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REVIEW

Potential of Borneo *Acacia* wood in fully biodegradable bio-composites' commercial production and application

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Abstract This review paper explores the potential of commercial production and application of *Acacia* wood—polylactic acid (PLA), and *Acacia* wood—polyhydroxyalkanoates (PHA) bio-composites. The factors affecting the mechanical and physical properties of these materials were identified and deliberated. It was found that *Acacia* wood has the prospective to be efficiently produced and used in Borneo. It can be used in a variety of applications, including but not limited to: fire breaker, timber resource, furniture production, soil re-conditioning, and as reinforced materials. Since, today, there is heightened awareness regarding sustainability, manufacturers are driven towards producing completely biodegradable products that are created using PLA and PHA bio-composites. This review provides an overview on the performance of the existing composites and bio-composites, and their implementation and utilization, while focusing on the Borneo region.

Introduction

Acacia mangium and *Acacia auriculiformis* are the *Mimosoideae* sub-family species of leguminous tree. *Acacia mangium* is also considered as *Fabaceae*, pea flowering tree family species. Back in 1967, the species of *Acacia* was introduced as a firebreak

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or barrier in Sabah. According to PERKASA [1], for the year 2020, along with the vast and mass commercialize and development programs, 1 million hectares of land were reserved in Sarawak, for reforestation and re-plantation of *Acacia* and other type of species that suitable for timber production. It was done to achieve the current and future need of raw materials, especially wood production, which is highly demanded in the timber industry and to conserve the natural forest as well. This species is also known to grown fast and have many applications. For reforestation and rehabilitation, the *Acacia* woods are used for land conditioner restoration [2–4].

A few setbacks are known to *Acacia mangium*. It is vulnerable to heart rot damage [5]. Heart rot damage was due to fungal or bacteria disease which cause decay at the center of the wood. Furthermore, its suitability for sawing and peeling remained unsatisfactory [6]. Thus, considerable efforts, such as introducing new clones and hybrid plant in the plantation, were done to overcome these setbacks. *Acacia* hybrid (mixture of *Acacia mangium* and *Acacia auriculiformis* species) and clone of second-generation *Acacia mangium* (also known as *Acacia* super bulk or *Acacia mangium* super bulk) were introduced in Sarawak. As compared to the previous generations, it has better properties, less tapering, straighter bole, high resistance to heart rot, and fast growth. *Acacia* hybrid maintained its mass propagated cuttings, while the second-generation *Acacia mangium* is an improved version due to the existing upgraded program.

As increasing awareness about the environmental impact of non-sustainable materials, from its first- and end-products manufacturing, and as well as due to pressure from the legislation and end user, consideration of the environmental impact on all of the stage life-cycles was approached and measured. It also caused the concept of 'eco-design' or 'eco-environmentally' to be considered in material selection [7]. In engineering composites, natural fiber based on lignocellulose, such as flax, jute, sisal, and wood, which is environmentally friendly, was considered as an alternative replacement for non-sustainable materials or products such as glass and carbon fiber [8–13]. Thus, in this review paper, the properties of *Acacia* wood, polylactic acid, and polyhydroxyalkanoates, together with its composites and current existing composites available in the market and research were discussed. The potential, utilization, and environmental effect of bio-composites in Borneo were also deliberated.

Acacia wood

Physical properties

Usually, the characterization of wood involves the physical properties of the basic radial, tangential, volumetric shrinkage, and density. Jusoh et al. [14] noted that *Acacia auriculiformis* had the highest basic density, followed by *Acacia* hybrid, *Acacia mangium*, and, finally, second-generation *Acacia mangium*. Meanwhile, in term of volumetric shrinkage, *Acacia auriculiformis* showed higher shrinkage than the other *Acacia* species [14]. Jusoh et al. [14] also found out that the second-generation *Acacia mangium* showed more rapid growth compared with *Acacia mangium*, which may be due to the lower basic density which it had. However, as

known, the wood rapid growth does not affect the wood density directly, and to date, there still no consistent relationship can be found between wood density and growth rate in diffuse-porous hardwoods [15, 16]. Zobel and Jett [17] reported that the fiber wall thickness may be related to the specific gravity in diffuse-porous hardwoods. Despite the fact, Bowyer et al. [16] showed that wood tends to shrink more when it is high in density. As compared with Mohd Hamami and Semsolbahri [18], their result showed that the shrinkage is 3.30%, which is less than the value recorded by Jusoh et al. [14] at 5.74%.

Rokeya et al. [19] got the average values of physical properties of *Acacia* hybrid in air-dry and green condition. From the obtained data [19], the volumetric shrinkage and specific gravity of *Acacia* hybrid was around 9.71 and 0.56%, separately. Meanwhile, according to Sattar et al. [20], the volumetric shrinkage and specific gravity for *Acacia auriculiformis* was 8.01 and 0.61%, and that for *Acacia mangium* was 7.01 and 0.52%. In Malaysia [21], 4-year-old *Acacia* hybrid specific gravity was recorded to be 0.51. Yakub [22] obtained data which indicated that the volumetric shrinkage of *Acacia* hybrid was more than the *Tectona grandis*.

Mechanical properties

Jusoh et al. [14] found out that the second generation of *Acacia mangium* showed slightly lowest modulus of rupture (MOR) of 55 N/mm^2 and modulus of elasticity (MOE) of 8185 N/mm^2, than the *Acacia mangium*, 78 N/mm^2 and 9992 N/mm^2, respectively. Thus, this showed that the factor that affected the low strength in the second generation of *Acacia mangium* is the low density, which is also supported by Bowyer et al. [16] and Panshin and De Zeeuw [23]. However, there is not much difference showed in the compression and static bending parallel to grain among *Acacia* hybrid, *Acacia auriculiformis*, and *Acacia mangium*. Based on the study made by Mohd Shukari et al. [24], 6-year-old *Acacia mangium* and 4-year-old *Acacia* hybrid showed similar strength.

Comparing the strength values of *Acacia* hybrid among various researchers, the reported strength values are not consistent. Data recorded from Mohd Shukari et al. [24] showed higher strength, while slightly lower values were shown by Mohd Hamami and Semsolbahri [18]. This may be caused by several factors, such as geographical difference, growth rates, age, and genetic details [15]. However, *Acacia mangium*, *Acacia* hybrid, and *Acacia auriculiformis* do not show any significant difference in their strength properties. Thus, this showed that *Acacia* species have nearly similar in strength. An exception was found on the second-generation *Acacia mangium*, which showed significant lower strength compared to the other reported *Acacia* species. This may be due to the lower density which it had compared to other species of *Acacia's*.

Using samples in green and air-dry conditions, Rokeya et al. [19] found that the *Acacia* hybrid [MOR: 734 kg/cm^2 (green), 756 kg/cm^2 (air-dry); MOE: 97 kg/cm^2 (green), 117 kg/cm^2 (air-dry)] showed lower static bending and compression parallel to the grain compared to the *Teak* [MOR: 867 kg/cm^2 (green), 1008 kg/cm^2 (air-dry); MOE: 120 kg/cm^2 (green), 131 kg/cm^2 (air-dry)]. Comparing three types of *Acacia* species, namely, *Acacia* hybrid, *Acacia auriculiformis* and *Acacia*

mangium, the modulus of elasticity, and modulus of rupture of *Acacia* hybrid, was found to be greater. The reported modulus of elasticity and modulus of rupture for *Acacia auriculiformis* and *Acacia mangium* were 652 and 658 kg/cm^2, and 79 and 83 kg/cm^2, respectively [20]. However, in Malaysia, according to Laurila [21], using samples of 4-year-old *Acacia* hybrid, the modulus of elasticity and modulus of rupture were reported as 82.83 and 713.47 kg/cm^2. Rokeya et al. [19] also reported that the hardness of various types of *Acacia* species increased from *Acacia mangium* (337 kg), to *Acacia* hybrid (458 kg), and to *Acacia auriculiformis* (572 kg). Even though the mechanical properties of *Acacia* hybrid for cleavage in both air-dry and green conditions were found to be comparable to normal timber testing values, both radial and tangential cleavage values under air-dry conditions were higher than the values under green conditions. In some cases, the perpendicular to grain tension and toughness values were lower. However, in general, the tested species were found to have satisfactory performance for different purposes [19].

