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# Production and Characterization of Hybrid Polymer Composites Based on Natural Fibers

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Additional information is available at the end of the chapter

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## Abstract

In this chapter, a review is made on the processing and properties of hybrid composites based on a polymer matrix and a blend of different natural (lignocellulosic) fibers. In particular, the processing methods are described and comparisons are made between the general properties with a focus on physical, mechanical and thermal properties. A discussion is presented on the effect of the polymer and fiber types, as well as reinforcement content. Properties improvement is also discussed using fiber surface treatment or the addition of coupling agents. Finally, auto-hybrid composites are presented with conditions leading to a positive deviation from the rule of hybrid mixture (RoHM) model.

**Keywords:** hybrid composites, polymer matrices, natural fibers, fiber concentration, mechanical properties

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## 1. Introduction

Composites are materials containing at least two constituents, each one with different chemical composition. Their combination provides a new material with better functional properties than each of the components separately [1].

The main component in the composite is the matrix, which can be a metal, ceramic or polymer, while the other part is a reinforcement which can be in particulate, laminate, short fiber or long fiber form [2]. Composite materials are widely used in construction, aerospace, aircraft, medicine, electrical and automotive industries [2–5]. Here, a focus is made on fiber reinforced composites made from a polymer matrix reinforced with fibers having a natural origin [6].

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2. Natural fibers

Natural fibers are biosourced materials extracted from plants (lignocellulosic) or animals [7]. Lignocellulosic fibers are produced by plants for which, on a dry basis, the cell walls are mainly composed of cellulose, with hemicelluloses, lignins, pectins and extractives in lower amounts. Chemical composition and distribution mostly depend on fiber source and varies within different parts even of the same type or family [7, 8]. According to their source, lignocellulosic fibers can be classified as bast fibers, leaf fibers, fruits-seeds fibers, grass-reed fibers and wood fibers [7, 9–12]. **Table 1** presents some examples of each category [13].

Fiber type	Characteristics	Examples
Bast	High cellulose content, flexible, obtained from plants phloem	Kenaf, hemp, flax
Seed	Fibers that have grown around seeds	Cotton, kapok
Fruit	Obtained from fruit shells	Coir, oil palm
Stalk	Cereal stalks byproducts	Wheat and corn straw
Grass	Obtained from grass plants	Bamboo, wild cane, esparto grass
Leaf	Obtained by decortication of plants leaves	Banana, sisal, pineapple, agave
Wood	Extracted from flowering and conifers trees	Maple, pine

**Table 1.** Lignocellulosic fibers classification [13].

Due to natural fibers’ strength, stiffness, availability, low cost, biodegradability and lower density (1.2–1.5 g/cm<sup>3</sup>) compared to synthetic fillers such as talc (2.5 g/cm<sup>3</sup>) and glass fiber (2.5 g/cm<sup>3</sup>) [14–16], they can be effectively used in lightweight composites production [8, 9, 17].

3. Natural fiber composites

Natural fiber composites are materials based on a polymer matrix reinforced with natural fibers [9]. The polymer matrix can be a thermoplastic or a thermoset, the main difference being that once thermoplastics are molded they can be remelted and reprocessed by applying heat and shear, while this is not the case for thermosets [14, 15]. But thermoset matrices generally provide higher rigidity and are more chemically stable. This is why they are more difficult to recycle. The main thermoset matrices used for natural fiber composite production are polyester, vinyl ester, phenolic, amino, derived ester and epoxy resins. Thermoset composites are commonly processed via resin transfer molding (RTM), sheet molding compound (SMC), pultrusion, vacuum-assisted resin transfer molding (VARTM) and hand lay-up. All these manufacturing processes do not need high pressure requirements. Another advantage of thermoset matrices is that fiber loading can be higher than for thermoplastics since the resin

is initially in a liquid form. So, lower viscosity improves fibers introduction and dispersion via different mixing equipment [18–22]. Fiber orientation as well as fiber content might improve mechanical properties in thermoset composites. Grass, leaf and bast fibers are more effective to increase the matrix mechanical properties, while surface treatment improves interfacial interactions. **Table 2** summarizes some work on natural fiber thermoset composites with their manufacturing process, fiber content, fiber treatments and fiber source, as well as the main results obtained from each work.

Matrix	Natural fiber source	Manufacturing process	Fiber content (%)	Fiber treatment	Mechanical properties					References
					E (GPa)	TS (MPa)	FM (GPa)	FS (MPa)	IS (J/m)	
Epoxy	Banana	Hand lay-up	10	NaOH solution	0.6–1.4	12.1–33.6	15–34	26–69	2–12	[23]
	Recycled cellulose	RTM	19, 28, 40, 46	–	–	–	0.5–5.5	60–140	5–22	[21]
	Flax	RTM	40–50	–	17.3–33.6	–	–	–	–	[19]
		Hand lay-up	50	–	8.6	–	–	–	–	[24]
		Compression molding and pultrusion	40	NaOH solution	2.7–32	50–283	8–27	0.4–4.1	–	[25]
	Oil palm	Compression molding	5, 10, 15, 20	NaOH solution	–	11–17	–	–	–	[26]
	Hemp	Hand lay-up	30	H <sub>2</sub> PO <sub>3</sub> solution NH <sub>4</sub> OH Geniosil GF-9 Toluene solution aminosilane	3–4.8	49.1–66.5	3–5.2	69–92.8	–	[27]
	Date palm	Hand lay-up	10	NaOH solution	1.5–2.5	10–40	–	–	–	[28]
	Sansevieria cylindrical leaf	Molding	1, 5, 7, 9	NaOH solution	–	98.3–114.9	–	17–26	–	[29]
Polyester	Jute	Hand lay-up	NA	–	–	–	–	–	3.8–4.1	[30]
	Macadamia nut shell	Hand lay-up	10, 20, 30, 40	–	–	–	4.1–4.6	26–38	–	[31]
	Flax	VARTM	20	–	15.3–20.3	188.6–230.7	2.1–2.3	16.3–17.5	–	[32]
	Curaua	RTM	0–40	–	–	–	0.1	–	20–190	[33]
	Wild cane grass	Hand lay-up	0–40	NaOH solution KMnO <sub>4</sub> solution	–	–	1.8–7	–	–	[34]
	Sisal	Mixing and compression molding	10, 20, 30, 40	NaOH solution	–	–	1.49–2.68	–	–	[35]
	Typha leaf	Compression molding	7.3, 10.3, 12.6	NaOH solution Sea water	–	–	3.5–6	25–70	–	[36]

Matrix	Natural fiber source	Manufacturing process	Fiber content (%)	Fiber treatment	Mechanical properties					References
					E (GPa)	TS (MPa)	FM (GPa)	FS (MPa)	IS (J/m)	
	Rice husk	Mixing and compression molding	57	GMAMAHSAH solutions	0.4–1.6	2.5–19	0.1–1.9	3–42	9.5–40	[22]
	Elephant grass	Hand lay-up	30.4, 31.3, 31.5	NaOH KMnO <sub>4</sub> solutions	0.6–2.2	31.5–118.1	–	–	–	[37]
	Bamboo	Mixing and compression molding	NA	H <sub>2</sub> O <sub>2</sub> +DTPA +Na <sub>2</sub> O <sub>3</sub> Si +NaOH solution, IEM +DBTDL	–	39–65	–	75–105	–	[38]
	Coir	Hand lay-up	NA	NaOH solutions	–	17.9–23.6	–	18.7–48	–	[39]
			10, 20, 30	–	–	10.6–15.6	–	25.9–38.5	25.6–161.9	[40]
Polyurethane	Kraft cellulose	Compression molding	5, 10, 15, 20	–	0–0.2	–	–	–	–	[41]
Phenolic	Bagasse	Compression molding	17.6	HClO <sub>2</sub> solution Furfuryl alcohol	–	–	–	–	17–28	[42]
	Curaua	Compression molding	17.6	HClO <sub>2</sub> solution Furfuryl alcohol	–	–	–	–	39–88	[42]
	Cellulose from eucalyptus	Molding	1, 3, 5, 7	NaOH solution, propyl-trimethoxy-silane	0.7–0.9	9.5–16.5	5.1–1.0	18.5–28.0	–	[43]
	Ramie	Compression molding	40.4	–	3.3, 1.2	72.3, 158	–	90–145	–	[44]
	Jute	Pultrusion	N/A	–	–	25–38	–	28–63	–	[45]
Vinyl ester	Bamboo	Compression molding	15	–	21.2–30.1	–	–	210–320	–	[46]
	Silk	Hand lay-up	0–15	–	0.9–1.3	40–71	–	–	–	[47]
	Cellulose	VARTM	20, 30, 40, 50	–	3–7	–	–	40–160	–	[20]
	Sisal	RTM	10, 15, 20, 25, 30	NaOH solution	1.7–2.9	38–75	2.1–4.5	75–180	–	[48]
	Kenaf	Pultrusion	40	–	9–12.5	135–145	1.6–1.9	150–190	–	[49]
	Pineapple leaf	Molding	20	NaOCl solution	–	–	1.9–3.9	68–119	19–105	[50]

E: Tensile modulus; TS: tensile strength; FM: flexural modulus; FS: flexural strength; IS: impact strength; GMA: glycidyl methacrylate; MAH: maleic anhydride; SAH: succinic anhydride; DTPA: diethylenetriaminepenta-acetic acid; IEM: isocyanatoethyl methacrylate; DBTDL: dibutyltin dilaurate.

**Table 2.** Mechanical and thermal properties of natural fiber composites based on thermoset matrices.

The most common thermoplastic matrices used for natural fiber composites production are the different grades of polypropylene (PP) and polyethylene (PE), as well as polycarbonate (PC), nylon (PA), polysulfones (PSU), polyethylene terephthalate (PET) and polystyrene (PS). More recently, biopolymers such as polylactic acid (PLA) have gained interest to produce 100% biosourced materials [51–55]. Typical manufacturing processes for these composites are extrusion, injection, calendering, compression molding and thermoforming. Some advantages of using thermoplastic matrices are their recyclability and the production can be continuous [56–61]. Depending on the matrix, fiber and additives content, fiber treatment and manufacturing process, the mechanical and thermal properties of these composites can be adjusted as presented in **Table 3**, with the main results obtained.

