Almost Forgotten Resources – Biomechanical Properties of Traditionally Used Bast Fibers from Northern Angola

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The wide use of natural fibers has a long-standing history in Africa. In northern Angola, three native fiber plant species, namely *Urena lobata*, *Triumfetta cordifolia*, and *Dombeya burgessiae*, were investigated with regard to their potential usage in modern applications, such as green composites. Bast fibers of the three species were analyzed morphologically, chemically, and mechanically to determine properties such as fiber density, cellulose content, Young's modulus, tensile strength, and breaking strain. In comparison to other natural fibers, all three species were characterized by high Young's moduli up to 60 GPa and tensile strengths up to 950 MPa, yet retting is crucial to unfold the maximum strength of the fibers. Extending the retting time revealed higher values but probably negatively influences economic efficiency. The results demonstrated that the analyzed plants deliver strong and resistant fibers; based on their biomechanical performance, they are alternatives to commercially used natural fibers, such as jute (*Corchorus* spp.). However, as with other natural fibers, there was high variation in the mechanical properties in the studied species.

Keywords: Bast fibers; Tensile tests; Mechanical properties; Young's modulus; Fiber characterization; Angola

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INTRODUCTION

The increasing awareness of environmental issues and the necessity of recycling due to the decline of the world-wide oil reserves has fostered renewed interest in composite materials using natural fibers as replacements for synthetic materials (Tahir *et al.* 2011).

Plant fibers as reinforcing structures in composites offer various advantages over synthetic materials, such as glass and carbon. They ensure carbon neutrality when being burned, which is important for ecological issues (Netravali and Chabba 2003). Furthermore, they are biodegradable, renewable, and less abrasive to production machinery; they show a high specific stiffness and superior properties as acoustic and thermal isolators (Netravali and Chabba 2003; Wambua *et al.* 2003; Elenga *et al.* 2009; Faruk *et al.* 2012). The costs of the fibers (on a volumetric basis) are low (Tahir *et al.* 2011; Faruk *et al.* 2012). Nevertheless, there are disadvantages, especially the high variation of mechanical properties depending on internal growth processes, geographic origin, nutrient availability, exposure to wind, water, and sunlight, or age of the plant (Netravali and Chabba 2003; Faruk *et al.* 2012). Further problems are the incompatibility with some polymer matrices and the hydrophilic character of all natural fibers, which leads to high levels of moisture absorption (Riccieri *et al.* 1999; Faruk *et al.* 2012). Additionally, low processing temperatures are needed to avoid fiber damage, which limits their use with some thermoplastic resins (Netravali and Chabba 2003).

However, bio-fiber reinforced polymeric materials are increasingly important for the production of light and stiff constructions in various industrial sectors. They are commonly used to manufacture casing and packaging structures, as not all components in these materials require advanced mechanical properties (Netravali and Chabba 2003). In the automotive industry, green composites are applied for the fabrication of door panels, dashboards, or spare wheel recesses, where the low splinter tendency, air permeability (facilitates lamination), and low density are appreciated (Carus 2008).

To be used industrially, the biomechanical properties of natural fibers must be characterized so that a suitable matrix polymer can be selected; this ensures the appropriate material properties of the composite. The mechanical properties of various commercially used natural fibers such as flax, hemp, jute, and sisal have been comprehensively examined (Muessig *et al.* 2010; Faruk *et al.* 2012). The characterization and evaluation of industrially unknown bio-fibers is important for the improvement of composites and contributes to a larger selection of technically usable biological material, which is crucial to avoid unilateral dependencies.

Urena lobata (also known as Congo jute), *Triumfetta cordifolia*, and *Dombeya burgessiae* possess promising bast fibers. These species belong to the Malvaceae and grow abundantly in all parts of tropical Africa (Brink and Achigan-Dako 2012). They partly appear as weeds in cultivated crops (Latham and Konda ku Mbuta 2014). In Angola, these fibers are traditionally utilized for the weaving of baskets, mats, textiles, nets, carpets, and other commodities (Brink and Achigan-Dako 2012). Moreover, various parts of the plants are applied as medicine (Latham and Konda ku Mbuta 2014). However, the traditional knowledge of these fibers tends to vanish among the younger generations and therefore needs to be recorded. These fibers may provide additional sources for the replacement of synthetic materials and also create opportunities for local communities to build small businesses by producing these fibers.

According to interviews with the local population, the investigated fibers became internationally important during the colonial era, when they were used in the production of coffee sacks for export purposes. The broad field of established traditional applications makes them interesting for the fabrication of industrial materials, such as composites.

Although the long traditional and partly commercial use of these fibers is documented, the biomechanical properties have not been analyzed. To evaluate the potential of the fibers for materials science, key parameters such as Young's modulus, breaking strain, and tensile strength were determined in tensile tests. These values were related to different retting times of the bast fibers. Additionally, chemical and morphological analyses as well as density measurements were conducted.

EXPERIMENTAL

Materials

In a botanical definition, the term fiber refers to a single cell that is much longer than it is wide (Kadereit *et al.* 2014). However, the term fiber is also applied to bundles of individual cells and will be used here in that sense as well.

