Not Only Delicious: Papaya Bast Fibres in Biocomposites

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Previous studies have shown favourable properties for papaya bast fibres, with a Young's modulus of up to 10 GPa and a tensile strength of up to 100 MPa. Because the fibres remain as residues on papaya plantations across the tropics in large quantities, their use in the making of green composites would seem to be worthy of consideration. This study aims to show that such composites can have very suitable mechanical properties, comparable to or even better than the common wood plastic composites (WPCs), and as such, represent a promising raw material for composites and a low-cost alternative to wood.

Keywords: Papaya bast fibres; Biocomposites; By-products; Biomechanical properties

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INTRODUCTION

The papaya plant (*Carica papaya*) is well known for its delicious fruits and its plentiful applications, *e.g.*, as a medicinal plant (Krishna *et al.* 2008; Lalla and Ogale 2015; Vij and Prashar 2015) or even as a meat tenderiser (Lieberei and Reisdorff 2007; Krishna *et al.* 2008). To date, no one has paid much attention to the papaya bast fibres. It is not known what papaya bast fibres were traditionally used for, and they are currently used only for floral decoration, on account of the decorative value of the fibre structure, as can be seen in Fig. 1B. From a biomechanical point of view, previous work on papaya's stem structure (Kempe *et al.* 2014) reveals a fibre material with the potential to provide reinforcing material in green composites (Kempe *et al.* 2015). Fibre characterisations using tensile tests have revealed a Young's modulus of up to 10 GPa and a tensile strength of up to 100 MPa (Kempe *et al.* 2015). Although the stiffness and strength of papaya fibres are indeed below average for natural fibres (Thygesen *et al.* 1997; Bismarck *et al.* 2005; Gurunathan *et al.* 2015), the density of 0.86 ± 0.07 g/cm^3 is in fact one of the lowest fibre densities in the plant world (Bledzki *et al.* 2001; Kempe *et al.* 2015), which may make these fibre composites attractive for lightweight engineering. Furthermore, material tests in the past showed that the fibre properties are virtually identical along the entire stem. Fibres at the stem base present a Young's modulus of 10.9 ± 3.8 GPa, and those at the apex present a modulus of 10.4 ± 2.3 GPa.

Biocomposites are one way to produce goods from renewable sources. This class of materials can be used in all kinds of different applications, ranging from medical devices to architectural decking, lightweight composites for sports equipment, and parts for automotive interiors (Carus *et al.* 2014). The cited authors showed that the production and use of biocomposites in the German automotive sector could increase fourfold over the period from 2012 to 2020 in view of their advantageous properties, such as the reduction of noise and overall component weight. Concurrently, a global rise is expected in bio-based composites due to the development of high-quality materials and a coincident increase in products (Endres *et al.* 2014). However, application of the natural fibres in engineering is impeded by the wide variation in their mechanical properties. At the same time, land is needed for the cultivation of bast fibre plants, which could lead to conflicts with areas designated for food production. Of particular interest, therefore, are plants that deliver both food and fibres, such as the well-known coconut palm (*Cocos nucifera*) (Tomczak *et al.* 2007) or, as presented here, the papaya (*Carica papaya*) (Kempe et al. 2015).

In commercial plantations (Fig. 1A), papaya plants are replaced after three to five years. The old plant stems are composted, and the plant tissues decay quickly. However, if the stems were to be subjected to fibre extraction, a large quantity of raw material could be made available for composites, with the total quantity estimated at 1.2 million tons every three to five years (Kempe *et al.* 2015). This could represent a cheap and easily accessible source of fibre material and could also provide additional income for papaya farmers in tropical and subtropical regions, especially in light of the steadily growing market demand for tropical fruits and the fact that papaya is produced in nearly 60 countries (Evans and Ballen 2015), yielding a gross production value of 4054 million US$ in 2013 (FAOSTAT 2016).

This article focuses on short-fibre reinforced polymers, which are often used in injection moulding or in extrusion and pressing processes. Two main components are needed for the combined material: the matrix and the filler. The matrix fixes the fibres in place and determines the outer form of the composite. Without the matrix, the aforementioned technologies would not be practicable. The matrix materials transfer forces to the fibres and, at the same time, provide protection. Raising the filler content affects the mechanical properties of the composite primarily by increasing the elastic and tensile modulus and helps to reduce the amount of polymer needed (Bledzki *et al.* 1998). In this study, papaya bast fibre reinforced composites are presented in a common polypropylene (PP) matrix, in contrast to wood-plastic composites (WPCs), which belong to the class of natural fibre composites (NFC).