The main objective of adding natural fibers in polymer matrices is to increase mechanical properties regardless of polymer and fiber type [21, 26, 31, 40, 52, 54, 55, 61–68]. Since natural fibers have lower density (1.2–1.5 g/cm<sup>3</sup>) compared to synthetic/inorganic reinforcement such as glass fibers (2.5 g/cm<sup>3</sup>), lightweight composites can be produced [28, 69, 70]. Nevertheless, lignocellulosic fibers are hydrophilic and polar which causes some incompatibility with the most common polymer matrices which are hydrophobic and nonpolar. This effect leads to poor mechanical properties due to a lack of interfacial adhesion between the fibers and the matrix. Furthermore, the high amount of hydroxyl groups available on the fiber surface is increasing water absorption, even when inside a composite [65, 71, 72]. These problems can be resolved by modification of the fibers surface such as mercerization (treatment in sodium hydroxide solution to remove lignins and hemicellulose) with subsequent addition of coupling agents [22, 73–75]. There is also the possibility to combine thermomechanical refining with coupling agent addition [71, 72]. More recently, fiber treatment with a coupling agent in solution has been proposed [76].

Matrix	Fiber source	Processing	Fiber content (%)	Fiber surface treatment	Additive		Mechanical properties					TD (°C)	References
					CA	BA	E (MPa)	TS (MPa)	FM (MPa)	FS (MPa)	IS (J/m)		
HDPE	Flax	Injection molding	0, 15, 30–		–	ACA	220–470	14–24	500–1600	15–26	60–230	–	[66]
	Wood	Compression molding	0–40	Thermo-mechanical refining	MAPE	ACA	–	–	0.9–3.9	–	–	–	[72]
	Wood	Extrusion	20, 30, 40	–	MAPE	–	2300–2900	–	1900–3400	–	–	–	[56]
	Wood	Extrusion	50, 60, 70, 80	–	MAPE	–	3130–4600	11.1–30.2	2470–3370	25.0–58.8	–	–	[77]
	Wood	Injection molding	40	Ethanol and toluene extraction NaClO <sub>2</sub> treatment NaOH solution	MAPE	–	3570–4940	23.8–48	–	–	–	–	[78]

Matrix	Fiber source	Processing	Fiber content (%)	Fiber surface treatment	Additive		Mechanical properties					TD (°C)	References
					CA	BA	E (MPa)	TS (MPa)	FM (MPa)	FS (MPa)	IS (J/m)		
	Wood	Injection molding	25, 35, 45	–	–	–	1200–2000	18.5–27.5	1200–2700	27.5–43	–	–	[59]
	Oil palm	Compression molding	30, 40	–	MAPP	–	650–1050	10–15	–	–	–	–	[65]
	Hemp	Compression molding	0–40	–	–	ACA	–	–	1093–1634	18.8–23	–	–	[55]
	Agave	Injection molding	0–20	–	–	ACA	225–550	15–24	1–2.7	–	–	–	[79]
	Hemp	Compression molding	40	Thermo-mechanical refining	MAPE–MAH	–	–	–	2–2.6	–	–	–	[71]
	Argan nut shell	Injection molding	5, 10, 15, 20, 25	NaOH solution	–	–	1136–1795	27.2–29.3	–	–	–	–	[80]
	UHMWPE	Wood powder molding	0–30	–	–	–	195–280	–	650–1260	–	–	–	[67]
LMDPE	Agave	Rotomolding	5, 10, 15–	–	–	–	255–440	13–18.8	495–590	12.5–16.5	0.9–7.5	–	[81]
	Agave	Rotomolding	15	Solutions of: MAPE NaOH Aldehyde Acrylic acid Methyl methacrylate Silane	–	–	167–217	13–18	420–520	13–17.8	83.8–148.5	–	[76]
	Hemp	Injection molding	30	Solutions of: MAPE NaOH MAPE	MAPE–	–	241–668	13.1–17.9	–	–	–	–	[73]
LLDPE	Maple wood	Rotomolding	0–20	–	–	ACA	26–184	3–16.4	119–680	–	–	–	[52]
	Wood	Injection molding	47	–	MAPP	–	–	30.2	–	–	–	–	[82]
	Agave	Compression molding	0–40	Solutions of: NaOH MAPE	–	–	224–381	10–22	389–1027	14–31	123–260	–	[75]
PS	Agave	Compression molding	10, 20, 30	–	–	ACA	3345–4929	30–62	–	–	–	400	[83]
	Wood fiber	Extrusion	10, 20, 30, 40	MAPS	–	–	–	31–49	–	54–94.5	–	–	[84]
	Wood flour	Extrusion	10, 20, 30, 40	MAPS	–	–	–	31–41.5	–	55–68	–	–	
PP	Argan nut shell	Injection molding	0–30	–	SEBS–g-MA	–	1034–1593	26.5–30	–	–	–	339.4–350	[85]
	Flax	Compression molding	10, 20, 26, 30	–	MAPP–PPAA	–	1000–3200	–	–	–	–	–	[86]



Matrix	Fiber source	Processing	Fiber content (%)	Fiber surface treatment	Additive		Mechanical properties					TD (°C)	References	
					CA	BA	E (MPa)	TS (MPa)	FM (MPa)	FS (MPa)	IS (J/m)			
PLA	Abaca	Injection molding	10, 15, 20, 25	Benzene diazonium treatment, NaOH solution	–	–	800–2700	24.5–31	800–3100	43–55	22.5–50	–	[87]	
	Coir bagasse	Injection molding	5, 10, 15, 20, 25, 30	NaOH solution	–	–	1100–1700	27.5–34.7	1400–2000	35–53	–	–	[88]	
	Wood	Compression molding	10, 20, 30, 40	–	MAPP	–	600–1600	–	2100–2400	44–52	10–17	–	[89]	
	NNC	Compression molding	1	–	MAPP	–	450–663	32.3–39.1	1809–2238	–	–	–	[90]	
	Sisal	Injection molding	10, 20, 30	NaOH solution	MAPP	–	500–1100	23–28	–	–	–	363.2–434.5	[91]	
	Pine cone	Injection molding	5, 10, 15, 20, 25, 30	NaOH solution	SEBS-g-MA SBS	–	1020–1550	21–27.5	–	–	–	321–355	[92]	
	Wood cotton	Compression molding	10, 20, 30	–	MAPP	–	–	28–50	–	37–152	–	–	[93]	
	Flax	Injection molding	15, 25, 40	–	–	–	–	–	2500–6000	–	–	282–340	[54]	
	Maple wood	Injection molding	15, 25, 40	–	–	–	–	–	2400–5900	–	–	282.3–342.7	[62]	
	Maple wood	Injection molding	5, 10, 15, 20, 25	–	–	–	1250–1890	59.8–61.5	3650–5260	96.6–107	21.7–34.3	250–360	[94]	
Post consumer PP+HDPE	Wood	Injection molding	20, 30, 40, 50, 55, 60, 65	–	–	–	–	5270–10300	56.8–64.6	5400–1088	77–91.8	–	–	[58]
	Cotton	Injection molding	10, 20, 30, 40, 50	–	–	–	–	1260–2500	58.1–62.6	3690–8220	97.9–106.2	17.5–24.3	250–360	[94]
	Agave Coir Pine	Injection molding	10, 20, 30	–	–	–	–	1242–1865	43–60	2300–3110	55–96	30–49	–	[95]
	Wood flour	Compression molding	0–40	–	MAPP-MAPE	–	247–394	12.7–15.3	950–1889	–	38–65.6	–	–	[61]
Post consumer HDPE	Wood flour	Compression molding	0–40	–	POE-MAPP-MAPE	–	–	–	1073–1958	16.6–22.4	–	–	–	[96]
	Flax	Injection molding	30	–	MAPP-EO-g-MAH	–	608–579	–	3090–2921	–	–	–	–	[97]
					–	–	332–608	–	1114–3090	–	–	–	–	[98]
														[99]
Post consumer HDPE	Pine wood	Compression molding	30	–	MAPE-CAPE	–	–	21.4–30.6	–	–	–	341.3–342.4	[60]	



Matrix	Fiber source	Processing	Fiber content (%)	Fiber surface treatment	Additive		Mechanical properties					TD (°C)	References
					CA	BA	E (MPa)	TS (MPa)	FM (MPa)	FS (MPa)	IS (J/m)		
Post consumer PP	Bagasse	Compression molding	30	–		TDM MAPE– CAPE TDM	– – –	22.3– 36.1	– –	– –	– –	348.5– 353.3	[60]
	Wood	Compression molding	50, 60	–		MAPE–	–	9–18	–	–	20– 35	–	[100]
	Wood	Extrusion	–	–		MAPP–	450– 490	27.3– 29.8	2230– 2940	43–51	–	285– 499	[101]
	Oil palm	Extrusion	–	–		MAPP–	340– 380	18.7– 19	1870– 2150	30.1– 33.8	–	268– 495	[101]

CA: coupling agent; BA: blowing agent; TD: thermal degradation; ACA: Azodicarbonamide; MAPE: Maleic anhydride-grafted polyethylene; MAPP: maleic anhydride-grafted polypropylene; MAH: maleic anhydride, SEBS-g-MA: styrene-(ethylene-octene)-styrene triblock copolymer grafted with maleic anhydride; PPAA: acrylic acid grafted polypropylene; POE: ethylene-octene copolymer; EO-g-MAH: maleic anhydride grafted ethylene-octene metallocene copolymer; CAPE: carboxylated polyethylene; TDM: titanium-derived mixture.

**Table 3.** Mechanical and thermal properties of natural fiber composites based on thermoplastic matrices.

Coupling agents are usually copolymers containing functional groups compatible with the fibers (hydroxyl groups) and the polymer matrix [74]. These reactions (chemical or physical) are increasing interfacial adhesion leading to improved mechanical properties and water absorption reduction [22, 65, 71–73, 75, 76, 99, 102, 103]. Coupling agents can be mixed with the polymer matrix by extrusion previously to fibers addition [65, 74, 92] but can also be added during composite compounding, i.e. mixing the matrix, fiber and coupling agent all together [55, 72, 83, 90, 97–99, 102–104]. Likewise, natural fibers can be functionalized by treating them with a coupling agent in solution, to increase compatibility with the polymer matrix [22, 71, 73–76].