Polylactic acid

Polylactic acid is categories under the aliphatic polyester family, which is usually produced from α-hydroxy acids. Polyglycolic acid or polymandelic acid may be included in it, which is considered to be biodegradable and compostable. PLA is thermoplastic, high-modulus, high-strength polymer that can be made from annually renewable resources, which yield better properties for medical device in the bio-absorbable and bio-compatible aspects [25]. Furthermore, it is easily processed on standard plastics processing equipment to yield molded parts, fibers, or films [26]. It is known that PLA mechanical properties and crystallization behavior are dependent on the stereo-chemical makeup and molecular weight of the backbone, especially the stereo-chemical makeup, which is easily controlled from the polymerization of L-Lactide, D-Lactide, D,L-Lactide, or meso-lactide, which form a block or random stereo-copolymers [26]. According to Hartmann [26], even though the molecular weight is controlled directly by the addition of hydroxyl compounds (i.e., alcohol, water, and lactic acid), the architecture of the stereo-chemical, the degree of crystallinity, and the processing temperature can be controlled, so that it achieved the desired overall mechanical properties of the material. Due to the impermeability of the crystalline region [27, 28], highly crystalline PLA will take months to hydrolyze to lactic acid, while amorphous PLA will take weeks to degrade.

Pure poly(D-Lactide) or poly(L-Lactide) is known to have equilibrium melting point of crystallization up to 207 °C high [29–31], whereas the typical melting point is in the range of 170–180 °C. This may be due to the impurities, slight racemization, and imperfect and small crystallites. The mixture of 1:1 ratio of pure poly(D-lactide) and pure poly(L-lactide) yields an insoluble gel stereo-complexation (racemic crystalline) during polymerization at 230 °C and has greater mechanical properties than either both types of pure polymer [32–38]. It has been reported that ultimate tensile strengths were at 50 MPa for 1:1 stereo-complex lower molecular weight PLA compared to pure L-PLA at 31 MPa [32, 33].

Polyhydroxyalkanoates

Naturally occurring bio-polyesters synthesized by microorganism are called PHA. According to Anderson and Dawes [39], PHA was first discovered by Lemogine in 1962 and was continually attracted to researchers and industries for commercialization, due to its chemical-diversity, bio-compatibility, biodegradability, and its renewable carbon resources [40]. Typically, a molecule of PHA contained of 600–35,000 (R)-hydroxyl fatty acid monomer units [41]. Each monomer unit harbors a side chain R group, which can take the form of unsaturated alkyl groups, substituted alkyl group, and branched alkyl group, even though it is usually found in saturated alkyl groups [42]. The PHA can be classified depending on the total number of carbon atom within its monomer as long-chain length PHA (LCL-PHA; 15 or more carbon atoms), medium-chain length PHA (MCL-PHA; 6 to 14 carbon atoms), and short-chain length PHA (SCL-PHA; 3 to 5 carbon atoms) [41]. Zinn and Hany [43] identified that there are about 140 monomers related to PHA, and this number increased with the introduction of new types of PHA with either through naturally occurring PHA, physical or chemical modification, or through genetically modified organisms (GMOs), which created a specialized functional group of PHA [44]. Thus, for various applications, PHA features diverse properties which can be tailored for applications ranging from medical products to biodegradable packaging materials. PHA is also considered as an active compound in pharmaceutical application, and currently being investigated for its potential as antibiotics, anti-cancer drug, anti-HIV drugs, etc. [45, 46]. Recently, upon reviewed by several researchers [45, 47–49], it was reported that there were various types of PHA materials with their unique properties suitable for the specific requirement.

Commonly, the tensile strength, Young's modulus, and elongation are the consideration required for the specific applications for PHA polymers. According to Rai et al. [45], the Young's modulus ranged from very stiff SCL-PHA (3.5×10^3 MPa) to very ductile MCL-PHA (0.008 MPa). Measurement of a material elongation at break is a stretch of original material length, which extended before it breaks and it is usually expressed in percentage. Chen [50] showed that PHA polymers can exist in different forms, including hard, rigid materials to the soft elastomeric material, which exhibited the wide range of elongation at break from 2 to 1000%. For PHA polymers, the tensile strength, which is the amount of force required to pull a material until it breaks, has typical range of 8.8–104 MPa [45]. The measurement of the aforementioned mechanical properties can be performed using a tensile testing instrument by standardized-based ASTM standards [51].

Factor and properties of existing engineered reinforced composites/bio-composites

There is a large quantity of literatures related to the mechanical performance of reinforced polymer composites. Reinforced polymer composites can be divided into three parts, i.e., non-degradable, partially degradable, and completely degradable

composites. The non-degradable composites are made from a mixture of synthetic fiber with petroleum-based polymer, i.e., glass–epoxy and glass-unsaturated polyester composites. Partially degradable reinforced composites are made from a mixture of either natural fiber or synthetic fiber with natural-based polymer or petroleum-based polymer. In this case, either the fiber of polymer matrix is non-biodegradable or there is at least one component (either the fiber or polymer matrix) is biodegradable, i.e., sisal-epoxy, flax-polypropylene, and newsprint-polypropylene composites. Completely degradable composites or the so-called bio-composites are made from a mixture of completely degradable natural fiber and natural-based polymer, i.e., hemp-polylactic acid composites.

There are several factors that affect the mechanical properties of polymer composites [52], such as the fiber characteristics, matrix behavior, interface strength, fiber dispersion, fiber orientation, processing conditions, and porosity. Fiber selection is very important. Each type of fiber has its own characteristics and properties. Furthermore, all plant fibers contain cellulose component as their major structure. Meanwhile, animal fibers contain mostly protein components. Regarding mineral fiber, it is banned by legislation in certain countries due to health and environment issues. In general, higher performance plant fibers have much better stiffness and strength, compared to animal fibers. However, certain animal fiber, such as silk, can be very strong in its strength, but having lower stiffness, and it is more expensive and needs time to be harvested [53]. Thus, this is the reason that plant fiber is more popular, due to its rapid growth and short harvesting time. Usually, the properties of natural fiber varied depending on the chemical composition, growing conditions, harvesting period, extraction method, treatment, and storage. The traditional manual harvesting method showed better results, whereas the flax fiber were found to have strength 20% higher than the modern mechanical harvesting method [54], and the strength of the fiber was usually reduced by 15% over 5 days after mature harvesting period [55].

Matrix selection is very important too, because it affects the overall bond strength of the composites. It also provides protections from environment, abrasion, corrosion, and load dispersion. Both thermosets and thermoplastics can be used to create composites reinforced with natural fibers [56]. Polymeric matrix is chosen due to its lightweight and strong properties. Furthermore, it can also be processed at a low temperature. Most natural fibers used in composites are unstable above 200 °C. If the processing temperature cannot be reduced below 200 °C, the heating time should be kept as short as possible, so that damage to the fiber can be minimized [57]. Thus, so far as the processing temperate is concern, only certain types of thermoplastics such as polyethylene, polypropylene, polystyrene, polyolefin, and thermosets such as epoxy, and unsaturated polyester (which cured at low temperature) can be used as a matrix for the composites [58]. Apart from the consideration of processing temperature, there is an emerging trend to replace the petroleum-based matrices with bio-based polymer matrices. According to Faruk et al. [59], bio-based matrix such as PLA showed good performance in its mechanical properties and gave higher strength and stiffness if compared to polypropylene when it formed composites with natural fibers.

Large void in composites also influenced the mechanical properties of the composites, and much effort was done to reduce it, especially in synthetic fiber composites. Madsen et al. [60] identified that porosity in the composite structure exists due to the unintentional inclusion of air through processing due to uncompressible structure of fiber and matrix, or it was an effect of the entrapped air in the fiber lumens and other hollow features within fibers and fiber bundles, or limited fiber wettability by the polymer resin. Depending on the orientation and fiber type, increasing in fiber content increased the porosity of the composites, and more rapidly, once it had exceeded the compression geometrical limit. Madsen and Lilholt [61] found that the porosity of flax/polypropylene composites had increased from 56 to 72 m% when the fiber content increased from 4 to 8 vol%.

The most common composite fabrication methods include extrusion, compression, and injection molding. Sometimes, processing technique for polymer composite with glass/carbon fiber is adapted to fabricate natural fiber polymer composites. Flax fiber and polypropylene thermoplastics and flax fiber polyester thermoset composites were successfully fabricated using pultrusion and resin transfer molding [62, 63]. Factors influenced the material properties during fabrication include the speed, pressure, and temperature of the processing. High temperature may cause the fiber to degrade. In general, most of the thermoplastic and thermoset matrices can be reinforced with short or long, randomly or aligned oriented fiber, or fiber in fabric form, by applying used of compression molding technique, with the viscosity of the matrix is controlled carefully, especially during pressing and heating. This is to ensure that the specific sample thickness is achieved and the matrix is fully impregnated into the fibers.