EXPERIMENTAL

Materials and Methods

Various papaya fibres were used for the composite samples. To compare the different cultivation areas, and to reflect the work of Kempe *et al.* (2015), macerated fibres from two sources were chosen: one-year-old greenhouse plants grown at the Institute for Botany of TU Dresden (Germany), and two-year-old commercial plantation plants from Caxito, Province Bengo in northern Angola (8°35´38´´S, 13°37´38´´E). While the greenhouse plants merely reached a basal diameter of 2 cm, plants from the plantation achieved a diameter of up to 20 cm, which, in turn, has an influence on the processing of the fibres. To isolate the fibres from the parenchymatous tissues, the plants were watered for one month. This microbiological retting process facilitates the removal of the fibres. The subsequently macerated and dried material was processed to fragments of approximately 10 mm in length (as shown in Fig. 1C) in a cutting mill, to ensure processing in a heater cooler mixer (HCM) (MTI-M35FU/KMV60, Detmold, Germany).

In this study, the papaya bast fibres were compared with the wood powder LIGNOCEL BK 40-90, purchased from J. Rettenmaier and Söhne GmbH + Co KG

Rosenberg, Germany. The softwood product consists of a maximum of 10% fibres with a size greater than 550 µm and a maximum of 95% with a size greater than 150 µm (manufacturer's specification).

The polymer component polypropylene, PP Moplen HP501L from LyondellBasell, Rotterdam, Netherlands was chosen to grant comparability to materials used in the industry. The used PP has a density of 0.9 g/cm^3 and a melt flow rate (MFR) of 6 g/10 min (230 °C, 2.16 kg). The PP grafted with maleic anhydride (MahPP) served as a bonding agent to create sufficient fibre-matrix adhesion. The MFR of SCONA TPPP 8112 FA (BYK Additives and Instrument, Wesel, Germany) is higher than 80 g/10 min, and its content of maleic anhydride is 1.4%.

The composites were manufactured in a M35FU/KMV60 heater cooler mixer by combining 30 wt.% filler material with 65 wt.% polymer and 5 wt.% bonding agent. The compound from the HCM was crushed in a cutting mill to approximately 5-mm size granules. Test specimens of type 1BA according to DIN EN ISO 527 (2012) were produced in a HAAKE MiniJet II (Braunschweig, Germany), as can be seen in Fig. 1d.

The tests included a total of 32 specimens, which were tensile tested according to DIN EN ISO 527 (2012) with a test speed of 2 mm/min at a Hegewald & Peschke Inspekt 10.

The processing method is supposed to be as application-oriented as possible. In this study, therefore, papaya bast fibres are not milled to a powder but merely crushed into fragments. If papaya fibres are processed into composites on-site, they will most likely be milled not into to a powder but rather, as we did, into a shredded fibrous material suitable for further processing.

For the purposes of microscopic analysis, sections taken from a young papaya stem were stained with Basic Blue 140 and Safranin O and examined using a Motic SMZ 168 binocular microscope.

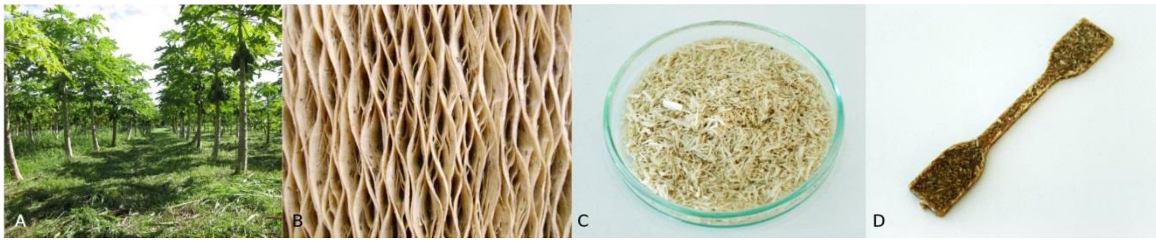

Fig. 1. (A) Papaya plantation, (B) papaya fibre mesh after maceration, (C) ground fibre material, and (D) test sample

RESULTS AND DISCUSSION

Mechanical tests revealed good overall performance by the papaya composites. The Young's moduli of wood powder composites increased by 107%, and papaya composites are capable of producing increases of 126% (plantation) to 162% (greenhouse). The tensile strength of the papaya composite specimens increased by 26.4% (greenhouse) and 21.4% (plantation), and the addition of wood powder did not have a significant effect on tensile strength, as can be seen in Table 1. Peltola *et al.* (2014) found similar results for bleached softwood and hardwood kraft pulp composites, as well as for wood fibre composites, although the results achieved by these materials did not reach the level of the papaya fibre composites.

