°C and has melting points of 130–230°C. Similar to the melting range, the mechanical properties can be varied from soft and elastic

plastics to stiff and high strengths depending on the molecular weight, crystallinity, and stereometry of the molecule. A drawback of PLA is poor toughness which limits the amount of applications (Murariu and Dubois, 2016).

However, research is going to reduce the brittleness of the material by adding plasticizers of which low molecular weight polyethylene glycol and and oligomeric lactic acid are the most common (Farah et al., 2016). Two main suppliers of PLA are NatureWorks (NatureWorks, 2019) and Corbion (Corbion, 2019). Other bio-based and biodegradable polymers are polyhydroxyalkanoates (PHAs). They are polyesters and are derived from bacteria which use them as energy storage medium. The most commercialized PHAs are P3HB, P(3HB-co-3HV), and P(3HB-co-3-hydroxyhexanoate) (P(3HB-co-3HH)). The t_g of these polymers is quite low namely 4°C for P3HB and −35°C for P(3HB-co-3HH). The melting temperature is 177 and 61°C, respectively. The tensile strength is 40 MPa for P3HB and 9 MPa for P(3HB-co-3HH) (Nakajima et al., 2017). Some examples of suppliers are Biomer (BIOMER and PHB, 2019), BIO-ON, (BIO-ON, 2019) and Kaneka (Kaneka, 2019).

Polyamide (PA) is a high-performance engineering polymer with high strength and good fatigue resistance making it an attractive polymer to use as matrix in composite materials. Unlike other bio-based polymers, biopolyamides are high performance polymers as they are long-lived, durable, and do not give rise to technical weaknesses. Evonik (2019) supplies these bio-based polyamides under the name Vestamid Terra of which even a 100% bio-based material is available (Vestamid Terra DS (PA 1010)). Other suppliers of bio-based polyamides are Arkema (Arkema, 2019) and DSM (DSM, 2019).

10.2.3 Interface fiber−matrix

To achieve the best composite performance, a strong interaction between fiber and matrix is critical. A bad adhesion between the fiber and matrix leads to rapid failure of the composite as the load cannot be efficiently distributed between the fibers. Natural fibers are hydrophilic due to the presence of hydroxyl groups from cellulose and lignin. On the other hand, the matrix is most of the time hydrophobic making the adhesion very difficult. In order to overcome this mismatch, the surface of natural fibers can be modified by chemical treatment to increase the compatibility with the resin (Sood and Dwivedi, 2018).

Possible treatments are alkali treatment, isocyanate treatment, peroxide treatment, vinyl grafting, acetylation, and treatment with coupling agents. Alkali treatment removes fiber constituents such as lignin, wax, oils, and hemicellulose and modifies the cellulose surface via following reaction:

$$\text{Cellulose-OH} + \text{NaOH} \rightarrow \text{Cellulose-O}^{-}\text{Na}^{+} + \text{H}_2\text{O}$$

The effect on the fiber is an increased roughness what results in a better interlocking and an increase of the amount of cellulose at the fiber surface meaning that more reaction sites are available (Li et al., 2007). An increase of

30% in tensile properties is possible for alkali treated flax/epoxy composites (de Weyenberg et al., 2003). Also, Mishra et al. (2003) reported that a 5% sodium hydroxide (NaOH) concentration results in better strength than when the fibers are treated with a 10% solution. The higher amount of NaOH seems to damage the fiber.

Isocyanates can react with the hydroxyl groups of the natural fiber to form a urethane binding. Strong covalent bonds are formed and improve the compatibility between fiber and matrix (Mohanty et al., 2001). Peroxides form radicals rapidly, which can react with the hydrogen atoms of the hydroxyl groups of the cellulose fibers. Examples of peroxides that are used are benzoyl peroxide and dicumyl peroxide. By treating sisal fibers with benzoyl peroxide and dicumyl peroxide, the tensile strength of sisal LDPE composites increases with increase in concentration of the peroxide up to 4% for dicumyl peroxide and up to 6% of benzoyl peroxide (Joseph et al., 1996).