Taking into the consideration of processing conditions, according to Ho et al. [64], by controlling the pressure, viscosity, temperature, and holding time, good quality of composites can be produced. Fiber strength reduced as the temperatures reached the range of 150 and 200 °C. However, if the heating is executed within 10 min, minimal strength reduction at approximately 10% can be realized [65]. In general, the optimum temperatures needed to be obtained, so that fiber degradation is minimized. This was demonstrated in a study conducted by Jiang and Hinrichsen [66], where using optimum temperature of 150 °C, the tensile strength properties of stacked flax reinforced poly(ester amide) composites were found to be at the highest. However, the flexural property was found to be less reliant, when the temperature below 150 °C, and it reduced significantly at higher temperatures. The optimum compression temperature, which gave good mechanical properties for jute yarn, and bacterial copolyester Biopol were found approximately at 180 °C [67]. For non-woven mat reinforced polypropylene, the highest strength was found at 200 °C [68].

Many studies showed that the best mechanical properties of composites were obtained when the fiber was aligned parallel to the applied load direction [69–71]. Nevertheless, natural fiber is difficult to align in one direction compared to the continuous synthetic fibers. Using injection molding technique for composite processing, only some alignment was achieved and the extent of the alignment was depending on the mold design and matrix polymer viscosity [72]. For sheet or compression molding, long natural fiber was used, they can be placed in sheet of

cards prior and subsequently to impregnated, so that a higher degree of fiber alignment is resulted. Thermoplastic fiber can act as support for the natural fiber, when it is aligned in the yarn direction, as it being converted in the matrix. Carpenter et al. [73] and their composites exhibited improved flexural, stiffness, and tensile strength on their aligned and twisted flax yarn in epoxy matrix compared to just unidirectional yarn. Continuous fiber tape has been produced using the fiber pectin using water as adhesive, whilst stretched drying [74]. Continuous synthetic fiber or natural fiber can also be used in pultrusion and filament winding, as it gave better fiber alignment within the composite.

Apart from fiber orientation, other challenges in natural fiber composites include the fiber dispersion, and the non-matching chemical characteristic between hydrophobic polymer matrices and hydrophilic fiber, vice versa [75]. Usually, longer fibers increase the agglomeration tendency. According to Heidi et al. [76], better adhesion interfacial came from better fiber dispersion, which is achieved by ensuring that all the fibers are fully surrounded by the matrix, which reduced the voids in the composites. Additive such as stearic acid was used in polyethylene and polypropylene to modify the dispersion, and maleated polypropylene (MAPP) was used to increase the interfacial bonding that increases fiber–matrix interaction, in which the dispersion was influenced with the pressure and temperature [75]. Fiber modification such as grafting can also be used, but it is far more expensive than other type of modification [75]. A few researchers suggested that using mixing processes such as twin-screw extruder would achieved far more intensive mixing than the single screw extruder as it led to better dispersion of fiber. On the other hand, the quality of mixing also depended on the screw configuration and extrusion temperature, and it may cause fiber damage and reduced fiber length [75, 77].

Interfacial bonding plays a vital role, especially between matrix and fiber, as it is another main factor that determines the mechanical properties of the composites. Strong and better interfacial bonding cause increased in the strength and toughness of composites, which lower the crack propagation when force was applied and transfer within it. Unfortunately, limited interaction can be seen between hydrophobic matrices and hydrophilic fibers, which lead to poor interfacial bonding that limits the mechanical performance and lower the moisture resistance in long term. Wettability can be regarded as an essential predecessor to bonding, as it brought fiber and matrix into close contact. According to Chen et al. [78], insufficient fiber wetting can act as stress concentrators which resulted from interfacial defects. The toughness, flexural, and tensile strength are affected by the fiber wettability [79]. Thus, chemical and physical treatments were used to improve the interfacial strength, which were associated with fibers wettability [80–82]. Heat treatment involves heating the fibers close to its fiber degradation temperature, which affects the mechanical, physical, and chemical properties of the fibers, such as water content, chemistry, cellulose crystallinity, strength, and degree of polymerization.

According to Pickering [83], specific chemical changed the free radical production, chain scission, and formation, such as carbonyl, peroxide groups, and carboxyl, occurred upon heat treatment. Similarly, the effect of heat treatment relied on the exposed gases (either surrounding gases or gas in the heating chamber), time,

and temperature, especially in the corona and plasma treatment. Cao et al. [84] showed that an increase in fiber crystallinity caused an improvement in the tensile strength above 60%, when using fibers heat treatment. Heat treatment was also improved sisal fiber strength by 37% [85]. It is usually related to the removal of aromatic impurities and increase in crystallinity. The heat treatment also resulted in more modest increment in composite properties; which is by 4% Young's modulus, 10% tensile strength, 33% flexural modulus, and 27% flexural strength. According to Huber et al. [86], improvement on the interfacial bonding using electron radiation for polypropylene and natural fibers was found in the range of 21 and 53%. This was explained as an effect of the produced free radicals resulted cross-linking between matrix and fibers. Meanwhile, due to fiber defibrillation, mechanical interlocking, and increased in surface area due to fiber beating, 10% increment in strength was seen in Kraft fiber reinforced with polypropylene [87].

Shah [88] found that the strengths are largely proportional to the stiffness for their natural fiber composites. Meanwhile, Zhang and Miao [89] showed that the composites reinforced with wrap spun yarn gave better flexural properties than the twisted yarn by discontinuous hemp fiber with polypropylene as carrier fiber, wrap spun by polypropylene, as well as flax silver with polypropylene, fiber wrap spun by polypropylene for unidirectional composites. Moreover, Baghaei et al. [90] also showed that using wrap spun hemp/PLA yarn from bleached hemp yarn and continuous polylactic acid strand to produce an oriented pre-preg (pre-impregnated fiber) gave better mechanical properties, exclusively in the form if biaxial lamination, which gave relatively high impact energy (25 kJ/m^2). Similar promising results were shown by Van de Weyenberg et al. [91] on their wrap spinning short hemp fiber yarn polylactic acid.

The development of composites is intended to produce high mechanical performance materials. Natural fiber composites can be handily produced using aligned fibers especially in reasonably raw form, or in continuous fiber or fabric form. Even though flax silver and flax yarn gave better performance, each state of processing required specialized equipment in the various stages involved carding, sketching, spinning, or hackling [91, 92]. It was noted that polylactic acid matrix outperformed polypropylene with higher properties, while another bio-derived matrix, shellac also showed comparable performance to polypropylene [65]. Table 1 shows the summary on type of fiber and matrix to form composites and their tensile and flexural strength, the respective methods.

Potential of bio-composites and/or hybrid composites in borneo—Acacia wood and biopolymer

Bio-composites is fully biodegradable composites, while hybrid composites is combination of additional element or composition in the composites, either additional fiber or polymer matrix. Recent studies showed promising results of bio-composites or hybrid composites using available fibers, generally in the world and specifically in Borneo, especially the fast growing *Acacia* wood fiber. Usually, *Acacia* woods were used as firebreak, separator, marking, and fence (tree protector)

Table 1 Composites' composition and the tensile and flexural strength, as well as the fabrication methods available in research literature

Fiber	Matrix	Tensile strength (MPa)	Flexural strength (MPa)	Methods	References
Non-degradable composites					
E-glass (aligned)	Epoxy	–	450	Pultruded	Goutianos et al. [93]
E-glass (chopped strand mat)	Epoxy	–	250	–	Le Guen and Newman [94]
E-glass (unidirectional)	Vinyl ester	905	–	–	Goutianos et al. [93]
E-glass (woven)	Vinyl ester	483	–	–	Goutianos et al. [93]
E-glass (aligned)	Unsaturated polyester	695	–	Compression molding	Hughes et al. [92]
E-glass (chopped strand mat)	Unsaturated polyester	201	278	Resin transfer molding	Angelov et al. [62]
Partially degradable Composites					
Sisal (aligned)	Epoxy	410	320	Alkaline-treated bundles' compression molding/leaky mold	Rong et al. [85]
Sisal (aligned)	Epoxy	330	290	Untreated bundles compression molding/leaky mold	Rong et al. [85]
Sisal (aligned)	Epoxy	211	–	Resin transfer molding	Van de Weyenberg et al. [91]
Sisal (aligned)	Epoxy	183	–	Resin transfer molding	Van de Weyenberg et al. [91]
Flax (aligned)	Epoxy	280/279	–	Enzyme-extracted resin transfer molding	Oksman [95]
Flax (aligned)	Epoxy	132	–	Resin transfer molding	Oksman et al. [96]
Flax yarn (aligned)	Epoxy	–	311	–	Van de Weyenberg et al. [91]
Flax yarn (aligned)	Epoxy	160	190	Hand lay-up (knitted yarn)	Goutianos et al. [93]
Flax yarn (aligned)	Epoxy	133	218	Autoclave	Van de Weyenberg et al. [91]
Flax hackled (aligned)	Epoxy	–	182	Pultruded	Goutianos et al. [93]