Table 1. Results from the Tensile Tests

Material	Young's modulus in MPa	Tensile strength in MPa	Elongation at max. force in %
PP	1559.8 (111.7)	34.5 (2.2)	8.3 (0.6)
Papaya greenhouse-PP-MahPP	4093.1 (78.3)	43.6 (0.4)	2.8 (0.2)
Papaya plantation-PP-MahPP	3408.7 (500.3)	41.9 (1.2)	2.7 (0.3)
Wood-PP-MahPP	3224.8 (118.1)	32.6 (0.3)	4.0 (0.1)

(Number of tested samples each is 8. Values are means and standard deviations are bracketed.)

Although previous investigations revealed higher tensile strengths for plantation fibres than for greenhouse fibres (Kempe *et al.* 2015), this study examined the composites of both, and they gave approximately equal values. Microsections of the samples, as shown in Fig. 2, may explain why the material performed in this way. The WPC microsections differed considerably from the papaya microsections because the bundle structures of the latter had been made visible by the retting process, whereas the wood was subjected to spontaneous shredding at random positions. Lignified wood cells were recognisable by their apparent growth zone, where the cells were in alignment. During the development of secondary xylem, the process of secondary wall deposition is gradual (Murmanis and Sachs 1969). The WPC was therefore found to contain particles with different levels of sclerenchymatisation, as can be seen in Fig. 2 (C2, C3). In contrast, the papaya bast fibre cells were not aligned but rather presented a typical bundle-like structure because of the bast fibre growth process, as shown in Fig. 3. The bundle sizes varied from 50 to 800 µm depending on the developmental stage of the plant. The composite samples with plantation fibres showed a higher percentage of larger fibre cross-sections compared to greenhouse samples, which can be seen in Fig. 2 (A1, A2, B1, and B2). Papaya fibres used in samples therefore have a different *L*/*D* ratio. Whereas the fibre length is approximately 10 mm, the diameter of plantation and greenhouse fibres varies apparently (Fig. 2, A1, B1). According to Migneault *et al.* (2009), higher *L*/*D* ratios can improve the mechanical properties, but other authors do not report an improvement of mechanical properties due to higher *L*/*D* ratios (Yam *et al.* 1990; Le Baillif and Oksman 2006). However, it is possible for *L*/*D* ratios to be changed completely during processing (Peltola *et al.* 2014). Bledzki *et al.* (1998) recommend short and tiny fibres (0.24 to 0.35 mm particle size on average), which have a higher specific surface area and therefore better compatibility, yielding a superior fibre material than that produced with long and thick fibres. This is reflected in the greater standard deviation of plantation fibre samples, which have a relatively high inhomogeneity when compared with greenhouse fibre samples. Furthermore, the material properties are affected by the density differences between the samples due to fibre size (Sobczak *et al.* 2012). Accordingly, the higher Young's modulus and tensile strength found in fibre material from plantations do not necessarily yield favourable composite samples.

Squashed fibre cells were observed in all of the samples (Fig. 2 A3, B3, C3). It is certain that both the retting and grinding processes have an impact on fibre quality.