A vinyl grafting was done by Mohanty et al. by subjecting jute fabrics to a graft graft-copolymerization with methyl methacrylate and acrylonitrile using $CuSO_4-KIO_4$ combination as initiator in the aqueous medium. Among the methyl methacrylate and acrylonitrile grafted samples, a 10% AN-grafted material shows the highest improvement of mechanical properties (Mohanty et al., 2000).

Acetylation is an esterification of the cellulose fibers.

$$\text{Cellulose-OH} + CH_3{-}C(=O){-}O{-}C(=O){-}CH_3 \text{ - > Cellulose-}OCOCH_3 + CH_3COOH$$

Hydrophilic OH groups are replaced by acetyl groups making the fiber more hydrophobic and this improves the dimensional stability of the composites (Bledzki et al., 2008).

Coupling agents are frequently used to improve the compatibility between natural fibers and organic matrices. To be compatible with PP, fibers can be treated with maleic anhydride grafted polypropylene (MAPP) providing covalent bonds at the interface. After this treatment, an increase of about 72% in flexural strength can be achieved compared to nontreated jute/PP composites (Mohanty et al., 2004). Silane coupling agents are used in the glass fiber industry to improve the adhesion with organic matrices. Silane coupling agent forms in water silanol groups which can react with the OH groups of the glass fibers. The organic functional group can interact with the matrix. As natural fibers contain OH groups the same process can be applied:

$$\text{RSi(OR')3} + \text{H2O - > RSi(OH)}_3 + 3\ \text{R'OH (with R' = methyl, ethyl)}$$

$$\text{Cellulose-OH} + \text{RSiOH3 - > Cellulose-OSiR} + \text{H2O}$$

The R group can contain different functional groups and depending on the functionality they can couple different matrices. An overview is given in the Table 10.2 below:

From the table, it is clear that silane can be used to couple a lot of organic resins, but it is important to select the right silane to achieve a good interaction.

TABLE 10.2 Compatibility between functionalized silanes and organic resin. ++ means a very good compatibility (Shin-Etsu, 2017).

	Thermoplastic										Thermoset					
Resin funtional group	**PE**	**PP**	**PS**	**Acrylic**	**PVC**	**PC**	**PA**	**PU**	**PET**	**ABS**	**Phenolic**	**Epoxy**	**PU**	**Polyimide**	**Unsaturated polyester**	**Furan**
Vinyl	++	++													+	
Epoxy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Styryl			+	+												
Methacryloxy	++	++	++	+		+		+		++					++	
Acryloxy	+	+	+	+		+		+		++					++	
Amino	+	+	++	++	++	+	++	+	+	+	++	++	+	+		++
Ureide							++				+		+	+		
Mercapto	+	+	+		+			+		+	+	+	+			
Isocyanate						+	+	++	+	+	+	+	++	+		+

Xie et al. wrote a comprehensive review about silane coupling agents used for natural fiber/polymer composites. In the report, it is mentioned that a proper treatment of fibers with silanes can increase the adhesion between fiber and matrix and improves the mechanical and outdoor performance of the resulting composites (Xie et al., 2010).

10.2.4 Bio-based composites

Bio-based composites can be prepared via traditional composite manufacturing techniques such as:

- Injection molding: a fast, high-volume closed molding process suitable for short fibers and thermoplastic matrices.
- Hand lay-up: this is a simple processing method, but needs skilled operators to obtain good-quality composites. A gel coat is first applied to the mold and afterward fiber reinforcements are placed in the mold. The thermoset resin is poured on the reinforcement and distributed by brushing or using paint rollers or squeezes. This process is repeated till the desired thickness is obtained. Curing occurs usually at room temperature.
- Resin transfer molding (RTM): the fiber reinforcement is placed in a closed mold and the liquid resin is injected by pressure. This method is suitable to produce complex parts with smooth finishes.
- Vacuum infusion or vacuum assisted (VA) RTM: fiber reinforcements are placed in a mold and are covered with a vacuum foil. The resin is driven into the laminate by vacuum force. This method is normally used to produce large structures.
- Pultrusion: this is a continuous process in which continuous fibers, rovings, or mats are impregnated with resin and pulled through a steel die.
- Compression molding: fiber reinforcements and matrix are already mixed in the right concentrations and are placed in a heated mold. The resin, if thermoset, is cured or reshaped when thermoplastic, under pressure.