Table 1 continued

Fiber	Matrix	Tensile strength (MPa)	Flexural strength (MPa)	Methods	References
Flax (woven)	Epoxy	104	–	Sized and dried prior to pre-preg	Phillips et al. [97]
Flax silver biaxial/major axis	Epoxy	200	194	Wrap spun silver, woven, weft:warp strength 10:1	Carpenter et al. [73]
Harakeke (aligned)	Epoxy	223	223	Compression molding	Le and Pickering [98]
Harakeke (aligned)	Epoxy	211	–	Compression molding	Newman et al. [99]
Harakeke (random)	Epoxy	–	188	Alkaline-treated vacuum bagged compression molding	Le Guen and Newman [94]
Hemp (aligned)	Epoxy	165	180	Compression molding	Islam et al. [100]
Hemp (dynamic sheet forming)	Epoxy	113	145	Compression molding	Islam et al. [100]
Asian palmyra	Epoxy	27	–	Hot compression molding	Balakrishna et al. [101]
Flax yarn (aligned)	Vinyl ester	248	24	Resin transfer molding	Goutianos et al. [93]
Flax yarn (woven)	Vinyl ester	111	128	Resin transfer molding	Goutianos et al. [93]
Flax silver (aligned)	Unsaturated polyester	304	–	Soxhlet extracted vacuum impregnated/compression molding	Le Guen and Newman [94]
Flax yarn (aligned)	Unsaturated polyester	143	198	Resin transfer molding (knitted yarn)	Goutianos et al. [93]
Flax (random)	Unsaturated polyester	61	91	Resin transfer molding	Rodriquez et al. [63]
Alfa (aligned)	Unsaturated polyester	149	–	Alkali treated, then bleached	Brahim and Cheikh [102]
Jute (woven)	Unsaturated polyester	50	103	Resin transfer molding	Rodriquez et al. [63]
Pineapple leaf (random)	Unsaturated polyester	53	80	Compression molding	Devi et al. [103]
Flax	Polypropylene	–	74	High-molecular-weight MAPP/injection molding	Snijder and Bos [104]

Table 1 continued

Fiber	Matrix	Tensile strength (MPa)	Flexural strength (MPa)	Methods	References
Flax	Polypropylene	52	60	Injection molding	Bledzki et al. [105]
Flax (aligned)	Polypropylene	40	–	Needle punched flax/polypropylene mats compression molding	Oksman [106]
Flax (aligned)	Polypropylene	–	212	Dew retted, boiled, MAA-PP coupled	Van de Velde and Kiekens [68]
Flax yarn (aligned)	Polypropylene	321	–	Filament wound	Madsen and Lilholt [61]
Flax yarn (aligned)	Polypropylene	89/70	–	Pultruded flax/polypropylene yarn	Angelov et al. [62]
Flax silver (aligned)	Polypropylene	–	146	Wrap spun flax silver/polypropylene hybrid yarn, compression molding	Zhang and Miao [89]
Hemp	Polypropylene	52	86	MAPP-coupled injection molding	Sain et al. [107]
Hemp (aligned)	Polypropylene	–	127	Wrap spun, short hemp/polypropylene hybrid yarn, compression molding	Zhang and Miao [89]
Wood bleach Kraft pulp	Polypropylene	50	78	MAPP-coupled injection molding	Li and Sain [108]
Jute	Polypropylene	74	112	MAPP-coupled injection molding	Rana et al. [109]
Newsprint	Polypropylene	53	94	MAPP-coupled injection molding	Sain et al. [107]
Kraft	Polypropylene	52	90	MAPP-coupled injection molding	Sain et al. [107]
Kenaf (random)	Polypropylene	46	58	Compression molding	Zampaloni et al. [110]
Cordenka	Polypropylene	90	–	MAPP-coupled injection molding	Fink and Ganster [111]
Cordenka	Polyamide	120	–	Injection molding	Feldmann and Bledzki [112]
Henequen	High-density polyethylene	27	–	Hot compression molding	Herrera-Franco and Valadez-González [70]
Kenaf	Polyethylene	85	–	Hot compression molding	El-Shekeil et al. [113]
Completely degradable Composites					
Flax (random)	Polylactic acid	100	–	Dew retted stripped/combed (strength 1339 MPa) film staking	Bodros et al. [114]

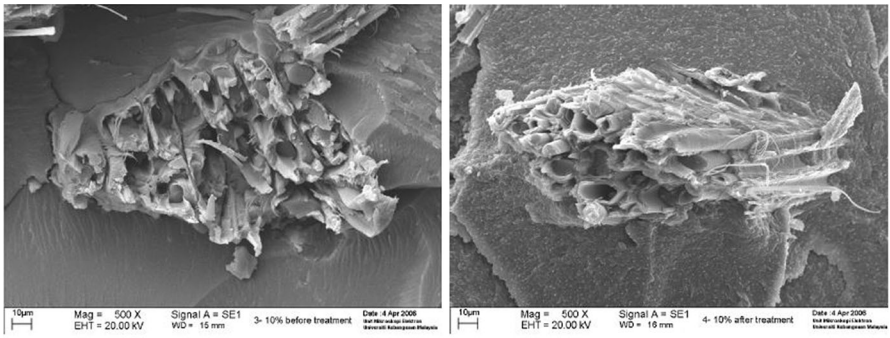
Table 1 continued

Fiber	Matrix	Tensile strength (MPa)	Flexural strength (MPa)	Methods	References
Hemp (aligned)	Polylactic acid	77	101	Wrap spun alkaline-treated short hemp hybrid yarn, compression molding	Bodros et al. [114]
Hemp (carded)	Polylactic acid	83	143	Alkaline-treated compression molding	Islam et al. [115]
Hemp (biaxial)	Polylactic acid	62	124	Wrap spun bleached hemp hybrid yarn, compression molding	Baghaei et al. [116]
Hemp (random)	Polylactic acid	55	–	–	Hu and Lim [117]
Jute	Polylactic acid	91	–	Injection molding	Arao et al. [118]
Kenaf selected (aligned)	Polylactic acid	223	254	Emulsion polylactic acid pre-preg compression molding	Ochi [119]
Kenaf (aligned)	Polylactic acid	82	126	Compression molding	Graupner and Mussig [120]
Lyocell (carded)	Polylactic acid	89	727	Resin transfer molding	Felline et al. [121]
Cordenka	Polylactic acid	108	–	Injection molding	Fink and Ganster [111]
Flax (random)	PolyL-lactic acid	99	–	Dew retted, stripped, combed (strength 1339 MPa) film staking	Bodros et al. [114]
Kenaf (aligned)	Polyhydroxybutyrate	70	101	Compression molding	Graupner and Mussig [120]
Lyocell	Polyhydroxybutyrate	66	105	Compression molding	Graupner and Mussig [120]
Flax (short non-woven)	Shellac	109	–	–	Herrmann et al. [65]
Cellulose (continuous)	Bio-Epoxy	92	727	Resin transfer molding	Felline et al. [121]

in Borneo due to its rapid growth and its adaptability to the regional climate suitability. Furthermore, the vast and wide timber forestation activities exposed soil to rain and other risk, which could cause soil erosion, and the *Acacia* wood is widely used in reforestation [2–4]. The reforestation with *Acacia* wood indirectly spurs the timber industries, especially in the production of timber derived products such furniture, pulp, paper, and composites [122]. According to Hayward [123], *Acacia* have the ability to survive in the most challenging environment. The *Acacia* wood source, including those of damage wood and waste wood, can be processed and engineered easily due to its high process-ability and lightweight properties, compared with other man-made fillers. Furthermore, the derived lignocellulose filler from *Acacia* wood posed a few advantages over inorganic fillers (i.e., renewable, low density, less abrasive, and greater deformability).