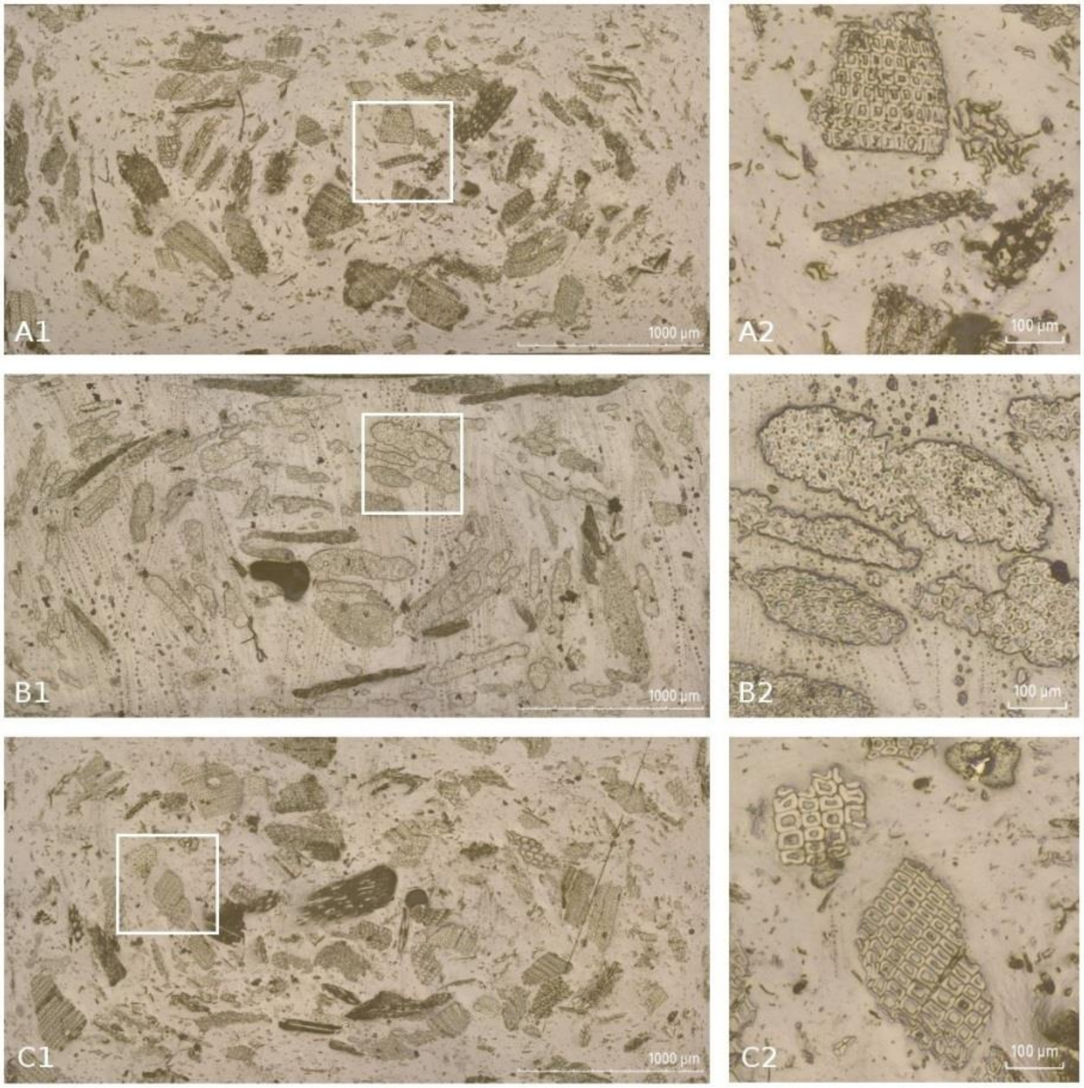

Fig. 2. Microsections of tested samples: (A1) greenhouse fibre composite and in detail (A2); (B1) plantation fibre composite and in detail (B2); (C1) WPC and in detail (C2)

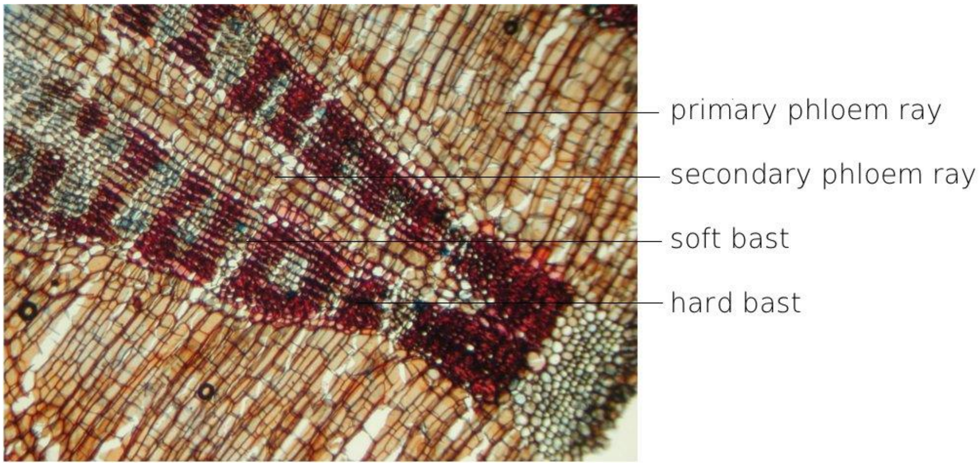

Fig. 3. Cross-section of Papaya bast fibres; fibre bundles, defined as hard bast (dyed red), are separated from one another by phloem rays and soft bast