However, when using natural fibers, the temperature should not be higher than 180°C to avoid degradation of the fibers and a predrying step is recommended to remove the absorbed moisture as this negatively influences the interaction between fiber and matrix (Venkateshwaran et al., 2013).

The fibers can be used as such or arranged in a network forming nonwovens (Fig. 10.5), unidirectional preforms (Fig. 10.6), or woven structures such as twill (Fig. 10.7) or plain weaves (Fig. 10.8).

Although there exist already several publications on bio-based composites with natural fibers (see reviews of Elanchezhian et al., 2018; Ku et al., 2011; Li et al., 2007; Mohammed et al., 2015; Pickering et al., 2016; Sood and Dwivedi, 2018), reports of composites consisting of a bio-based fiber and resin are rather rare probably due to the immaturity and limited availability of high-quality matrices.

FIGURE 10.5 Jute nonwoven.

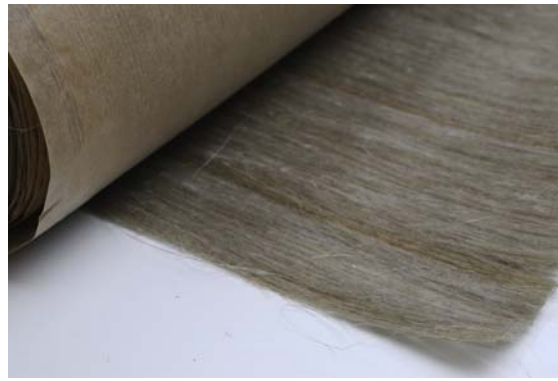

FIGURE 10.6 UD flax tape.

FIGURE 10.7 Flax twill weave.

FIGURE 10.8 Flax plain (basket) weave.

Table 10.3 shows the different manufacturing methods and mechanical properties of different composite materials with bio-based fibers and matrices. Also, the tensile properties of two non-bio-based reference composites (i.e., glass and carbon fiber) are presented to compare their properties with the bio-based composites.

The results from the table show that there are some differences in the tensile properties of the bio-based composites not only due do the use of different fibers or matrices, but also by differences in manufacturing method and fiber volume content. As fiber volume content increases, the tensile properties should also increase until there is not enough resin to distribute the load to the fibers or there must be a mismatch between fiber and matrix. When comparing the tensile properties of the bio-based composites with glass nonwoven composites prepared by hand lay-up better result can be obtained and thus biocomposites can offer a more sustainable alternative. However, the UD glass example shows that much higher strengths can be obtained with glass composites, meaning that bio-based fibers can only match with the stiffness of glass fibers which was already clear from Table 10.1. Compared to carbon composites, the current biocomposites cannot offer the same performance regarding the tensile properties.

10.2.5 Applications

The green image of bio-based composites (CO_2 emission reduction) makes, rather than their technical performance or price, them to be used in applications like automotive, construction, packaging, and consumer goods. For automotive, the main motivations are weight reduction (about 10%−30%), day-to-day fuel efficiency, and CO_2 emission reduction. Parts that are made are door and instrument panels, body panels, underbody panels, roof tops, and front-end fenders. Manufacturers that incorporated bio-based composites are,

TABLE 10.3 Tensile properties of different bio-based fibers and three non-bio-based references.

Bio-based reinforcement	Bio-based resin	Treatment	Fiber volume fraction	Manufacturing method	Tensile strength (MPa)	Tensile modulus (GPa)	References
Flax unidirectional	Epoxy	/	32.1	VARTM	/	18	Schuster et al. (2014)
Flax unidirectional	Polyester	/	41.1	VARTM	/	13	Schuster et al. (2014)
Flax UD	Epoxy	/	30	Resin infusion	150	16	Michelena et al. (2015)
Hemp plain weave	Epoxy	/	40	RTM	63	5.8	Di Landro and Janszen (2014)
Flax woven	Epoxy	/	/	VARTM	80	1.2	Bertomeu Perelló et al. (2012)
Flax UD (cross- ply lay up [0/90]S)	PFA	/	/	Compression molding	64	8.5	Giannis et al. (2008)
Flax UD + nonwoven	Epoxy	/	/	Compression molding	185	14	Brighton et al. (2015)
Flax UD + nonwoven	Epoxy	Silane (1%)	/	Compression molding	178	12	Brighton et al. (2015)
Flax UD + nonwoven	Epoxy	Alkali (5%)	/	Compression molding	175	11	Brighton et al. (2015)
Flax fiber bundles	PPolyester	/	40	VARTM	140	6	Haag et al. (2017)
Kenaf fiber bundle	PLA	/	70	Compression molding	223	23	Ochi (2008)