The modification using chemical treatment further improved the performance of the wood and matrix, as it altered the cell wall and changed the biological, physical, and mechanical properties [124]. Acetylation treatment is one of the natural fiber modification methods and it showed improvement in the lignocellulose mechanical properties [125], as long as the treatment temperature condition does not exceed 100 °C. According to Abdul Khalil et al. [126], as the reaction exceeded 120 min at 140 °C, it reduced the wood weight percentage, which was due to the degradation of cell wall of the due to high temperature. Hill et al. [127] stated that most of the reaction between chemical reagent and fiber depended upon the reactivity's of the relative of hydroxyl group in the substrate and the rate of reagent diffusion into the fiber. The order of reaction started from the removal of lignin followed by hemicellulose and α-cellulose. However, the degree of reactivity is directly affected by the type of plant fiber and the chemical reagent used.

A few studies found out that polymer composites reinforced with *Acacia* wood showed promising results. Mosadeghzad et al. [128] showed that the composites of *Acacia* wood sawdust treated with 10% sodium hydroxide (NaOH) and unsaturated polyester resin extracted from recycled polyethylene terephthalate (PET) showed



(a) **(b)**

Fig. 1 Scanning electron microscope (SEM) on the fractured of 20 vol% *Acacia* sawdust unsaturated polyester composites extracted from recycled PET **a** untreated and **b** treated Source taken from Mosadeghzad et al. [128]

better result than the untreated composites. The highest tensile strength achieved was about 20 MPa and the highest flexural strength reached was about 43 MPa. Figure 1 shows the pullout of *Acacia* wood from the composites matrix.

Shebani et al. [129] found that the *Acacia* wood showed higher tensile strength (23.45 MPa) compared to *Eucalyptus*, *Pine* and *Oak*. The Increase in the strength of the composites was due to the careful control of the content of lignin and cellulose, whereas it gives better adhesion and dispersion between fiber and polymer matrix [130, 131]. The particle length of the *Acacia* also affected the composite strength, as it provided favorable and higher surface area that improved the wood compatibility and matrix polymer, which produced efficient stress transfer in linear low-density polyethylene matrix [129].

Abdul Khalil et al. [126] showed that the modified acetylation *Acacia mangium* wood flour—polypropylene composites showed higher flexural strength of 55 MPa than unmodified *Acacia mangium* wood flour—polypropylene composites, which is at 45 MPa. Meanwhile, alkaline-treated *Acacia leucopghloea* fiber epoxy showed improvement in the impact strength, around 236 J/m compared to the unmodified composites with 220 J/m. Similar results were also obtained by Mylsamy and Rajendran [132] and Venkateshwaran et al. [133]. This may be due to the better interfacial bonding between fiber and matrix, which allowed energy to be absorbed and stopped the crack promulgation [134].

Rusli et al. [135] conducted an experiment using 4-year-old clones of *Acacia* hybrid and *Acacia mangium*. It was found that the modulus of elasticity and modulus of rupture for *Acacia* hybrid (337 and 3.6 MPa) were far greater than the *Acacia mangium* (231 and 2.56 MPa). Almost all parts of *Acacia* wood have the potential to be utilized. One of them is the bark. Saini et al. [136] researched on the poly(vinyl chloride)—*Acacia* bark flour composites in terms of particle size and filler content. It showed that the tensile modulus of poly(vinyl chloride)—nano *Acacia* bark flour composites was almost double to the poly(vinyl chloride)—*Acacia* bark flour composites. The increase in tensile modulus was due to better reinforcing action of the micro-filler [137]. The filler particle dispersion and size within the matrix also affects the composite properties. In general, well-dispersed and small particles gave better properties [138]. Similar results also showed by Taflick et al. [139] for *Acacia* bark residues polypropylene composites.

Most of the studies showed a lot of potential on the use of *Acacia* wood in composites. In fact, *Acacia* wood can become the main type of wood to be planted and re-produced worldwide, and specifically Borneo. The cost production and maintenance of wood were also lower compared with other type of wood. In moving toward sustainability and eco-friendly, the use of *Acacia* wood, and degradable polymer, such as PLA and PHA, are not just as an alternative, but they could be main solution the depletion of non-renewable resources. The extraction of *Acacia* resin may be used to produce bio-based polymer, similar to those PLA and PHA. It has relatively high stiffness and strength, low CO_2 emission, renewable, low cost, biodegradability, and low-density properties [140]. Meanwhile, during processing, it is non-abrasive, which allowed strength and stiffness improvement in thermoplastics. Furthermore, some of the *Acacia* species are rich in tannins, which are related to polyphenols that largely used for water treatment, leather tanning, chemical

product filtering, and pharmaceutical products [141]. Thus, this shows that more studies needed to be done on *Acacia* and its compatibility with purely degradable polymer as composites.

Variation of mechanical properties has been shown by Aji et al. [142], where the hybridized pineapple leaf and kenaf fiber reinforced with high-density polyethylene showed increased in flexural and tensile strength, whilst reduced in water absorption and impact strength. Meanwhile, at a ratio of 3:1 and the total fiber content of 67%, hybridized banana and sisal fiber polyester composites [143] showed maximum tensile strength (56 MPa). This was due to the small banana fiber diameter, which allowed stress transfer in the composites. This showed that there is a potential of bio-composites and hybridized composites.

Summary

Acacia and its associated polymer composites show promising potential, especially due to their superior physical and mechanical properties. *Acacia* wood's rapid growth and its adaptability in tropical climate demonstrates its potency in becoming the highly sustainable prime timber resource for industries as well as for reforestation. Enhanced engineering methods that include extraction, treatment, interfacial, and processing make it possible for *Acacia* wood bio-composites to be designed for each specific application ranging from biomedical application to packaging requirements. Advances in *Acacia* have revealed that its resins possess the properties of bio-based polymer, which may also be used in bio-composite fabrication. In addition, hybrid composites have shown promising to have a promising future as they minimize the usage of expensive materials and as well as reduce the use of petroleum-based polymer and synthetic fiber, which is non-degradable and non-environmental friendly. The challenges faces by researcher and industry are the high cost and low support from the government and industries, which, therefore, default to petroleum-based products.

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References

1. PERKASA (2009) Seminar on viability assessment of indigenous tree species and propagation techniques for planted forest development in Sarawak. Sarawak Timber Ind Dev Corp Newslett 5(6):6–8
2. Yamashita N, Ohta S, Hardjono A (2008) Soil changes induced by *Acacia mangium* plantation establishment: comparison with secondary forest and imperata cylindrica grassland soils in South Sumatra, Indonesia. Forest Ecol Manag 254:362–370
3. Inagaki M, Titin J (2009) Evaluation of site environments for agroforestry production. In: Gotoh T, Yokota Y (eds) Development of agroforestry technology for the rehabilitation of tropical forest. Japan International Research Center for Agricultural Sciences, Tsukuba, pp 26–31
4. Yang L, Liu N, Ren H, Wang J (2009) Facilitation by two exotic Acacia: *Acacia auriculiformis* and *Acacia mangium* as nurse plants in South China. Forest Ecol Manag 257:1786–1793