Since natural fibers start to degrade at lower temperature (150–275°C) than most polymer matrices (350–460°C) [60, 63, 74, 83, 105], fiber mercerization and coupling agent addition were shown to improve the thermal stability of the fibers and therefore of the final composites [24, 29, 73, 75, 85, 91, 92].

#### 4. Hybrid composites

To improve on the properties of natural fiber composites and/or overcome some of their limitations such as moisture absorption, thermal stability, brittleness and surface quality, the concept of hybrid composite was developed. The idea is to combine natural fibers with other fibers or particulate reinforcements, which can be of natural or synthetic origin such as glass fibers or rubber particles [15, 51, 63, 106–109]. The main purpose of blending different reinforcements is to obtain a material with better properties than using a single reinforcement. Assuming there is no chemical/physical interaction between each type of fibers, the resulting

properties of hybrid composites ( $P_H$ ) should follow the rule of hybrid mixtures (RoHM) given as [106, 110, 111]:

$$P_H = P_{C1}V_{C1} + P_{C2}V_{C2} \quad (1)$$

where  $P_{C1}$  and  $P_{C2}$  are the properties of composite C1 and C2, respectively, while  $V_{C1}$  and  $V_{C2}$  are their respective volume fractions such that:

$$V_{C1} + V_{C2} = 1 \quad (2)$$

Naturally, the model can be generalized for more than two types of reinforcement.

Natural and synthetic reinforcements combination has showed to improve several composite characteristics such as thermal stability [106, 112–114], impact strength [63, 115–117] and water uptake [70, 112–114, 118, 119]. But the combination of two different types of lignocellulosic fibers was shown to control water absorption [53, 103, 110] and increased impact strength [103, 120], especially when using coupling agents.

The final properties of hybrid composites depend are function of different factors [53, 74, 104, 120], and **Table 4** summarizes some of the most important mechanical and thermal properties of hybrid composites based on thermoset matrices. The effect of fiber and matrix type, as well as fiber surface treatment is reported with their mechanical properties and thermal degradation temperature. Similarly, **Table 5** reports the corresponding information for hybrid composites based on thermoplastic matrices. In general, it is observed that combining natural fibers with inorganic reinforcements leads to improved thermal stability and impact strength, as well as higher flexural and tensile moduli. Moreover, **Table 6** shows that water uptake decreases by combining two natural fibers from different sources, or using natural fibers with inorganic reinforcements in hybrid composites based on thermoplastics matrices.

Matrix	Fibers	Manufacturing process	Fiber treatment	Mechanical properties					TD (°C)	References
				E (GPa)	TS (MPa)	FS (MPa)	FM (GPa)	IS (kJ/m <sup>2</sup> )		
Polyester	Hemp/wool	Pultrusion	–	16.84	122.12	180	11	–	–	[18]
	Palmyra palm leaf/jute	Compression molding	NaOH solution	2.3–5.1			15.3–19.3	24.7–36.4	–	[121]
	Banana/sisal	Hand lay-up + compression molding	–	1.1–1.5			2.7–4.2	~16–37	–	[122]
	Coir/silk		NaOH solution		11.4–17.4		37.4–42		–	[123]

Matrix	Fibers	Manufacturing process	Fiber treatment	Mechanical properties					TD (°C)	References
				E (GPa)	TS (MPa)	FS (MPa)	FM (GPa)	IS (kJ/m <sup>2</sup> )		
Epoxy	Oil palm/glass	Compression molding	–	~2.5–5.5	~20–75	~30–138	~1.5–8	~7–16	–	[124]
	Banana/kenaf	Hand lay-up	Solutions of: NaOH SLS	–	45–139	75–172.2	–	~15–28	–	[125]
	Ramie/cotton	Compression molding	–	–	24.2–118	–	6.3–27.4	–	–	[126]
	Sisal/roselle	RTM	–	–	30.1–58.7	48.4–63.5	–	1.39–1.41	–	[127]
	Sisal/glass	Hand lay-up	–	–	~78–95	~70–265	~2.1–11	~66–88	–	[128]
	Sisal/jute/glass	Hand lay-up	–	–	111.2–232.1	214.1–308.6	–	–	–	[118]
	Hemp/glass fibers	Hand lay-out + compression molding	NaOH solution	–	–	–	–	–	345	[107]
	Banana/jute	Hand lay-up + compression molding	–	0.6–0.7	16.6–19	57.2–59.8	8.9–9.1	13.44–18.23	376.5–380	[108]
	Banana/sisal	Hand lay-up	–	0.6–0.7	16.1–18.6	57.3–62	8.9–9.3	13.2–17.9	–	[129]
	Jute/bagasse	Hand lay-up	NaOH HCl solution	0.3–0.7	0.6–1.7	6.9–15.9	0.6–1.7	6.9–15.9	438.2–475.9	[109]
Polyurethane	Jute/coir	Hand lay-up	NaOH Cyclohexane/ethanol Furfuryl alcohol	~0.3–0.7	~8.5–35	~39–37	~0.5–1.5	–	–	[130]
	Banana/silica	Hand lay-up	–	6.5–9.1	–	–	–	–	–	[111]
	Sisal/silica	Hand lay-up	–	4.7–6.1	–	–	–	–	–	[111]
Polyurethane	Hemp/wool	Pultrusion	–	18.91	122.66	~142	~12	–	–	[18]
Vinyl ester	Hemp/wool	Pultrusion	–	15.27	112.54	~143	~13	–	–	[18]
	Jute/ramie	VARTM	–	6.7–6.8	6.2–6.7	–	–	18–19	–	[131]
	Coconut/sisal/glass	Molding	–	–	–	–	–	1993–16373	–	[117]

Matrix	Fibers	Manufacturing process	Fiber treatment	Mechanical properties					TD (°C)	References
				E (GPa)	TS (MPa)	FS (MPa)	FM (GPa)	IS (kJ/m <sup>2</sup> )		
	Vetiver/glass	Hand lay-up	NaOH solution	1–2.4	53.2–69.8	97.3–131.9	2–3.6	–	–	[116]
	Jute/vetiver	Hand lay-up	NaOH solution	1.7–1.9	63.3–71.7	114.8–133.1	2.9–3.6	–	–	[116]

E: tensile modulus, TS: tensile strength, FS: flexural strength, FM: flexural modulus, IS: impact strength, TD: thermal degradation.

**Table 4.** Mechanical and thermal properties of natural fiber hybrid composites based on thermoset matrices.

Manufacturing process	Composite	Coupling agent	Filler content (%)	Filler surface treatment	Mechanical properties					TD (°C)	References
					E (MPa)	TS (MPa)	FS (MPa)	FM (GPa)	IS (J/m)		
	PP-glass/ flax fibers	MAPP (5%)	40 (vol)	–	522–629	21.9–25.5	–	–	37.9–49.6	–	[106]
	MAPE-GTR rubber/hemp fiber	–	10, 30, 50, 60	–	120–243	9.8–14.3	–	363–781	139.6–294–239.8	–	[63]
	PP-Kenaf/coir/MMT	MAPP (5%)	30	–	300–360	11–12	–	–	–	–	[132]
	PP-NNC/Maple fibers	MAPP (2%)	21	–	444.9	25.4	–	1735.2	–	–	[104]
	PP-wood/SiO <sub>2</sub>	MAPP (4.5%)	50	–	–	32–45	48–65	2400–3540	–	348	[133]
	PP-wood/CaCO <sub>3</sub>										
	PP-wood/milled glass fibers										
	PP-sisal/glass fibers	MAPP (1%, 2%, 3%)	30	–	41.75–55.1	970–1686	47.4–67.5	1900–2800	59.3–81.6	346–384	[70]
	PP-jute/flax fibers	MAPP (19.12%)	25.96%	PP/jute and MAPP/flax woven fabrics were treated with NaOH solution	29.7–42.6	2437.3–2852.4	50.1–68.8	1399.7–2331.8	–	–	[134]

Manufacturing process	Composite	Coupling agent	Filler content (%)	Filler surface treatment	Mechanical properties					TD (°C)	References
					E	TS	FS	FM	IS		
					(MPa)	(MPa)	(MPa)	(GPa)	(J/m)		
	LDPE-banana/coir fibers	MAPP (5%)	15	Solutions of: NaOH Acetylation bleaching with H <sub>2</sub> SO <sub>4</sub>	36.2–50		29.5–52.4		9.3–13.6	473	[135]
	HDPE-coir/Oil palm fibers	MAPE (2%, 4%)	40	Hot water and soap	8–13.5	550–630	17–27	1570–2380	–	–	[120]
	HDPE-kenaf/pineapple leaf fibers (PALF)	–	40	–	27–30	550–680	23–28	1700–2100	–	–	[110]
	PS-banana/glass fibers	–	20	Solutions of: NaOH Benzoyl chloride PSMA	29–38.8	1462.2–1558.3	7.9–11.3	489.7–698.8	–	–	[136]
Injection + compression	PP-SBR rubber/birch wood	MAPP (3%, 5%)	0–40	–	10.5–25	520–1560	–	–	–	–	[51]
Injection molding	PP-sisal/glass fiber	N/A (3.5%)	10, 20, 30	Boiled in methanol and benzene mixture and with NaOH solution	–	–	–	–	100	190–230	[112]
	PP-sisal/glass fibers	MAPP (3%)	30	–	29.2–31.6	2330–2430	66.7–68.8	4.03–4.14	16.7–20	331.3–464.7	[113]
	RPP-date palm wood/glass fiber	–	30	–	19.5–21	1100–1300	–	–	–	361.8–479.4	[114]
	PP-hemp/glass fibers	MAPP (5%)	40	–	52.5–59	3800–4300	97–101	5000–5400	49–55.4	360–474	[57]
	PP-wood flour/glass fiber	MAPP PP-g-MA POE-g-MA	40	–	28–45.4	–	39.7–62.8	2680–3497	–	345–363	[137]