Continued

TABLE 10.3 Tensile properties of different bio-based fibers and three non-bio-based references.—cont'd

Bio-based reinforcement	Bio-based resin	Treatment	Fiber volume fraction	Manufacturing method	Tensile strength (MPa)	Tensile modulus (GPa)	References
Hemp short fiber	PLA	/	30	Compression molding	41	5.6	Hu and Lim (2007)
Hemp short fiber	PLA	/	40	Compression molding	45	7.4	Hu and Lim (2007)
Hemp short fiber	PLA	/	50	Compression molding	44	7	Hu and Lim (2007)
Hemp short fiber	PLA	Alkali (6%)	30	Compression molding	39	7.6	Hu and Lim (2007)
Hemp short fiber	PLA	Alkali (6%)	40	Compression molding	54	8.5	Hu and Lim (2007)
Hemp short fiber	PLA	Alkali (6%)	50	Compression molding	42	7	Hu and Lim (2007)
Flax twill	PLA	/	40	Compression molding	110	14	Biotex (2018)
Flax nonwoven	PHB	/	20	Compression molding	30	4	Barkoula et al. (2010)
Flax nonwoven	PHB	/	30	Compression molding	30	7	Barkoula et al. (2010)
Flax nonwoven	PHB	/	40	Compression molding	40	8.5	Barkoula et al. (2010)

Kenaf nonwoven	PLA	/	70	Wet impregnation	60	6.4	Nishino et al. (2003)
Flax short fibers	PLA	/	28	Compression molding	53	8.3	Oksman et al. (2003)
Kenaf carded	PLA	/	35	Compression molding	53	7.1	Graupner and Müssig (2011)
Hemp carded	PLA	/	35	Compression molding	58	8.1	Graupner and Müssig (2011)
PLA UD	PLA	/	/	Compression molding	107	6.2	Goutianos et al. (2019)
Cellulose fibers	PA	/	/	Pultrusion	120	5	Feldmann and Bledzki (2014)
Ramie plain woven	PLA	Cyclic loading	/	Compression molding	77	11	Zhou et al. (2013)
Glass nonwoven	Polyester	/	19	Hand lay-up	99	4	Varga et al. (2010)
Glass UD	Epoxy	/	30	Hand lay-up	432	18	Ekşi and Genel (2017)
Carbon UD	Epoxy	/	48	Vacuum bagging	1059	80	Rahmani et al. (2014)

for example, Ford, Opel, Daimler Chrysler, BMW, Fiat, Audi, Peugeot, Renault, Mercedes Benz, and Volvo (Campaner et al., 2010).

In the construction sector, bio-based composites can be used for decking, railing systems, window frames, fencing, and panels (Ariadurai, 2012). Further, researchers of the TU Eindhoven developed a pedestrian bridge made of a PLA core and skins made of flax and hemp combined with a bio-based epoxy matrix (Lepelaar et al., 2016).

Besides the green image, the good demping properties and looks of natural fiber composites make them attractive for designers to create consumer and sporting goods. This includes tennis rackets, surfboards, skis and ski pole, bicycles, archers, woofer cones, helmets, scooters, guitars, trays, and chairs (Pil et al., 2016).

10.2.6 Tendency: looking for sustainable bio-based carbon fibers

It is clear that natural fibers and PLA fibers can compete with glass fibers or thermoplastic fibers as more sustainable alternative to make composites, but their mechanical properties are far below that of carbon fiber (tensile modulus: 230−600 GPa, tensile strength 3000−6000 MPa) meaning that it is not possible to use them in high performance composite materials.