5. Hashim MN, Maziah Z, Sheikh AA (1990) The incidence of heartrot in *Acacia mangium* Willd. plantations: a preliminary observation. In: Appanah S, Ng FSP, Roslan I (eds) Malayan forestry and forest products research. Forestry Research Institute Malaysia, Kepong, pp 54–59
6. Weinland G, Zuhaidi A (1990) Management of *Acacia mangium* stands: tending issues. In: Appanah S, Ng FSP, Roslan I (eds) Malayan forestry and forest products research. Forestry Research Institute Malaysia, Kepong, pp 41–53
7. Garkhail SK, Meurs E, Van de Beld T, Peijs T (1999) Thermoplastic composites based on biopolymers and natural fibres. Int Conf Compos Mater 1:1–10
8. Morton WE, Hearle JWS (2008) Physical properties of textile fibres. Woodhead Publishing, Cambridge
9. Maldas D (1996) Cellulose-filled composites. In: Salamone JC (ed) Polymeric materials encyclopedia. CRC Press, Florida, p 1079
10. Mieck K-P, Lützkendorf R, Reussmann T (1996) Needle-Pubched hybrid nonwovens of flax and PP fibers-textile semi-products for manufacturing of fiber composites. Polym Compos 17:873–878
11. Hornsby PR, Hinrichsen E, Tarverdi K (1997) Preparation and properties of polypropylene composites reinforced with wheat and flax straw fibres: part II analysis of composite microstructure and mechanical properties. J Mater Sci 32:1009–1015
12. Peijs T, Garkhail S, Heijenrath R, van Den Oerver M, Bos H (1998) Thermoplastic composites based on flax fibres and polypropylene: influence of fibre length and fibre volume fraction on mechanical properties. Macromol Symp 127:193–203
13. Peijs T, van Melick HGH, Garkhail SK, Pott GT, Baillie CA (1998) Natural-fibre-mat reinforced thermoplastics based on upgraded flax fibres for improved moisture resistance. In: Crivillie Visconti I (ed) 8th European conference on composite materials (ECCM-8), science, technology and applications. Woodhead Publishing, Cambridge, pp 119–126
14. Jusoh I, Abu Zaharin F, Adam NS (2014) Wood quality of Acacia hybrid and second-generation *Acacia mangium*. BioResources 9:150–160
15. Zobel BJ, Buijtenen JP (1989) Wood variation—its causes and control. Springer, Heidelberg
16. Bowyer JL, Shmulsky R, Haygreen JG (2006) Forest products and wood science: an introduction. Springer, Heidelberg
17. Zobel BJ, Jet JB (1995) Genetics of wood production. Springer, Heidelberg, pp 1–289
18. Mohd Hamami S, Semsolbahri B (2003) Wood structures and wood properties relationship in planted Acacias: Malaysian examples. Int Symp Sustain Util 1:24–34
19. Rokeya UK, Akter Hossain M, Rowson Ali M, Paul SP (2010) Physical and mechanical properties of (*Acacia auriculiformis* × *A. mangium*) hybrid Acacia. J Bangladesh Acad Sci 34:181–187
20. Sattar MA, Kabir MF, Bhattacharjee DK (1994) Physical and mechanical properties of *Bambusa arundinacea*, *Bambusa longispiculata*, *Bambusa vulgaris* and *Dendrocalamus giganteus* [in Bangladesh]. Bangladesh Agric Res Counc 15:6–18
21. Laurila R (1995) Wood properties and utilization potential of eight fast-growing tropical plantation tree species. J Trop For Prod 1:209–221
22. Yakub M, Omar Ali M, Bhattacharjee DK (1979) Strength properties of Chittagong teak (*Tectona grandis*) representing different age groups. Government of the People's Republic of Bangladesh, Forest Research Institute
23. Pashin AJ, De Zeeuw C (1980) Textbook of wood technology: structure, identification, properties and uses of the commercial woods of the United States and Canada. McGraw-Hill, New York
24. Mohd Shukari M, Abdul Rasip AG, Mohd Lokmal N (2002) Comparative strength properties of six-year-old *Acaia mangium* and 4-year-old Acacia hybrid. J Trop For Prod 8:115–117
25. Garlotta D (2001) A literature review of poly(lactic acid). J Polym Environ 9:63–84
26. Hartmann MH (1998) High molecular weight polylactic acid polymers. In: Kaplan DL (ed) Biopolymers from renewable resources. Springer, Berlin, pp 367–411
27. Kharas GB, Sanchez-Riera F, Severson DK (1994) Polymers of lactic acid. In: Mobley DP (ed) Plastics from microbes—microbial synthesis of polymers and polymer precursors. Hanser Publishers, Munich, pp 93–258
28. Kricheldorf HR, Kreiser-Saunders I, Jurgens C, Wolter D (1996) Polylactides—synthesis, characterization and medical application. Macromol Symp 103:85–102
29. Gilding DK, Reed AM (1979) Biodegradable polymers for use in surgery—polyglycolic/poly(actic acid) homo- and copolymers: 1. Polymer 20:1459–1464
30. Kricheldorf HR, Kreiser-Saunders I, Boettcher C (1995) Polylactones: 31. Sn(II)octoate-initiated polymerization of L-lactide: a mechanistic study. Polymer 36:1253–1259

31. Vasanthakumari R, Pennings AJ (1983) Crystallization kinetics of poly(L-lactic acid). Polymer 24:175–178
32. Loomis GL, Murdoch JR (1990) U.S. Patent 4 317, 515
33. Loomis GL, Murdoch JR (1988) U.S. Patent 4 719, 246
34. Spinu M (1994) U.S. Patent 5 317, 64
35. Ikada Y, Jamshidi H, Tsuji H, Hyon SH (1987) Stereocomplex formation between enantiomeric poly(lactides). Macromolecules 20:904–906
36. Yui N, Dijkstra PJ, Feijen J (1990) Stereo block copolymers of L- and D-lactides. Macromol Chem Phys 191:481–488
37. Tsuji H, Ikada Y (1993) Stereocomplex formation between enantiomeric poly(lactic acids). 9. Stereocomplexation from the melt. Macromolecules 26:6918–6926
38. Stevels WM, Ankone MJK, Dijkstra PJ, Feijén J (1995) Stereocomplex formation in ABA triblock copolymers of poly(lactide) (A) and poly(ethylene glycol) (B). Macromol Chem Phys 196:3687–3694
39. Anderson AJ, Dawes EA (1990) Occurrence, metabolism, metabolic role, and industrial uses of bacterial polyhydroxyalkanoates. Microbiol Rev 54:450–472
40. Shah AA, Hasan F, Hameed A, Ahmed A (2008) Biological degradation of plastics: a comprehensive review. Biotechnol Adv 26:246–265
41. Khanna S, Srivastava AK (2005) Recent advances in microbial polyhdroxyalkanoates. Process Biochem 40:607–619
42. Lu J, Tappel RC, Nomura CT (2009) Mini-review: biosynthesis of poly(hydroxyalkanaotes). Polym Rev 49:226–248
43. Zinn M, Hany R (2005) Tailored material properties of polyhydroxyalkanoates through biosynthesis and chemical modification. Adv Eng Mater 7:408–411
44. Escapa IF, Morales V, Martino VP, Pollet E, Avérous L, García JL, Prieto MA (2011) Disruption of beta-oxidation pathway in *Pseudomonas putida* KT2442 to produce new functionalized PHAs with thioester groups. Appl Microbiol Biotechnol 89:1583–1598
45. Rai R, Keshavarz T, Roether JA, Boccaccini AR, Roy I (2011) Medium chain length polyhydroxyalkanoates, promising new biomedical materials for the future. Mater Sci Eng R Rep 72:29–47
46. De Roo G, Kellerhals MB, Ren Q, Witholt B, Kessler B (2002) Production of chiral R-3-hydroxyalkanoic acids and R-3-hydroxyalkanoic acid methylesters via hydrolytic degradation of polyhydroxyalkanoate synthesized by pseudomonads. Biotechnol Bioeng 77:717–722
47. Philip S, Keshavarz T, Roy I (2007) Polyhydroxyalkanoates: biodegradable polymers with a range of applications. J Chem Technol Biotechnol 82:233–247
48. Olivera ER, Arcos M, Naharro G, Luengo JM (2010) Unusual PHA biosynthesis. In: Chen G-Q (ed) Plastics from bacteria: natural functions and applications. Springer, Berlin, pp 133–186
49. Chen G-Q (2010) Plastics completely synthesized by bacteria: polyhydroxyalkanoates. In: Chen G-Q (ed) Plastics from bacteria: natural functions and applications. Springer, Berlin, pp 17–37
50. Chen G-Q (2010) Introduction of bacterial plastics PHA, PLA, PBS, PE, PTT, and PPP. In: Chen G-Q (ed) Plastics from bacteria: natural functions and applications. Springer, Berlin, pp 1–16
51. Wu C-S, Liao H-T (2014) The mechanical properties, biocompatibility and biodegradability of chestnut shell fibre and polyhydroxyalkanoate composites. Polym Degrad Stabil 99:274–282
52. Pickering KL, Aruan Efendy MG, Le TM (2016) A review of recent developments in natural fibre composites and their mechanical performance. Compos Part A Appl Sci Manuf 83:98–112
53. Shah DU, Porter D, Vollrath F (2014) Can silk become an effective reinforcing fibre? A property comparison with flax and glass reinforced composites. Compos Sci Technol 101:173–183
54. Bos HL, Van den Oever MJA, Peters O (2002) Tensile and compressive properties of flax fibres for natural fibre reinforced composites. J Mater Sci 37:1683–1692
55. Carr DJ, Cruthers NM, Laing RM, Niven BE (2005) Fibers from three cultivars of New Zealand flax (*Phormium tenax*). Text Res J 75:93–98
56. Holbery J, Houston D (2006) Natural-fiber-reinforced polymer composites in automotive applications. JOM 58:80–86
57. Summerscales J, Dissanayake NPJ, Virk AS, Hall W (2010) A review of bast fibres and their composites. Part 1-fibres as reinforcemetns. Compos Part A Appl Sci Manuf 41:1329–1335
58. Dos Santos PA, Giriolli JC, Amarasekera J, Moraes G. (2008) Natural fibers plastic composites for automotive applications In: Troy MI (ed) 8th Annual automotive composites conference and exhibition (ACCE 2008), SPE Automotive and Composites Division, pp. 492–500