Manufacturing process	Composite	Coupling agent	Filler content (%)	Filler surface treatment	Mechanical properties					TD (°C)	References
					E	TS	FS	FM	IS		
					(MPa)	(MPa)	(MPa)	(GPa)	(J/m)		
		SBS-g-MA (3%, 6%)									
	PP-wood/kenaf fibers	MAPP (1%)	40	–	39–44	2771–3008	–	–	–	–	[138]
	PLA-kenaf/corn husk	–	30	NaOH solution Sodium lauryl sulfate solution Silane and potassium permanganate	–	1547	–	–	–	–	[139]
	PLA-banana/nano-clay	–	33	–	67	4965–5577	105–108	7715–7725	119–120	295–397	[140]
	HDPE-Pine/agave fibers	MAPE (3%)	20, 30	–	20.5–26.5	415–650	24–32	670–1180	37–47	–	[53]
	HDPE-coir/agave fibers	MAPE (3%)	20, 30	NaOH solution	19.5–25.9	355–500	23.3–31.9	890–1190	42–68	–	[103]
	HDPE-sisal/hemp	MA solution (10%)	25, 30	NaOH solution	15.7–19.2	–	–	–	–	–	[141]
	PP-coir shell/coir fibers	SEBS-g-MA (8%)	20	NaOH solution Benzoyl peroxide solution	26.5–29.5	1050–1300	–	–	–	344–349	[74]
	PLA-banana/sisal fibers	–	30	–	57–79	1700–4100	91–125	4200–5600	–	–	[142]
	PLA-hemp/lyocell	–	40	–	41.4–71.5	4643–7035	–	–	–	–	[143]
	PLA-hemp/kenaf fibers	–	40	–	34.4–61	4920–7039	–	–	–	–	
	HDPE-wood/hollow	–	50	–	26.2–31	3300–3600	–	–	–	–	[119]

Manufacturing process	Composite	Coupling agent	Filler content (%)	Filler surface treatment	Mechanical properties					TD (°C)	References
					E	TS	FS	FM	IS		
					(MPa)	(MPa)	(MPa)	(GPa)	(J/m)		
Extrusion	glass microspheres										
	HDPE-wood/bast fibers	–	60	Vinyl triethoxysilane	42–44	650–700	73–77	4900–5250	–	–	[144]
	HDPE-wood/Kevlar	–	60	Allyl and 3–trimethoxy silyl-propyl	13.8–19.8	3050–4100	24.5–3600	2200–3400	–	–	[145]
Extrusion calendering	PP-jute/glass	–	20, 30, 40	–	42–63	4660–7170	72.8–102.5	3550–5950	–	–	[69]

MAPP: maleic anhydride-grafted PP; MAPE: maleic anhydride-grafted PE; GTR: ground tire rubber; LDPE: low density polyethylene; HDPE: high density polyethylene; PS: polystyrene; SBR: styrene butadiene rubber; RPP: recycled polypropylene; PP-g-GMA: glycidyl methacrylate-grafted PP; POE-g-MA: maleic anhydride-grafted ethylene-octene copolymer; SEBS-g-MA: maleic anhydride-grafted hydrogenated styrene-butadiene-styrene; PLA: polylactic acid.

Table 5. Mechanical and thermal properties of hybrid composites based on thermoplastic matrices.

Matrix	Reinforcements	Observations	References
MAPE	GTR rubber/hemp fiber	GTR decreases water uptake	[63]
PP	Kenaf/coir/MMT	Water uptake is reduced by hybridization	[132]
	Wood/SiO <sub>2</sub>	SiO <sub>2</sub> , CaCO <sub>3</sub> and milled grass decreased water uptake	[133]
	Wood/CaCO <sub>3</sub>		
	Milled glass fibers		
	Hemp/glass fibers	Glass fiber reduced water uptake	[57]
	Wood/glass fibers	Increasing fiber glass weight ratio, water uptake was reduced.	[146]
HDPE	Pine/agave fibers	Pine fiber decreased water uptake in hybrid composites	[53]
	Coir/agave fibers	Coir reduced water uptake in hybrid composites	[103]

PP: polypropylene; HDPE: high density polyethylene; MAPE: maleic anhydride-grafted polyethylene; GTR: ground tire rubber; MMT: montmorillonite.

Table 6. Water uptake in hybrid composites using thermoplastic matrices.

5. Auto-hybrid composites

Composites reinforced with two sizes of the same type of reinforcement are referred to as auto-hybrid composites. As these composites only have a single type of reinforcement, they are



easier to recycle. But most importantly, these materials were shown to exhibit a positive deviation from the RoHM depending on fiber concentration, weight ratio, size and type [64, 102, 147]. Nevertheless, the auto-hybridization effect seems to be more influenced by the total fiber content than coupling agent addition [64, 147]. However, coupling agent addition is always important to improve tensile strength [102]. As total fiber content, fiber type and coupling agent content, all affect the level of deviation from the RoHM, and optimization of these parameters is a new challenging field of research to develop better composite performances. **Table 7** summarizes the limited amount of work on auto-hybrid composites using natural fibers as reinforcement.

Processing	Composite	Coupling agent	Fiber diameter (μm)	Fiber content (%)	Crystallinity index (%)	Main results	References
Injection	PP-hemp fibers	MAPP (3%, 5%)*	Fiber: 300–710 Powder: 45–180	20, 30	–	Hybridization more effective at 20 wt.% reinforcement Optimum weight ratio of 20/80 (powder/fibers) 3% of coupling agent was more efficient Ductility and impact strength decreased with fiber content Tensile and flexural modulus increased with fiber content	[147]
	HDPE-pine fibers	MAPE (3%)	Short fiber: 40–105	10, 20, 30	56.2–61.1	Coupling agent increased tensile strength, and decreased tensile modulus, flexural strength and impact strength of auto-hybrids	[102]
	HDPE-agave fibers		Long fiber: 300–425		53.3–57.4	Total fiber concentration affected hybridization being more effective at 20 and 30 wt.% Higher values of mechanical properties were obtained at 30/70 (short/long) weight ratio (without coupling agent) in auto-hybrids Crystallinity index decreased with coupling agent addition	
	PP-pine fiber – PP-agave fibers	–	Short fiber: 50–212	10, 20, 30	–	Hybridization did not affect flexural and tensile strength Hybridization was more effective at 30/70 (short/	[64]

Processing	Composite	Coupling agent	Fiber diameter (μm)	Fiber content (%)	Crystallinity index (%)	Main results	References
			Long fiber: 300–425			long) and 50/50 (short/long) weight ratio Positive hybridization effect was higher at 20 and 30 wt.% fiber content Impact strength was higher at 20 wt.% with a 30/70 (short/long) weight ratio Water absorption was not affected by fiber size	
Compression molding	LLDPE-maple fibers	MAPE (3%)	Short fibers: 0–45 Medium fibers: 125–250 Long fibers: 355–450	5, 10, 15, 20	13–32	Positive deviation of RoHM at 30/70 (smaller/longer) weight ratio, regardless of fiber size 20 wt.% showed higher RoHM positive deviation and auto-hybridization was more effective Positive deviation of RoHM is affected by fiber size and total fiber content Tensile and flexural modulus increased with fiber content, but not with fiber size Impact strength and torsion modulus of hybrid composites are affected by fiber weight ratio	[148]

\*MAPP was not used in auto-hybrid composites.

Table 7. Overview of the different investigations on auto-hybrid composites based on natural fibers.

6. Conclusion

Natural fibers are now interesting alternative to replace synthetic fibers due their good specific properties (per unit weight). They have been used to develop different composites based on thermoset and thermoplastic matrices. As for any composite, their mechanical, thermal and physical properties are function of the properties of the matrix and the reinforcement, as well as fiber loading, fiber source and manufacturing process. Nevertheless, interfacial conditions are always important to optimize the general properties.

The main disadvantages of using natural fibers are water uptake, low thermal stability, as well as low mechanical properties due to fiber agglomeration and poor interfacial adhesion, especially at high concentration. The problem is usually more important in thermoplastics than

thermosets due to their difference in initial resin viscosity. But most of the limitations associated to natural fiber composites can be controlled or overcome by the addition of coupling agents and/or fiber surface modifications.

Finally, another possibility to improve the properties of natural fiber composites is to add a second reinforcement to produce hybrid composites. These materials were shown to have improved mechanical and thermal properties over neat natural fiber composites as they follow the rule of hybrid mixture (RoHM) regardless of the matrix, manufacturing processing and fiber combination. Based on this concept, different class of materials was also developed such as all natural fiber hybrid composites (combination of two different natural fibers) and auto-hybrid composites (combination of two different sizes of the same fiber). The latter is highly interesting as positive deviations from the RoHM were reported. This is usually the case around 20 wt.% of total fiber content with around 30/70 short/long fiber ratio regardless of coupling agent addition, fiber type and processing method. This opens the door to a new field of investigation as several parameters can be controlled to optimize the final properties of the materials and to design new applications for these multi-functional composites.