On the other hand, the most commonly applied technique to produce carbon fibers starts from polyacrylonitrile (PAN), a polymer synthesized from crude oil. Through a wet spinning process, this polymer is converted into a precursor fiber. The precursor fiber is then subjected to three processes, all under controlled conditions: stabilization, carbonization, and graphitization. The stabilization process is performed in an oxygen atmosphere at 200−300°C. This process converts thermoplastic PAN to a nonplastic cyclic or a ladder compound. After stabilization, the fibers are carbonized in an inert atmosphere up to 1000°C. To further enhance the orientation of the crystallites, the fiber can undergo a graphitization process at 1500−3000°C (Rahaman et al., 2007).

From an environmental point of view, this production process could be improved in several ways: from the natural resources (crude oil) to the wet-spinning process (based on solvents) and the energy-consuming stabilization, carbonization, and graphitization steps.

Therefore, research is going on to reduce the cost and the dependence on fossil sources by looking at biomass-derived precursors. One of these research projects is the H2020 project LIBRE (LIBRE − Lignin Based Carbon Fibers for Composites, 2019).

First aspect targeted by LIBRE is the natural resource: instead of fossil-based PAN, the project uses blends from modified lignin and biopolymers. Lignin is a constituent of wood, forming the glue that holds cellulose and the hemicellulose together. Hence, it is also a valuable byproduct of the paper and pulp industry, produced in quantities exceeding 50 million tons annually. For now, the majority of this byproduct disposed as low-cost fuel. However, it has a large potential for

value-added products, for example, carbon fibers. Next aspect in LIBRE is the spinning process: instead of solvent-based wet-spinning, the lignin blends are converted into precursor fibers through melt-spinning. Finally, the project also targets the energy-consuming heat treatment steps: using microwave and radio frequency (MW/RF) heating technologies, it is possible to reduce energy use and greenhouse gas emissions during the manufacturing process.

Other bio-based carbon fiber precursors, besides lignin, that are investigated are glycerol and lignocellulosic sugars (Milbrandt and Booth, 2016). However, a technical report from Milbrandt and Booth concluded that currently no biomass-based carbon fiber has been developed with the required properties to be used in aerospace, wind, and automotive applications (Milbrandt and Booth, 2016). So, further research is necessary to find bio-based carbon fibers that can compete with the non-bio-based carbon fibers qua performance and cost.

10.3 Coating and finishing

In order to impart the required functional properties to a fabric, the material is subjected to physical and chemical treatments. Coating and finishing refers to the processes performed after dyeing the fabric. Coating can be defined as applying a polymer or elastomer (in viscous or solid form) directly to the surface of a fabric and drying and curing it, if necessary. Several coating layers may be applied, resulting in better performance (Smith, 2018). A process related to coating is finishing, in which a chemical or polymer covers only the yarns and not the whole fabric. In fabric coating the small holes in between the individual yarns are covered (Fung, 2002). Some coating and finishing technologies will be shortly discussed hereafter.

Fabric finishing is usually performed by a padding or impregnation process. This process step is commonly used in textile industry to impart among others water and oil repellency, softening, or easy-care properties to a textile. During padding (also called foulard) a textile is impregnated with functional additives and a binder via immersion in a solution (often water-based). The solution contains a specific concentration of additives and binder. The concentration of these products depends of the desired effect and the wet pick-up of the textile. After the textile is immersed in the solution, the textile is squeezed between two rolls to remove the excess of solution. Fig. 10.9 represents the foulard process.

Liquids can also be sprayed directly onto a textile. Spraying is very well suited to apply low concentrations and for functionalizing delicate fabrics which cannot be padded (e.g., carpet). A concern of spraying is the difficulty to obtain uniform coatings and therefore the spray parameters need to be governed and controlled well (Joshi and Butola, 2013).

Coating is essentially spreading a polymer (in the form of a solid material, viscous dispersion, or viscous solution) onto a fabric to form a continuous layer. The material needs to be viscous so that it does not penetrate through the fabric. Thickening agents need to be added sometimes to increase the viscosity