59. Faruk O, Bledzki AK, Fink HP, Sain M (2014) Progress report on natural fiber reinforced composites. Macromol Mater Eng 299:9–26
60. Madsen B, Thygesen A, Lilholt H (2009) Plant fibre composites—porosity and stiffness. Compos Sci Technol 69:1057–1069
61. Madsen B, Lilholt H (2003) Physical and mechanical properties of unidirectional plant fibre composites—an evaluation of the influence of porosity. Compos Sci Technol 63:1265–1272
62. Angelov I, Wiedmer S, Evstatiev M, Friedrich K, Mennig G (2007) Pultrusion of a flax polypropylene yarn. Compos Part A Appl Sci Manuf 38:1431–1438
63. Rodriguez E, Petrucci R, Puglia D, Kenny JM, Vazquez A (2005) Characterization of composites based on natural and glass fibers obtained by vacuum infusion. J Compos Mater 39:265–282
64. Ho M-P, Wang H, Lee J-H, Ho C-K, Lau K-T, Leng J, Hui D (2012) Critical factors on manufacturing processes of natural fibre composites. Compos Part B Eng 43:3549–3562
65. Herrmann AS, Nickel J, Riedel U (1998) Construction materials based upon biologically renewable resources—from components to finished parts. Polym Degrad Stab 59:251–261
66. Jiang L, Hinrichsen G (1999) Flax and cotton fiber reinforced biodegradable polyester amide composites, 2. Characterization of biodgradation. Macromol Mater Eng 268:13–17
67. Mohanty AK, Khan MA, Sahoo S, Hinrichsen G (2000) Effect of chemical modification on the performance of biodegradable jute yarn-Biopol® composites. J Mater Sci 35:2589–2595
68. Van de Velde K, Kiekens P (2003) Effect of material and process parameters on the mechanical properties of unidirectional and multidirectional flax/polypropylene composites. Compos Struct 62:443–448
69. Amor IB, Rekik H, Kaddami H, Raihane M, Arous M, Kallel A (2010) Effect of palm tree fiber orientation on electrical properties of palm tree fiber-reinforced polyester composites. J Compos Mater 44:1553–1568
70. Herrera-Franco PJ, Valadez-Gonzalez A (2005) A study of the mechanical properties of short natural-fiber reinforced composites. Compos Part B Eng 36:597–608
71. Norman DA, Robertson RE (2003) The effect of fiber orientation on the toughening of short fiber-reinforced polymers. J Appl Polym Sci 90:2740–2751
72. Joseph PV, Joseph K, Thomas S (1999) Effect of processing variables on the mechanical properties of sisal-fiber-reinforced polypropylene composites. Compos Sci Technol 59:1625–1640
73. Carpenter JEP, Miao M, Brorens P (2007) Deformation behaviour of composites reinforced with four different linen flax yarn structures. Adv Mater Res 29–30:263–266
74. Khalfallah M, Abbes B, Abbes F, Guo YQ, Marcel V, Duval A, Vanfleteren F, Rousseau F (2014) Innovative flax tapes reinforced Acrodur biocomposites: a new alternative for automotive applications. Mater Des 64:116–126
75. Sanadi AR, Caulfield DF, Jacobson RE (1997) Agro-fiber/thermoplastic composites. In: Rowell RM, Rowell J (eds) Paper and composites from agro-based resources. CRC Press, Boca Raton, pp 377–401
76. Heidi P, Bo M, Roberts J, Kalle N (2011) The influence of biocomposite processing and composition on natural fiber length, dispersion and orientation. J Mater Sci Eng A 1:190–198
77. Beckermann GW, Pickering KL (2008) Engineering and evaluation of hemp fibre reinforced polypropylene composites: fibre treatment and matrix modification. Compos Part A Appl Sci Manuf 39:979–988
78. Chen P, Lu C, Yu Q, Gao Y, Li J, Li X (2006) Influence of fiber wettability on the interfacial adhesion of continuous fiber-reinforced PPESK composite. J Appl Polym Sci 102:2544–2551
79. Wu XF, Dzenis YA (2006) Droplet on a fiber: geometrical shape and contact angle. Acta Mech 185:215–225
80. Bénard Q, Fois M, Grisel M (2007) Roughness and fibre reinforcement effect onto wettability of composite surfaces. Appl Surf Sci 253:4753–4758
81. Sinha E, Panigrahi S (2009) Effect of plasma treatment on structure, wettability of jute fiber and flexural strength of its composite. J Compos Mater 43:1791–1802
82. Liu ZT, Sun C, Liu ZW, Lu J (2008) Adjustable wettability of methyl methacrylate modified ramie fiber. J Appl Polym Sci 109:2888–2894
83. Pickering K (2008) Properties and performance of natural-fibre composites. Woodhead Publishing, Cambridge
84. Cao Y, Sakamoto S, Goda K (2007) Effects of heat and alkali treatments on mechanical properties of kenaf fibers. 16th Int Conf Compos Mater 1:1–4

85. Rong MZ, Zhang MQ, Liu Y, Yang GC, Zeng HM (2001) The effect of fiber treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites. Compos Sci Technol 61:1437–1447
86. Huber T, Biedermann U, Muessig J (2010) Enhancing the fibre matrix adhesion of natural fibre reinforced polypropylene by electron radiation analyzed with the single fibre fragmentation test. Compos Interfaces 17:371–381
87. Beg MDH, Pickering KL (2008) Mechanical performance of Kraft fibre reinforced polypropylene composites: influence of fibre length, fibre beating and hygrothermal ageing. Compos Part A Appl Sci Manuf 39:1748–1755
88. Shah DU (2014) Natural fibre composites: comprehensive Ashby-type materials selection charts. Mater Des 62:21–31
89. Zhang L, Miao M (2010) Commingled natural fibre/polypropylene wrap spun yarns for structured thermoplastic composites. Compos Sci Technol 70:130–135
90. Baghaei B, Skrifvars M, Berglin L (2013) Manufacture and characterisation of thermoplastic composites made from PLA/hemp co-wrapped hybrid yarn prepregs. Compos Part A Appl Sci Manuf 50:93–101
91. Van de Weyenberg I, Ivens J, De Coster A, Kino B, Baetens E, Verpoest I (2003) Influence of processing and chemical treatment of flax fibres on their composites. Compos Sci Technol 63:1241–1246
92. Hughes M, Carpenter J, Hill C (2007) Deformation and fracture behaviour of flax fibre reinforced thermosetting polymer matrix composites. J Mater Sci 42:2499–2511
93. Goutianos S, Peijs T, Nystrom B, Skrifvars M (2006) Development of flax fibre based textile reinforcements for composite applications. Appl Compos Mater 13:199–215
94. Le Guen MJ, Newman RH (2007) Pulped Phormium tenax leaf fibres as reinforcement for epoxy composites. Compos Part A Appl Sci Manuf 38:2109–2115
95. Oksman K (2001) High quality flax fibre composites manufactured by the resin transfer moulding process. J Reinf Plast Compos 20:621–627
96. Oksman K, Wallstrom L, Berglund LA, Toledo RD (2002) Morphology and mechanical properties of unidirectional sisal—epoxy composites. J Appl Polym Sci 84:2358–2365
97. Phillips S, Baets J, Lessard L, Hubert P, Verpoest I (2013) Characterization of flax/epoxy prepregs before and after cure. J Reinf Plast Compos 32:777–785
98. Le MT, Pickering KL (2015) The potential of harakeke fibre as reinforcement in polymer matrix composites including modelling of long harakeke fibre composite strength. Compos Part A Appl Sci Manuf 76:44–53
99. Newman RH, Le Guen MJ, Battley MA, Carpenter JEP (2010) Failure mechanisms in composites reinforced with unidirectional Phormium leaf fibre. Compos Part A Appl Sci Manuf 41:353–359
100. Islam MS, Pickering KL, Foreman NJ (2011) Influence of alkali fiber treatment and fiber processing on the mechanical properties of hemp/epoxy composites. J Appl Polym Sci 119:3696–3707
101. Balakrishna A, Rao DN, Rakesh AS (2013) Characterization and modeling of process parameters on tensile strength of short and randomly oriented Borassus Flabellifer (Asian Palmyra) fiber reinforced composite. Compos Part B Eng 55:479–485
102. Brahim SB, Cheikh RB (2007) Influence of fibre orientation and volume fraction on the tensile properties of unidirectional Alfa-polyester composite. Compos Sci Technol 67:140–147
103. Devi LU, Bhagawan SS, Thomas S (1997) Mechanical properties of pineapple leaf fiber-reinforced polyester composites. J Appl Polym Sci 64:1739–1748
104. Snijder MHB, Bos HL (2000) Reinforcement of polypropylene by annual plant fibers: optimization of the coupling agent efficiency. Compos Interfaces 7:69–79
105. Bledzki AK, Mamun AA, Lucka M, Gutowsk VS (2008) The effects of acetylation on properties of flax fibre and its polypropylene composites. Express Polym Lett 2:413–422
106. Oksman K (2000) Mechanical properties of natural fibre mat reinforced thermoplastic. Appl Compos Mater 7:403–414
107. Sain M, Suhara P, Law S, Bouilloux A (2005) Interface modification and mechanical properties of natural fiber-polyolefin composite products. J Reinf Plast Compos 24:121–130
108. Li HJ, Sain MM (2003) High stiffness natural fiber-reinforced hybrid polypropylene composites. Polym Plast Technol Eng 42:853–862
109. Rana AK, Mandal A, Mitra BC, Jacobson R, Rowell R, Banerjee AN (1998) Short jute fiber-reinforced polypropylene composites: effect of compatibilizer. J Appl Polym Sci 69:329–338