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## References

- [1] Josmin PJ, Kuruvilla J. Advances in polymer composites: Macro-and microcomposites-state of the art, new challenges, and opportunities. In: Jose JP, Malhotra SK, Thomas S, Kuruvila J, Goda K, Sreekala MS, editors. *Polymer Composites*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA; 2012. p. 1–16. DOI: 10.1002/9783527645213.ch1

- [2] Wang RM, Zheng SR, Zheng YP. Introduction to polymer matrix composites. In: Wang RM, Zheng SR, Zheng YP, editors. *Polymer Matrix Composites and Technology*. Cambridge, UK; Sawston: Elsevier; 2011. p. 1-25. DOI: 10.1533/9780857092229.1
- [3] Naebe M, Abolhasani MM, Khayyam H, Amini A, Fox B. Crack damage in polymers and composites: A review. *Polym Rev.* 2016; 56:31–69. DOI: 10.1080/15583724.2015.1078352
- [4] Yan L, Kasal B, Huang L. A review of recent research on the use of cellulosic fibres, their fibre fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering. *Compos Part B Eng.* 2016;92:94–132. DOI: 10.1016/j.compositesb.2016.02.002
- [5] Scholz M-S, Blanchfield JP, Bloom LD, Coburn BH, Elkington M, Fuller JD, et al. The use of composite materials in modern orthopaedic medicine and prosthetic devices: A review. *Compos Sci Technol.* 2011;71:1791–803. DOI: 10.1016/j.compositesb.2016.02.002
- [6] Wang J, Gangarao H, Liang R, Liu W. Durability and prediction models of fiber-reinforced polymer composites under various environmental conditions : A critical review. *J Reinf Plast Compos.* 2015;35:179–211. DOI: 10.1177/0731684415610920
- [7] Kicińska-Jakubowska A, Bogacz E, Zimniewska M. Review of natural fibers. Part I—vegetable fibers. *J Nat Fibers.* 2012;9:150–67. DOI: 10.1080/15440478.2012.703370
- [8] Fuqua MA, Huo S, Ulven CA. Natural fiber reinforced composites. *Polym Rev.* 2012;52:259–320. DOI: 10.1080/15583724.2012.705409
- [9] Mohammed L, Ansari MNM, Pua G, Jawaid M, Islam MS. A review on natural fiber reinforced polymer composite and its applications. 2015;2015:1-15. DOI: 10.1155/2015/243947
- [10] Faruk O, Bledzki AK, Fink HP, Sain M. Biocomposites reinforced with natural fibers: 2000-2010. *Prog Polym Sci.* 2012;37:1552–96. DOI: 10.1016/j.progpolymsci.2012.04.003
- [11] Jayavani S, Harekrishna D, Varghese TO, Nayak SK. Recent development and future trends in coir fiber reinforced green polymer composites: Review and evaluation. *Polym Compos.* DOI: 10.1002/pc.23529
- [12] Sathishkumar T, Naveen J, Satheeshkumar S. Hybrid fiber-reinforced polymer composites— A review. *J Reinf Plast Compos.* 2014;33:454–71. DOI: 10.1177/0731684413516393
- [13] Gurunathan T, Mohanty S, Nayak SK. A review of the recent developments in biocomposites based on natural fibres and their application perspectives. *Compos Part A Appl Sci Manuf.* 2015;77:1–25. DOI:10.1016/j.compositesa.2015.06.007
- [14] Yan L, Chouw N, Jayaraman K. Flax fibre and its composites - A review. *Compos. A review of recent research on the use of cellulosic fibres, their fibre fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering. Compos Part B Eng.* 2016;92:94–132.doi:10.1016/j.compositesb.2016.02.002

- [15] Zhang Y, Li Y, Ma H, Yu T. Tensile and interfacial properties of unidirectional flax/glass fiber reinforced hybrid composites. *Compos Sci Technol*. 2013;88:172–7. DOI:10.1016/j.compscitech.2013.08.037
- [16] Nekhlaoui S, Essabir H, Kunal D, Sonakshi M, Bensalah MO, Bouhfid R, et al. Comparative study for the talc and two kinds of moroccan clay as reinforcements in polypropylene-SEBS-g-MA matrix. *Polym Compos*. 2014;36:675–84. DOI 10.1002/pc.22986
- [17] Koronis G, Silva A, Fontul M. Green composites: A review of adequate materials for automotive applications. *Compos Part B Eng*. 2013;44:120–7. DOI:10.1016/j.compositesb.2012.07.004
- [18] Peng X, Fan M, Hartley J, Al-Zubaidy M. Properties of natural fiber composites made by pultrusion process. *J Compos Mater*. 2011;46:237–46. DOI: 10.1177/0021998311410474
- [19] Poilâne C, Cherif ZE, Richard F, Vivet A, Ben Doudou B, Chen J. Polymer reinforced by flax fibres as a viscoelastoplastic material. *Compos Struct*. 2014;112:100–12. DOI: 10.1016/j.compstruct.2014.01.043
- [20] Alhuthali A, Low IM. Mechanical properties of cellulose fibre reinforced vinyl-ester composites in wet conditions. *J Mater Sci*. 2013;48:6331–40. DOI: 10.1007/s10853-013-7432-4
- [21] Alamri H, Low IM. Mechanical properties and water absorption behaviour of recycled cellulose fibre reinforced epoxy composites. *Polym Test*. 2012;31:620–8. DOI: 10.1016/j.polymertesting.2012.04.002
- [22] Rozman HD, Musa L, Abubakar A. Rice husk-polyester composites: The effect of chemical modification of rice husk on the mechanical and dimensional stability properties. *J Appl Polym Sci*. 2005;97:1237–47. DOI 10.1002/app.21268
- [23] Venkateshwaran N, Elaya Perumal A, Arunsundaranayagam D. Fiber surface treatment and its effect on mechanical and visco-elastic behaviour of banana/epoxy composite. *Mater Des*. 2013;47:151–9. DOI: 10.1016/j.matdes.2012.12.001
- [24] Gindl-Altmutter W, Keckes J, Plackner J, Liebner F, Englund K, Laborie MP. All-cellulose composites prepared from flax and lyocell fibres compared to epoxy-matrix composites. *Compos Sci*. 2012;72:1304–9. DOI: 10.1016/j.compscitech.2012.05.011
- [25] Van de Weyenberg I, Chi Truong T, Vangrimde B, Verpoest I. Improving the properties of UD flax fibre reinforced composites by applying an alkaline fibre treatment. *Compos Part A Appl Sci Manuf*. 2006;37:1368–76. DOI: doi:10.1016/j.compositesa.2005.08.016
- [26] Bakri MK Bin, Jayamani E, Heng SK, Hamdan S. Reinforced oil palm fiber epoxy composites: An investigation on chemical treatment of fibers on acoustical, morphological, mechanical and spectral properties. *Mater Today Proc*. 2015;2:2747–56. DOI: 10.1016/j.matpr.2015.07.266



- [27] Szolnoki B, Bocz K, Soti PL, Bodzay B, Zimonyi E, Toldy A, et al. Development of natural fibre reinforced flame retarded epoxy resin composites. *Polym Degrad Stab.* 2015;119:68–76. DOI: 10.1016/j.polymdegradstab.2015.04.028
- [28] Abdal-hay A, Suardana NPG, Jung DY, Choi K-S, Lim JK. Effect of diameters and alkali treatment on the tensile properties of date palm fiber reinforced epoxy composites. *Int J Precis Eng Manuf.* 2012;13:1199–206. DOI: 10.1007/s12541-012-0159-3
- [29] Ashok Kumar M, Hemachandra Reddy K, Ramachandra Reddy G, Vishnu Mahesh KR. Characterization of light weight epoxy composites from short *Sansevieria Cylindrica* fibers. *Fibers Polym.* 2012;13:769–74. DOI: 10.1007/s12221-012-0769-5
- [30] Dobah Y, Bouchak M, Bezazi A, Belaadi A, Scarpa F. Multi-axial mechanical characterization of jute fiber/polyester composite materials. *Compos Part B Eng.* 2016;90:450–6. DOI: 10.1016/j.compositesb.2015.10.030
- [31] Dong C, Davies IJ. Flexural properties of macadamia nutshell particle reinforced polyester composites. *Compos Part B Eng.* 2012;43:2751–6. DOI: 10.1016/j.compositesb.2012.04.035
- [32] Fuentes CA, Ting KW, Dupont-Gillain C, Steensma M, Talma AG, Zuijderduin R, et al. Effect of humidity during manufacturing on the interfacial strength of non-pre-dried flax fibre/unsaturated polyester composites. *Compos Part A Appl Sci Manuf.* 2016;84:209–15. DOI: 10.1016/j.compositesa.2016.01.023
- [33] Monteiro SN, Lopes FPD, Nascimento DCO, da Silva Ferreira A, Satyanarayana KG. Processing and properties of continuous and aligned curaua fibers incorporated polyester composites. *J Mater Res.* 2013;2:2–9. DOI: 10.1016/j.jmrt.2013.03.006
- [34] Prasad AVR, Rao KM, Gupta AVSSKS, Reddy B V. A Study on flexural properties of wildcane grass fiber-reinforced polyester composites. *J Mater Sci.* 2011;46:2627–34. DOI 10.1007/s10853-010-5117-9
- [35] Wu CS, Yen FS, Wang CY. Polyester/natural fiber biocomposites: Preparation, characterization, and biodegradability. *Polym Bull.* 2011;67:1605–19. DOI 10.1007/s00289-011-0509-9
- [36] Sana R, Foued K, Yosser BM, Mounir J, Slah M, Bernard D. Flexural properties of typha natural fiber-reinforced polyester composites. *Fibers Polym.* 2015;16:2451–7. DOI: 10.1007/s12221-015-5306-x
- [37] Rao KMM, Prasad AVR, Babu MNVR, Rao KM, Gupta AVSSKS. Tensile properties of elephant grass fiber reinforced polyester composites. *J Mater Sci.* 2007;42:3266–72. DOI 10.1007/s10853-006-0657-8
- [38] Liu W, Chen T, Wen X, Qiu R, Zhang X. Enhanced mechanical properties and water resistance of bamboo fiber-unsaturated polyester composites coupled by isocyanatoethyl methacrylate. *Wood Sci Technol.* 2014;48:1241–55. DOI 10.1007/s00226-014-0668-6