In terms of price segments, papaya fibre composites represent a worthwhile alternative. Polylactic acid (PLA) is a well-known biopolymer, whose worldwide production rose from 175 tons in 2011 to 675 tons in 2015. Production is forecast to rise to a volume of 800 tons in 2020. The price of PLA currently stands at 1.80 euros/kg, compared with 1.40 euros/kg for PP (Endres *et al.* 2014). Ideally, the price of the composite would be lower than that of the pure polymer. It is difficult to compare prices in light of the changing circumstances and the relatively small and unstable production volumes of natural fibres. This is the point at which it becomes pertinent to discuss the use of by-products. Wood powder-filled polymers, such as WPCs, represent another approach to this idea. Market surveys show that the most favourable prices for NFC granulate start at 1.00 to 2.40 euros (Endres *et al.* 2014). Based on the above polymer prices, the calculations including wood powder prices of 0.52 euros/kg (Vogt *et al.* 2006) yield composite prices of 1.42 euros/kg (PLA) or 1.14 euros/kg (PP). Although a manufacturing chain has not yet been established, papaya fibres could probably be produced even more cheaply than wood powder and also yield better material properties in composites.

CONCLUSIONS

1. Renewable resources contribute to the achievement of ambitious climate protection goals thanks to their biodegradability and, in the case of papaya bast fibres, due to their carbon neutrality. It has become increasingly necessary to reuse residual materials in order to avoid competition with food production, and it is certainly possible to reuse papaya fibres in biocomposites. As papaya bast fibres accumulate in plantations anyway, they do not give rise to competition for cultivation areas and are therefore excellently suited to engineering applications. The only prerequisites for their use are a one-month period of storage in water to allow retting of the bast and subsequent drying in the sun.
2. Under laboratory conditions, the papaya bast fibres exhibited good processability, including for injection moulding, which is the most common production process in plastics engineering. Their composites therefore present very suitable mechanical properties that are comparable with, or even better than, those of a typical WPC. Composite technology is not yet established in papaya-producing countries, but it should be easy to pass on modern technical standards in order to create new sources of income while also promoting biodegradable products.

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REFERENCES CITED

Bismarck, A., Mishra, S., and Lampke, T. (2005). "Plant fibres as reinforcement for green composites," in: *Natural Fibres, Biopolymers and Biocomposites*, A. K. Mohanty, M. Mishra, L. T. Drzal (eds.), CRC Press, Boca Raton, FL, 37-108.

Bledzki, A. K., Reihmane, S., and Gassan, J. (1998). "Thermoplastics reinforced with wood fillers: A literature review," *Polymer-Plastics Technology and Engineering* 37(4), 451-468. DOI: 10.1080/03602559808001373

Bledzki, A. K., Zhang, W., and Chate, A. (2001). "Natural-fibre-reinforced polyurethane microfoams," *Composites Science and Technology* 61(16), 2405-2411. DOI: 10.1016/S0266-3538(01)00129-4

Carus, M., Eder, A., Dammer, L., Korte, H., Scholz, L., Essel, R., and Breitmayer, E. (2014). "WPC/NFC Market Study 2014-03, European and Global Markets 2012 and Future Trends," nova-Institut GmbH, Hürth, Germany

DIN EN ISO 527 (2012). "Plastics – Determination of tensile properties," DIN Deutsches Institut für Normung e.V., Beuth Verlag GmbH, Berlin, Germany

Endres, H.-J., Kohl, M., and Berendes, H. (2014). "Biobasierte Kunststoffe und biobasierte Verbundwerkstoffe," *Marktanalyse nachwachsende Rohstoffe, Schriftenreihe Nachwachsende Rohstoffe* 34, Fachagentur Nachwachsende Rohstoffe e. V. (FNR), Germany.

Evans, E. A., and Ballen, F. H. (2015). "An overview of global papaya production, trade, and consumption," FE913, Food and Resource Economics Department, UF/IFAS Extension.

FAOSTAT (2016). © FAO Statistics Division (http://faostat3.fao.org/download/Q/QV/E), Accessed on 10 March, 2016.