110. Zampaloni M, Pourboghrat F, Yankovich S, Rodgers B, Moore J, Drzal L, Mohanty AK, Misra M (2007) Kenaf natural fiber reinforced polypropylene composites: a discussion on manufacturing problems and solutions. Compos Part A Appl Sci Manuf 38:1569–1580
111. Fink HP, Ganster J (2006) Novel thermoplastic composites from commodity polymers and man-made cellulose fibers. Macromol Symp 244:107–118
112. Feldmann M, Bledzki AK (2014) Bio-based polyamides reinforced with cellulosic fibres—processing and properties. Compos Sci Technol 100:113–120
113. El-Shekeil YA, Sapuan SM, Abdan K, Zainudin ES (2011) Effect of alkali treatment and pMDI isocyanate additive on tensile properties of kenaf fiber reinforced thermoplastic polyurethane composite. Int Conf Adv Mater Eng 15:20–24
114. Bodros E, Pillin I, Montrelay N, Baley C (2007) Could biopolymers reinforced by randomly scattered flax fibre be used in structural applications? Compos Sci Technol 67:462–470
115. Islam MS, Pickering KL, Foreman NJ (2010) Influence of alkali treatment on the interfacial and physico-mechanical properties of industrial hemp fibre reinforced polylactic acid composites. Compos Part A Appl Sci Manuf 41:596–603
116. Baghaei B, Skrifvars M, Salehi M, Bashir T, Rissanen M, Nousiainen P (2014) Novel aligned hemp fibre reinforcement for structural biocomposites: porosity, water absorption, mechanical performances and viscoelastic behavior. Compos Part A Appl Sci Manuf 61:1–12
117. Hu R, Lim JK (2007) Fabrication and mechanical properties of completely biodegradable hemp fiber reinforced polylactic acid composites. J Compos Mater 41:1655–1669
118. Arao Y, Fujiura T, Itani S, Tanaka T (2015) Strength improvement in injection-molded jute-fiber-reinforced polylactide green-composites. Compos Part B Eng 68:200–206
119. Ochi S (2008) Mechanical properties of kenaf fibers and kenaf/PLA composites. Mech Mater 40:446–452
120. Graupner N, Mussig J (2011) A comparison of the mechanical characteristics of kenaf and lyocell fibre reinforced poly(lactic acid) (PLA) and poly(3-hydroxybutyrate) (PHB) composites. Compos Part A Appl Sci Manuf 42:2010–2019
121. Felline F, Pappada S, Gennaro R, Passaro A (2013) Resin transfer moulding of composite panels with bio-based resins. SAMPE J 49:20–24
122. Chaw CS, Mitlohner R (2011) *Acacia mangium* willd: ecology and silviculture in Vietnam. Center for International Forestry Research (CIFOR), Bogor. https://doi.org/10.17528/cifor/003694
123. Hayward B (2009) The Acacia tree: a sustainable resource for Africa. Rowes the Printers, Penzance
124. Sreekala MS, Thomas S, Neelakantan NR (1996) Utilization of short oil palm empty fruit bunch fiber (OPEFB) as a reinforcement in phenol-formaldehyde resins: studies on mechanical properties. J Polym Eng 16(4):265–294
125. Abdul Khalil HPS, Ismail H (2000) Effect of acetylation and coupling agent treatments upon biological degradation of plant fibre reinforced polyester composites. Polym Test 20:65–75
126. Abdul Khalil HPS, Rozman HD, Ismail H, Rosfaizal Ahmad MN (2002) Polypropylene (PP)-*Acacia mangium* composites: the effect of acetylation on mechanical and water absorption properties. Polym Plast Technol Eng 41:453–468
127. Hill CAS, Khalil HPS, Hale MD (1998) A study of the potential of acetylation to improve the properties of plant fibres. Ind Crops Prod 8:53–63
128. Mosadeghzad Z, Ahmad I, Daik R, Ramli A, Jalaludin Z (2009) Preparation and properties of Acacia sawdust/UPR composite based on recycled PET. Malaysian Polym J 4:30–41
129. Shebani AN, Van Reenan AJ, Meincken M (2009) The effect of wood species on the mechanical and thermal properties of wood—LLDPE composites. J Compos Mater 43:1305–1318
130. Bledzki AK, Gassan J, Theis S (1998) Wood-filled thermoplastic composites. Mech Compos Mater 34:563–568
131. Bledzki AK, Gassan J (1999) Composites reinforced with cellulose based fibres. Prog Polym Sci 24:221–274
132. Mylsamy K, Rajendran I (2011) The mechanical properties, deformation and thermos mechanical properties of alkali treated and untreated Agave continuous fibre reinforced epoxy composites. Mater Des 32:3076–3084
133. Venkateshwaran N, Elaya Perumal A, Arunsundaranayagam D (2013) Fiber surface treatment and its effect on mechanical and visco-elastic behaviour of banana/epoxy composite. Mater Des 47:151–159

134. El-Shekeil YA, Sapuan SM, Khalina A, Zainudin ES, Al-Shuja'a OM (2012) Effect of Alkali treatment on mechanical and thermal properties of kenaf fiber-reinforced thermoplastic polyurethane composite. J Therm Anal Calorim 109:1435–1443
135. Rusli R, Samsi HW, Kadir R, Ujang S, Jalaludin Z, Misran S (2013) Properties of small diameter Acacia hybrid logs for biocomposites production. Borneo Sci 33:9–15
136. Saini G, Bhardwaj R, Choudhary V, Narula AK (2010) Poly(vinyl chloride)–Acacia bark flour composite: effect of particle size and filler content on mechanical, thermal, and morphological characteristics. J Appl Polym Sci 117:1309–1318
137. Mansur R, Natov M, Vassileva S (2002) Wood-polyvinylchloride composites as wood substitutes. J Univ Chem Technol Metallurgy 37:77
138. Inoue T, Suzuli T (1995) Selective crosslinking reaction in polymer blends. III. The effects of the crosslinking of dispersed EPDM particles on the impact behavior of PP/EPDM blends. J Appl Polym Sci 56:1113–1125
139. Taflick T, Maich EG, Ferreira LD, Bica CID, Rodrigues SRS, Nachtigall MB (2015) Acacia bark residues as filler in polypropylene composites. Polimeros 25:289–295
140. Ashori A (2008) Effects of nanoparticles on the mechanical properties of rice straw/polypropylene composites. Biores Technol 99:4661–4667
141. Charão LS (2005) Polinização em. Acacia Mearsii De Wild. Revista de Ciências Agro-Ambientais 3:92–109
142. Aji IS, Zainudin ES, Abdan K, Sapuan SM, Khairul MD (2012) Mechanical properties and water absorption behavior of hybridized kenaf/pineapple leaf fibre-reinforced high-density polyethylene composite. J Compos Mater 47:979–990
143. Idicula M, Joseph K, Thomas S (2010) Mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites. J Reinf Plast Compos 29:12–29