- [39] Jayabal S, Sathiyamurthy S, Loganathan KT, Kalyanasundaram S. Effect of soaking time and concentration of NaOH solution on mechanical properties of coir-polyester composites. *Bull Mater Sci.* 2012;35:567–74. DOI: 10.1007/s12034-012-0334-2
- [40] Jayabal S, Natarajan U. Influence of fiber parameters on tensile, flexural, and impact properties of nonwoven coir-polyester composites. *Int J Adv Manuf Technol.* 2011;54:639–48. DOI: DOI 10.1007/s00170-010-2969-8
- [41] Hadjadj A, Jbara O, Tara A, Gilliot M, Malek F, Maafi EM, et al. Effects of cellulose fiber content on physical properties of polyurethane based composites. *Compos Struct.* 2015;135:217–23. DOI: 10.1016/j.compstruct.2015.09.043
- [42] Trindade WG, Hoareau W, Megiatto JD, Razera IAT, Castellan A, Frollini E. Thermoset phenolic matrices reinforced with unmodified and surface-grafted furfuryl alcohol sugar cane bagasse and curaua fibers: Properties of fibers and composites. *Biomacromolecules.* 2005;6:2485–96. DOI: 10.1021/bm058006+
- [43] Rojo E, Alonso MV, Olier M, Del Saz-Orozco B, Rodriguez F. Effect of fiber loading on the properties of treated cellulose fiber-reinforced phenolic composites. *Compos Part B Eng.* 2015;68:185–92. DOI: 10.1016/j.compositesb.2014.08.047
- [44] Wang H, Xian G, Li H, Sui L. Durability study of a ramie-fiber reinforced phenolic composite subjected to water immersion. *Fibers Polym.* 2014;15:1029–34. DOI 10.1007/s12221-014-1029-7
- [45] Singh B, Gupta M. Performance of pultruded jute fibre reinforced phenolic composites as building materials for door frame. *J Polym Environ.* 2005;13:127–37. DOI: 10.1007/s10924-005-2944-x
- [46] Xie J, Qi J, Hu T, De Hoop CF, Hse CY, Shupe TF. Effect of fabricated density and bamboo species on physical–mechanical properties of bamboo fiber bundle reinforced composites. *J Mater Sci.* 2016;51:7480–90. DOI 10.1007/s10853-016-0024-3
- [47] Ravindra Rama S, Rai SK. Performance analysis of waste silk fabric-reinforced vinyl ester resin laminates. *J Compos Mater.* 2011;45:2475–80. DOI: 10.1177/0021998311401097
- [48] Mahato K, Goswami S, Ambarkar A. Morphology and mechanical properties of sisal fibre/vinyl ester composites. *Fibers Polym.* 2014;15:1310–20. DOI 10.1007/s12221-014-1310-9
- [49] Fairuz AM, Sapuan SM, Zainudin ES, Jaafar CNA. The effect of gelation and curing temperatures on mechanical properties of pultruded kenaf fibre reinforced vinyl ester composites. *Fibers Polym.* 2015;16:2645–51. DOI 10.1007/s12221-015-5535-z
- [50] Mohamed AR, Sapuan SM, Khalina A. Mechanical and thermal properties of josapine pineapple leaf fiber (PALF) and PALF-reinforced vinyl ester composites. *Fibers Polym.* 2014;15:1035–41. DOI 10.1007/s12221-014-1035-9



- [51] Kakroodi AR, Leduc S, González-Núñez R, Rodrigue D. Mechanical properties of recycled polypropylene/SBR rubber crumbs blends reinforced by birch wood flour. *Polym Polym Compos*. 2012;20:439–44.
- [52] Raymond A, Rodrigue D. Foams and wood composite foams produced by rotomolding. *Cell Polym*. 2013;32:199–212.
- [53] Perez-Fonseca AA, Robledo-Ortiz JR, Ramirez-Arreola DE, Ortega-Gudino P, Rodrigue D, Gonzalez-Nunez R. Effect of hybridization on the physical and mechanical properties of high density polyethylene-(pine/agave) composites. *Mater Des*. 2014;64:35–43. DOI: 10.1016/j.matdes.2014.07.025
- [54] Teymoorzadeh H, Rodrigue D. Biocomposites of wood flour and polylactic acid : Processing and properties. *J Renew Mater*. 2015;9:1–6.
- [55] Kavianiboroujeni A, Cloutier A, Rodrigue D. Mechanical characterization of asymmetric high density polyethylene/hemp composite sandwich panels with and without a foam core. *J Sandw Struct Mater*. 2015;17:748–65. DOI: 10.1177/1099636215597667
- [56] Migneault S, Koubaa A, Erchiqui F, Chaala A, Englund K, Krause C, et al. Effect of fiber length on processing and properties of extruded wood-fiber/HDPE composites. *J Appl Polym Sci*. 2008;110:1085–92. DOI 10.1002/app.28720
- [57] Panthapulakkal S, Sain M. Injection-molded short hemp fiber/glass fiber-reinforced polypropylene hybrid composites—Mechanical, water absorption and thermal properties. *J Appl Polym Sci*. 2007;103:2432–41. DOI 10.1002/app.25486
- [58] Sykacek E, Hrabalova M, Frech H, Mundigler N. Extrusion of five biopolymers reinforced with increasing wood flour concentration on a production machine, injection moulding and mechanical performance. *Compos Part A Appl Sci Manuf*. 2009;40:1272–82. DOI:10.1016/j.compositesa.2009.05.023
- [59] Bouafif H, Koubaa A, Perré P, Cloutier A. Effects of fiber characteristics on the physical and mechanical properties of wood plastic composites. *Compos Part A Appl Sci Manuf*. 2009;40 :1975–81. DOI:10.1016/j.compositesa.2009.06.003
- [60] Lei Y, Wu Q, Yao F, Xu Y. Preparation and properties of recycled HDPE/natural fiber composites. *Compos Part A Appl Sci Manuf*. 2007;38:1664–74. DOI:10.1016/j.compositesa.2007.02.001
- [61] Kazemi Y, Cloutier A, Rodrigue D. Mechanical and morphological properties of wood plastic composites based on municipal plastic waste. *Polym Compos*. 2013;34:487–93. DOI 10.1002/pc.22442
- [62] Teymoorzadeh H, Rodrigue D. Biocomposites of wood flour and polylactic acid : Processing and properties. *J Biobased Mater Bioenergy*. 2015;9:1–6. doi:10.1166/jbmb.2015.1510 1

- [63] Ramezani Kakroodi A, Kazemi Y, Rodrigue D. Mechanical, rheological, morphological and water absorption properties of maleated polyethylene/hemp composites: Effect of ground tire rubber addition. *Compos Part B Eng.* 2013;51:337–44. DOI: 10.1016/j.compositesb.2013.03.032
- [64] Perez-Fonseca AA, Robledo-Ortiz J, Moscoso-Sanchez FJ, Rodrigue D, Gonzalez-Nunez R. Injection molded self-hybrid composites based on polypropylene and natural fibers. *Polym Compos.* 2014;35:1798–806. DOI 10.1002/pc.22834
- [65] Kakou CA, Arrakhiz FZ, Trokourey A, Bouhfid R, Qaiss A, Rodrigue D. Influence of coupling agent content on the properties of high density polyethylene composites reinforced with oil palm fibers. *Mater Des.* 2014;63:641–9. DOI: 10.1016/j.matdes.2014.06.044
- [66] Tissandier C, Gonzalez-Nunez R, Rodrigue D. Asymmetric microcellular composites: Mechanical properties and modulus prediction. *J Cell Plast.* 2015;50:1–34. DOI: 10.1177/0021955X14528191
- [67] Mahfoudh A, Cloutier A, Rodrigue D. Characterization of UHMWPE/wood composites produced via dry-blending and compression molding. *Polym Compos.* 2013;34:510–6. DOI 10.1002/pc.22455
- [68] Moscoso-Sanchez FJ, Mendizabal E, Jasso-Gastinel CF, Ortega-Gudino P, Robledo-Ortiz JR, Gonzalez-Nunez R, et al. Morphological and mechanical characterization of foamed polyethylene via biaxial rotational molding. *J Cell Plast.* 2015;51:489–503. DOI: 10.1177/0021955X14566207
- [69] Uawongsuwan P, Yang Y, Hamada H. Long jute fiber-reinforced polypropylene composite: Effects of jute fiber bundle and glass fiber hybridization. *J Appl Polym Sci.* 2015;132:1–13. DOI: 10.1002/app.41819
- [70] Nayak SK, Mohanty S. Sisal Glass Fiber Reinforced PP hybrid composites: Effect of MAPP on the dynamic mechanical and thermal properties. *J Reinf Plast Compos.* 2009;29:1551–68. DOI: 10.1177/0731684409337632
- [71] Fang H, Zhang Y, Deng J, Rodrigue D. Effect of fiber treatment on the water absorption and mechanical properties of hemp fiber/polyethylene composites. *J Appl Polym Sci.* 2013;127:942–9. DOI: 10.1002/app.37871
- [72] Tissandier C, Zhang Y, Rodrigue D. Effect of fibre and coupling agent contents on water absorption and flexural modulus of wood fibre polyethylene composites. In: Altstädt V, Keller J-H, Fathi A, editors. *Proceedings of PPS-29: The 29th International Conference of the Polymer Processing Society.* Nuremberg, Germany: AIP Publishing; 2014. p. 411–5. DOI: 10.1063/1.4873810
- [73] Chimeni DY, Toupe JL, Dubois C, Rodrigue D. Effect of hemp surface modification on the morphological and tensile properties of linear medium density polyethylene