Gurunathan, T., Mohanty, S., and Nayak, S. K. (2015). "A review of the recent developments in biocomposites based on natural fibres and their application perspectives," *Composites: Part A- Applied Science and Manufacturing* 77, 1-25. DOI: 10.1016/j.comositesa.2015.06.007

Kempe, A., Lautenschläger, T., Lange, A., and Neinhuis, C. (2014). "How to become a tree without wood- Biomechanical analysis of the stem of *Carica papaya* L.," *Plant Biology* 16(1), 264-271. DOI: 10.1111/plb.12035

Kempe, A., Göhre, A., Lautenschläger, T., Rudolf, A., Eder, M., and Neinhuis, C. (2015). "Evaluation of bast fibres of the stem of *Carica papaya* L. for application as reinforcing material in green composites," *Annual Research and Review in Biology* 6(4), 245-252. DOI:10.9734/ARRB/2015/15407

Krishna, K. L., Paridhavi, M., and Patel, J. A. (2008). "Review on nutritional, medicinal, and pharmacological properties of Papaya (*Carica papaya* Linn.)," *Natural Product Radiance* 7(4), 364-373.

Lalla, J. K., and Ogale, S. (2015). "Pharmacognistic evaluation of leaves of *Carica papaya* Linn.," *World Journal of Pharmacy and Pharmaceutical Sciences* 4(8), 1066-1081.

Le Baillif, M., and Oksman, K. (2006). "The influence of the extrusion process on bleached pulp fiber and its composites," Proceedings of the Progress in Wood and Biofibreplastic Composites conference, Toronto, May 2006.

Lieberei, R., and Reisdorff, C. (2007). "Obstliefernde Pflanzen," in: *Nutzpflanzenkunde*, Thieme-Verlag, Stuttgart, Germany 172-175. DOI: 10.1055/b-002-43898

Migneault, S., Koubaa, A., Erchiqui, F., Chaala, A., Englund, K., and Wolcott, W. P. (2009). "Effects of processing method and fiber size on the structure and properties of wood-plastic composites," *Composites Part A-Applied Science and Manufacturing* 40, 80-85. DOI: 10.1016/j.compositesa.2008.10.004

Murmanis, L., and Sachs, I. B. (1969). "Seasonal development of secondary xylem in *Pinus strobus* L.," *Wood Science and Technology* 3(3), 177-193. DOI: 10.1007/BF00367210

Peltola, H., Pääkkönen, E., Jetsu, P., and Heinemann, S. (2014). "Wood based PLA and PP composites: Effect of fibre type and matrix polymer on fibre morphology, dispersion, and composite properties," *Composites Part A-Applied Science and Manufacturing* 61, 13-22. DOI: 10.1016/j.compositesa.2014.02.002

Sobczak, L., Lang, R. W., and Haider, A. (2012). "Polypropylene composites with natural fibers and wood – General mechanical property profiles," *Composites Science and Technology* 72, 550-557. DOI: 10.1016/j.compscitech.2011.12.013

Thygesen, L. G., Eder, M., and Burgert, I. (1997). "Dislocations in single hemp fibres-investigations into the relationship of structural distortions and tensile properties at the cell wall level," *Journal of Materials Science* 42(2), 558-564. DOI: 10.1007/s10853-006-1113-5

Tomczak, F., Sydenstricker, T. H. D., and Satyanarayana, K. G. (2007). "Studies on lignocellulosic fibres of Brazil. Part II: Morphology and properties of Brazilian coconut fibres," *Composites Part A-Applied Science and Manufacturing* 38(7), 1710-1721. DOI: 10.1016/j.compositesa.2007.02.004

Vij, T., and Prashar, Y. (2015). "A review on medicinal properties of *Carica papaya* Linn.," *Asian Pacific Journal of Tropical Disease* 5(1), 1-6. DOI: 10.1016/S2222-1808(14)60617-4

Vogt, D., Karus, M., Ortmann, S., Schmidt, C., and Gahle, C. (2006). "Wood-Plastic-Composites (WPC) Holz-Kunststoff-Verbundwerkstoffe - Märkte in Nordamerika, Japan und Europa mit Schwerpunkt auf Deutschland – Technische Eigenschaften – Anwendungsgebiete – Preise – Märkte –Akteure," nova-Institut GmbH, Hürth, Germany.

Yam, K. L., Gogoi, B. K., Lai, C. C., and Selke, S. E. (1990). "Composites from compounding wood fibers with recycled high density polyethylene," *Polym. Eng. Sci.* 30(11), 693-699. DOI: 10.1002/pen.760301109

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