- (LMDPE) composites. *Compos Interfaces*. 2016;23:405–21. DOI: 10.1080/09276440.2016.1144163
- [74] Essabir H, Bensalah MO, Rodrigue D, Bouhfid R, Qaiss A. Structural, mechanical and thermal properties of bio-based hybrid composites from waste coir residues: Fibers and shell particles. *Mech Mater*. 2016;93:134–44. DOI: 10.1016/j.mechmat.2015.10.018
- [75] Cisneros-Lopez EO, Aznaldo J, Fuentes-Talavera FJ, Gonzalez-Nunez R, Robledo-Ortiz JR, Rodrigue D. Effect of agave fiber surface treatment on the properties of polyethylene composites produced by dry-blending and compression molding. *Polym Compos*. DOI 10.1002/pc.23564
- [76] Cisneros-Lopez EO, Pérez-Fonseca AA, Fuentes-Talavera FJ, Aznaldo J, Gonzalez-Nunez R, Rodrigue D, et al. Rotomolded polyethylene-agave fiber composites: Effect of fiber surface treatment on the mechanical properties. *Polym Eng Sci*. 56: 856–65. DOI: 10.1002/pen.24314
- [77] Li Y. Effect of coupling agent concentration, fiber content, and size on mechanical properties of wood/HDPE composites. *Int J Polym Mater*. 2012;61:882–90. DOI: 10.1080/00914037.2011.617338
- [78] Ou R, Xie Y, Wolcott MP, Yuan F, Wang Q. Effect of wood cell wall composition on the rheological properties of wood particle/high density polyethylene composites. *Compos Sci Technol*. 2014;93:68–75. DOI: 10.1016/j.matdes.2014.02.018
- [79] Tissandier C, Vazquez R, González R, Rodrigue D. Microcellular agave fiber-high density polyethylene composites produced by injection molding. *Mater Sci Eng*. 2012;2:677–92.
- [80] Essabir H, Achaby ME, Hilali EM, Bouhfid R, Qaiss A. Morphological, structural, thermal and tensile properties of high density polyethylene composites reinforced with treated Argan nut shell particles. *J Bionic Eng*. 2015;12:129–41. DOI: 10.1016/S1672-6529(14)60107-4
- [81] López-Bañuelos RH, Moscoso FJ, Ortega-Gudiño P, Mendizabal E, Rodrigue D, Gonzalez-Nuñez R. Rotational molding of polyethylene composites based on agave fibers. *Polym Eng Sci*. 2012;52:2489–97. DOI: 10.1002/pen.23168
- [82] Kuo PY, Wang SY, Chen JH, Hsueh HC, Tsai MJ. Effects of material compositions on the mechanical properties of wood-plastic composites manufactured by injection molding. *Mater Des*. 2009;30:3489–96. DOI: 10.1016/j.matdes.2009.03.012
- [83] Moscoso FJ, Martínez L, Canche G, Rodrigue D, González-Núñez R. Morphology and properties of polystyrene/agave fiber composites and foams. *J Appl Polym Sci*. 2013;127:599–606. DOI: 10.1002/app.37843

- [84] Aggarwal PK. Influence of maleated polystyrene on the mechanical properties of bio-based fibers-polystyrene composites. *J Indian Acad Wood Sci.* 2011;8:184–9. DOI 10.1007/s13196-012-0034-y
- [85] Essabir H, Bensalah MO, Rodrigue D, Bouhfid R, Qaiss A el kacem. Biocomposites based on Argan nut shell and a polymer matrix: Effect of filler content and coupling agent. *Carbohydr Polym.* 2016;143:70–83. DOI: 10.1016/j.carbpol.2016.02.002
- [86] Sojoudiasli H, Heuzey M-C, Carreau PJ. Rheological, morphological and mechanical properties of flax fiber polypropylene composites: influence of compatibilizers. *Cellulose.* 2014;21:3797–812. DOI 10.1007/s10570-014-0375-3
- [87] Rahman MR, Huque MM, Islam MN, Hasan M. Mechanical properties of polypropylene composites reinforced with chemically treated abaca. *Compos Part A Appl Sci Manuf.* 2009;40:511–7. DOI: 10.1016/j.compositesa.2009.01.013
- [88] Arrakhiz FZ, Malha M, Bouhfid R, Benmoussa K, Qaiss A. Tensile, flexural and torsional properties of chemically treated alfa, coir and bagasse reinforced polypropylene. *Compos Part B Eng.* 2013;47:35–41. DOI: 10.1016/j.compositesb.2012.10.046
- [89] Ashori A, Nourbakhsh A. A comparative study on mechanical properties and water absorption behavior of fiber-reinforced polypropylene composites prepared by OCC fiber and aspen fiber. *Polym Compos.* 2008;29:574–8. DOI 10.1002/pc.20582
- [90] Hassanabadi HM, Alemdar A, Rodrigue D. Polypropylene reinforced with nanocrystalline cellulose: Coupling agent optimization. *J Appl Polym Sci.* 2016; 132: 42438. DOI: 10.1002/app.42438
- [91] Kaewkuk S, Sutapun W, Jarukumjorn K. Effects of interfacial modification and fiber content on physical properties of sisal fiber/polypropylene composites. *Compos Part B Eng.* 2013;45:544–49. doi:10.1016/j.compscitech.2012.05.011
- [92] Arrakhiz FZ, El Achaby M, Benmoussa K, Bouhfid R, Essassi EM, Qaiss A. Evaluation of mechanical and thermal properties of pine cone fibers reinforced compatibilized polypropylene. *Mater Des.* 2012;40:528–35. DOI: 10.1016/j.matdes.2012.04.032
- [93] Kim S-J, Moon J-B, Kim G-H, Ha C-S. Mechanical properties of polypropylene/natural fiber composites: Comparison of wood fiber and cotton fiber. *Polym Test.* 2008;27:801–6. DOI: 10.1016/j.polymertesting.2008.06.002
- [94] Way C, Wu DY, Cram D, Dean K, Palombo E. Processing stability and biodegradation of polylactic acid (PLA) composites reinforced with cotton linters or maple hardwood fibres. *J Polym Environ.* 2013;21:54–70. DOI 10.1007/s10924-012-0462-1
- [95] Pérez-Fonseca AA, Robledo-Ortíz JR, González-Núñez R, Rodrigue D. Effect of thermal annealing on the mechanical and thermal properties of polylactic acid-cellulosic fiber biocomposites. *J Appl Polym Sci.* 2016;133(31):1–10. DOI: 10.1002/app.43750

- [96] Kazemi Y, Cloutier A, Rodrigue D. Design analysis of three-layered structural composites based on post-consumer recycled plastics and wood residues. *Compos Part A Appl Sci.* 2013;53:1–9. DOI: 10.1016/j.compositesa.2013.06.002
- [97] Toupe JL, Trokourey A, Rodrigue D. Simultaneous optimization of the mechanical properties of postconsumer natural fiber/plastic composites: Phase compatibilization and quality/cost ratio. *Polym Compos.* 2014;35:730–46. DOI 10.1002/pc.22716
- [98] Toupe JL, Trokourey A, Rodrigue D. Simultaneous optimization of the mechanical properties of postconsumer natural fiber/plastic composites: processing analysis. *J Compos Mater.* 2015;49:1355–67. DOI: 10.1177/0021998314533714
- [99] Toupe JL, Chimeni DY, Trokourey A, Rodrigue D. Optimizing the performance of natural fiber reinforced plastics composites : Influence of combined optimization paths on microstructure and mechanical properties. *Polym Polym Compos.* 2015;23:535–44.
- [100] Cruz-Estrada RH, Martínez-Tapia GE, Canché-Escamilla G, González-Chí PI, Martín-Barrera C, Duarte-Aranda S, et al. A preliminary study on the preparation of wood-plastic composites from urban wastes generated in Merida, Mexico with potential applications as building materials. *Waste Manag Res.* 2010; 28:838–47. DOI: 10.1177/0734242X09350059
- [101] Ratanawilai T, Nakawiro K, Deachsrijan A, Homkhiew C. Influence of wood species and particle size on mechanical and thermal properties of wood polypropylene composites. *Fibers Polym.* 2014;15:2160–8. DOI 10.1007/s12221-014-2160-1
- [102] Pérez-Fonseca AA, Robledo-Ortíz JR, Moscoso-Sánchez FJ, Fuentes-Talavera FJ, Rodrigue D, González-Núñez R. Self-hybridization and coupling agent effect on the properties of natural fiber/HDPE composites. *J Polym Environ.* 2015;23:126–36. DOI 10.1007/s10924-014-0706-3
- [103] Perez-Fonseca AA, Arellano M, Rodrigue D, Gonzalez-Nunez R, Robledo-Ortiz JR. Effect of coupling agent content and water absorption on the mechanical properties of coir-agave fibers reinforced polyethylene hybrid composites. *Polym Compos.* DOI 10.1002/pc.23498
- [104] Yousefian H, Ben Azouz K, Rodrigue D. New multi-scale hybrid system based on maple wood flour and nano crystalline cellulose: Morphological, mechanical and physical study. *J Polym Environ.* 2016;24:48–55. DOI 10.1007/s10924-016-0752-0
- [105] Arrakhiz FZ, El Achaby M, Malha M, Bensalah MO, Fassi-Fehri O, Bouhfid R, et al. Mechanical and thermal properties of natural fibers reinforced polymer composites: Doum/low density polyethylene. *Mater Des.* 2013;43:200–5. DOI: 10.1016/j.matdes.2012.06.056



- [106] Ghasemzadeh-Barvarz M, Duchesne C, Rodrigue D. Mechanical, water absorption, and aging properties of polypropylene/flax/glass fiber hybrid composites. *J Compos Mater.* 2015;49: 3781–98. DOI: 10.1177/0021998314568576
- [107] Dhakal HN, Zhang ZY, Bennett N. Influence of fibre treatment and glass fibre hybridisation on thermal degradation and surface energy characteristics of hemp/unsaturated polyester composites. *Compos Part B Eng.* 2012;43:2757–61. DOI: 10.1016/j.compositesb.2012.04.036
- [108] Boopalan M, Niranjanaa M, Umapathy MJ. Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites. *Compos Part B Eng.* 2013;51:54–7. DOI: 10.1016/j.compositesb.2013.02.033
- [109] Saw SK, Datta C. Thermomechanical properties of jute/bagasse hybrid fibre reinforced epoxy thermoset composites. *BioResources.* 2009;4:1455–76.
- [110] Aji I, Zainudin E, Abdan K, Sapuan S, Khairul M. Mechanical properties and water absorption behavior of hybridized kenaf/pineapple leaf fibre-reinforced high-density polyethylene composite. *J Compos Mater.* 2013;47:979–90. DOI: 10.1177/0021998312444147
- [111] da Silva LJ, Panzera TH, Christoforo AL, Rubio JCC, Scarpa F. Micromechanical analysis of hybrid composites reinforced with unidirectional natural fibres, silica microparticles and maleic anhydride. *Mater Res.* 2012;15:1003–12. DOI: 10.1590/S1516-14392012005000134
- [112] Birat KC, Panthapulakkal S, Kronka A, Agnelli JAM, Tjong J, Sain M. Hybrid biocomposites with enhanced thermal and mechanical properties for structural applications. *J Appl Polym Sci.* 2015;132, 42452. DOI: 10.1002/app.42452
- [113] Jarukumjorn K, Suppakarn N. Effect of glass fiber hybridization on properties of sisal fiber-polypropylene composites. *Compos Part B Eng.* 2009;40:623–7. DOI: 10.1016/j.compositesb.2009.04.007
- [114] AlMaadeed MA, Kahraman R, Noorunnisa Khanam P, Madi N. Date palm wood flour/glass fibre reinforced hybrid composites of recycled polypropylene: Mechanical and thermal properties. *Mater Des.* 2012;42:289–94. DOI: 10.1016/j.matdes.2012.05.055
- [115] Kumar MA, Reddy GR, Rao HR, Reddy KH, Reddy BHN. Assessment of glass/drumstick fruit fiber (*Moringa oleifera*) reinforced epoxy hybrid composites. *Int J Polym Mater.* 2012;61:759–67. DOI: 10.1080/00914037.2011.610046
- [116] Vinayagamoorthy R, Rajeswari N. Mechanical performance studies on *Vetiveria zizanioides*/jute/glass fiber-reinforced hybrid polymeric composites. *J Reinf Plast Compos.* 2013;33:81–92. DOI: 10.1177/0731684413495934
- [117] Nicolai FNP, Botaro VR, Cunha Lins VF. Effect of saline degradation on the mechanical properties of vinyl ester matrix composites reinforced with glass and natural fibers. *J Appl Polym Sci.* 2008;108:2494–502. DOI 10.1002/app.27909

- [118] Ramesh M, Palanikumar K, Reddy KH. Influence of fiber orientation and fiber content on properties of sisal-jute-glass fiber-reinforced polyester composites. *J Appl Polym Sci.* 2015; 133, 42968. DOI: 10.1002/app.42968
- [119] Yalcin B, Amos SE, D'Souza AS, Clemons CM, Gunes IS, Istaitieh K. Improvements in processing characteristics and engineering properties of wood flour-filled high density polyethylene composite sheeting in the presence of hollow glass microspheres. *J Plast Film Sheeting.* 2012;28:165–80. DOI: 10.1177/8756087911434185
- [120] Kakou CA, Essabir H, Bensalah M-O, Bouhfid R, Rodrigue D, Qaiss A. Hybrid composites based on polyethylene and coir/oil palm fibers. *J Reinf Plast Compos.* 2015;34:1684–97. DOI: 10.1177/0731684415596235
- [121] Shanmugam D, Thiruchitrambalam M. Static and dynamic mechanical properties of alkali treated unidirectional continuous Palmyra palm leaf stalk fiber/jute fiber reinforced hybrid polyester composites. *Mater Des.* 2013;50:533–42. DOI: 10.1016/j.matdes.2013.03.048
- [122] Idicula M, Neelakantan NR, Oommen Z, Joseph K, Thomas S. A study of the mechanical properties of randomly oriented short banana and sisal hybrid fiber reinforced polyester composites. *J Appl Polym Sci.* 2005;96:1699–709. DOI: 10.1002/app.21636
- [123] Noorunnisa Khanam P, Ramachandra Reddy G, Raghu K, Venkata Naidu S. Tensile, flexural, and compressive properties of coir/silk fiber-reinforced hybrid composites. *J Reinf Plast Compos.* 2010;29:2124–7. DOI: 10.1177/0731684409345413
- [124] Khalil HPSA, Hanida S, Kang CW, Fuaad NAN. Agro-hybrid Composite: The effects on mechanical and physical properties of oil palm fiber (EFB)/glass hybrid reinforced polyester composites. *J Reinf Plast Compos.* 2007;26:203–18. DOI: 10.1177/0731684407070027
- [125] Alavudeen A, Rajini N, Karthikeyan S, Thiruchitrambalam M, Venkateshwaren N. Mechanical properties of banana/kenaf fiber-reinforced hybrid polyester composites: Effect of woven fabric and random orientation. *Mater Des.* 2015;66:246–57. DOI: 10.1016/j.matdes.2014.10.067
- [126] Paiva Júnior C, de Carvalho L, Fonseca V, Monteiro S, d'Almeida JR. Analysis of the tensile strength of polyester/hybrid ramie–cotton fabric composites. *Polym Test.* 2004;23:131–5. DOI: 10.1016/S0142-9418(03)00071-0
- [127] Athijayamani A, Thiruchitrambalam M, Natarajan U, Pazhanivel B. Effect of moisture absorption on the mechanical properties of randomly oriented natural fibers/polyester hybrid composite. *Mater Sci Eng A.* 2009;517:344–53. DOI: 10.1016/j.msea.2009.04.027
- [128] Amico SC, Angrizani CC, Drummond ML. Influence of the stacking sequence on the mechanical properties of glass/sisal hybrid composites. *J Reinf Plast Compos.*



- [129] Venkateshwaran N, ElayaPerumal A, Alavudeen A, Thiruchitrambalam M. Mechanical and water absorption behaviour of banana/sisal reinforced hybrid composites. *Mater Des.* 2011;32:4017–21. DOI: 10.1016/j.matdes.2011.03.002
- [130] Misra RK, Saw SK, Datta C. The influence of fiber treatment on the mechanical behavior of jute-coir reinforced epoxy resin hybrid composite plate. *Mech Adv Mater Struct.* 2011;18:431–45. DOI: 10.1080/15376494.2010.528157
- [131] Li Y, Xie L, Ma H. Permeability and mechanical properties of plant fiber reinforced hybrid composites. *Mater Des.* 2015;86:313–20. DOI: 10.1016/j.matdes.2015.06.164
- [132] Islam MS, Talib ZA, Hasan M, Ramli I, Haafiz MKM, Jawaid M, et al. Evaluation of mechanical, morphological, and biodegradable properties of hybrid natural fiber polymer nanocomposites. *Polym Compos.* 2015. DOI 10.1002/pc.23616
- [133] Lin ZD, Hong XJ, Chen C, Guan ZX, Zhang XJ, Tan SZ, et al. Polypropylene hybrid composites with wood flour and needle-like minerals. *Plast Rubber Compos.* 2012;41:114–9. DOI: 10.1179/1743289811Y.0000000026
- [134] Karaduman Y, Onal L, Rawal A. Effect of stacking sequence on mechanical properties of hybrid flax/jute fibers reinforced thermoplastic composites. *Polym Compos.* 2015;36:2167–73. DOI 10.1002/pc.23127
- [135] Arifuzzaman Khan GM, Alam Shams MS, Kabir MR, Gafur MA, Terano M, Alam MS. Influence of chemical treatment on the properties of banana stem fiber and banana stem fiber/coir hybrid fiber reinforced maleic anhydride grafted polypropylene/low-density polyethylene composites. *J Appl Polym Sci.* 2013;128:1020–9. DOI:10.1002/app.38197
- [136] Haneefa A, Bindu P, Aravind I, Thomas S. Studies on tensile and flexural properties of short banana/glass hybrid fiber reinforced polystyrene composites. *J Compos Mater.* 2008;42:1471–89. DOI: 10.1177/0021998308092194
- [137] Zhang X, Yang H, Lin Z, Tan S. Polypropylene hybrid composites filled by wood flour and short glass fiber: Effect of compatibilizer on structure and properties. *J Thermoplast Compos Mater.* 2013;26:16–29. DOI: 10.1177/0892705711417030
- [138] Mirbagheri J, Mehdi T, John C. H, Ismaeil G. Tensile properties of wood flour/kenaf fiber polypropylene hybrid composites. *J Appl Polym Sci.* 2007;105:3054–9. DOI 10.1002/app.26363
- [139] Kwon HJ, Sunthornvarabhas J, Park JW, Lee JH, Kim HJ, Piyachomkwan K, et al. Tensile properties of kenaf fiber and corn husk flour reinforced poly(lactic acid) hybrid bio-composites: Role of aspect ratio of natural fibers. *Compos Part B Eng.* 2014;56:232–7. DOI: 10.1016/j.compositesb.2013.08.003
- [140] Sajna V, Mohanty S, Nayak SK. Hybrid green nanocomposites of poly(lactic acid) reinforced with banana fibre and nanoclay. *J Reinf Plast Compos.* 2014;33:1717–32. DOI: 10.1177/0731684414542992

- [141] Pal N, Aggarwal L, Gupta VK. Tensile behavior of sisal/hemp reinforced high density polyethylene hybrid composite. *Mater Today Proc.* 2015;2:3140–8. DOI: 10.1016/j.matpr.2015.07.102
- [142] Asaithambi B, Ganesan G, Ananda Kumar S. Bio-composites: Development and mechanical characterization of banana/sisal fibre reinforced poly lactic acid (PLA) hybrid composites. *Fibers Polym.* 2014;15:847–54. DOI 10.1007/s12221-014-0847-y
- [143] Graupner N, Herrmann AS, Müssig J. Natural and man-made cellulose fibre-reinforced poly(lactic acid) (PLA) composites: An overview about mechanical characteristics and application areas. *Compos Part A Appl Sci Manuf.* 2009;40:810–21. DOI: 10.1016/j.compositesa.2009.04.003
- [144] Lu G, Wang W, Shen S. Mechanical properties of wood flour reinforced high density polyethylene composites with basalt fibers. *Mater Sci.* 2014;20:464–7. DOI: 10.5755/j01.ms.20.4.6441
- [145] Ou R, Zhao H, Sui S, Song Y, Wang Q. Reinforcing effects of Kevlar fiber on the mechanical properties of wood-flour/high-density-polyethylene composites. *Compos Part A Appl Sci Manuf.* 2010;41:1272–8. DOI: 10.1016/j.compositesa.2010.05.011
- [146] Mohebbi B, Younesi H, Ghotbifar A, Kazemi-Najafi S. Water and moisture absorption and thickness swelling behavior in polypropylene/wood flour/glass fiber hybrid composites. *J Reinf Plast Compos.* 2010;29:830–9. DOI: 10.1177/0731684408100702
- [147] Ramezani Kakroodi A, Leduc S, Rodrigue D. Effect of hybridization and compatibilization on the mechanical properties of recycled polypropylene-hemp composites. *J Appl Polym Sci.* 2012;124:2494–500. DOI 10.1002/app.35264
- [148] Rodriguez-Castellanos W, Rodrigue D. Auto-hybridization of polyethylene/maple composites: The effect of fiber size and concentration. *Polym Polym Compos.* 2016.

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