The Young's modulus, tensile strength, and breaking strain of the bast fibers derived from *Urena lobata* L., *Triumfetta cordifolia* A. Rich., and *Dombeya burgessiae* Gerrard ex Harv. were experimentally determined by static tension tests. The fibers were harvested in the province of Uíge in northern Angola. After cutting one-year-old plants near the ground, the bark including the associated fibers was peeled from the remaining wooden core. Subsequently, the fiber layer was separated from the bark by peeling off the epidermal tissue with a knife (Fig. 1a, b). Because bast fibers are connected to the adjacent cells, retting is necessary to remove non-cellulosic material (*e.g.*, pectins) and to release individual fibers (Tahir *et al.* 2011). Traditionally, retting involves immersing fibers in small rivers or streams with permanently flowing water. In this study, the fibers were immersed in plastic buckets with tap water that was changed daily for three (3W) or six weeks (6W) (water temperature: 18 °C, water to fiber ratio: 50:1); then, the fibers were air-dried (Fig. 1c). For each species, one set of fibers remained untreated (UT) in order to analyze the influence of retting on biomechanical properties.

Fig. 1. (a) *Triumfetta cordifolia* plant with fruits in July 2014 in the Uíge province of Angola; (b) separating bast fibers and bark; (c) bast fibers of *T. cordifolia* after three weeks of retting

Methods

Morphological analyses

To observe the distribution of the fiber cells within the plants, fresh shoot axes were preserved in 96% ethanol (subsequently diluted to 70%) and analyzed using a light microscope (Carl Zeiss Axioskop 2, Jena, Germany) and a reflected light microscope (Olympus SZX16, Jena, Germany). The axes were cut with a razor blade and stained with Astra-blue/Safranin (Morphisto GmbH, Frankfurt a.M., Germany).

The cross-sectional area of bast fibers and the lumen size of the fiber cells were determined using Image-Pro Plus 7.0 software (Media Cybernetics Inc., Rockville, USA). For each species, the lumen of 20 emergent cells of bundles closest to the cambium and 20 mature cells of adjacent bundles (towards the periphery of the stem) were measured.

Wide-angle X-ray diffraction (WAXD) was used to calculate average microfibril angles (MFA) of the cell wall according to Lichtenegger *et al.* (1998). The measurements took place at the Institute of Physics at Montanuniversität Leoben in Austria.

Chemical analyses

Cellulose contents were investigated according to Kuerschner and Hoffer (1931). Lignin contents were determined as described (Theander and Westerlund 1986). Toluene-ethanol extraction was used to analyze contents of residual extracts within the fibers. The chemical analyses took place at the Institute of Wood and Plant Chemistry of the Technische Universität Dresden in Germany. Two samples of UT-, 3W- and 6W-fibers were analyzed for each plant species.

Density measurements

Fiber density was determined using a precision balance and a pycnometer with an accuracy of 0.01 g and 0.05 mL. Eight samples of UT, 3W, and 6W fibers were analyzed.

Mechanical analyses

All specimens were subjected to tension tests using a Zwickiline Z2.5 (Zwick GmbH, Ulm, Germany) equipped with a 50 N load cell. The samples were tested at a strain rate of 1 mm/min (position-controlled) until failure. For each species, 100 samples each of UT fibers and 3W fibers were tested; for *T. cordifolia* and *D. burgessiae*, an additional 50 samples of 6W fibers were analyzed. All tension tests were conducted at constant room temperature (22 °C) and without further preconditioning of the retted and unretted fibers. Stress-strain diagrams were compiled with the X-Line software (Zwick GmbH, Ulm, Germany).

Fiber samples usually represent bundles with approximately rectangular cross-sections. Therefore, width and thickness were investigated. The width of specimens was determined by light microscopy. The thickness was measured with a light microscope (3W and 6W fibers) or a Vernier caliper (UT fibers). Young's moduli were calculated from the average thickness of 20 samples. Prior to tension tests, each specimen was fixed on two pieces of paper with adhesive (Pattex Ultra Gel) to avoid slipping within the clamps. Young’s moduli were calculated from the slope of the initial linear part of the stress-strain curve. Ultimate tensile strength and breaking strain were determined also.

RESULTS AND DISCUSSION

Morphological Properties

The cross-sections of all investigated species revealed Tilia-type structures (Kadereit *et al.* 2014) with a cylindrical organization of conductive elements and a continuous cambium. The bast fibers were bundles of individual sclerenchyma cells located within the secondary phloem (Fig. 2). The size of the lumen of individual fiber cells decreased with increasing distance from the cambium (Fig. 3). The difference of the lumen was 58.1%, 73.8%, and 61.0% in *T. cordifolia*, *U. lobata*, and in *D. burgessiae*, respectively. See below for information regarding determined microfibril angles (MFA) of the secondary cell wall of the fiber cells and average cross sectional bast fiber contents of the investigated plant species (Table 1).

Table 1. Morphological Properties of Analyzed Plant Species

Plant	Bast Fiber Content (%)	Microfibril Angle (MFA) (°)	Lumen Size of Emergent Fiber Cells (µm)	Lumen Size of Mature Fiber Cells (µm)	Difference of Lumen Size (%)
T. cordifolia	9 –j12	7 ± 5	11.48 (± 2.66)	4.81 (± 1.23)	-58.1
U. lobata	9 – 10	6 ± 4	9.21 (± 1.98)	2.41 (± 0.49)	-73.8
D. burgessiae	10 – 13	7 ± 5	8.93 (± 1.44)	3.47 (± 0.44)	-61.0

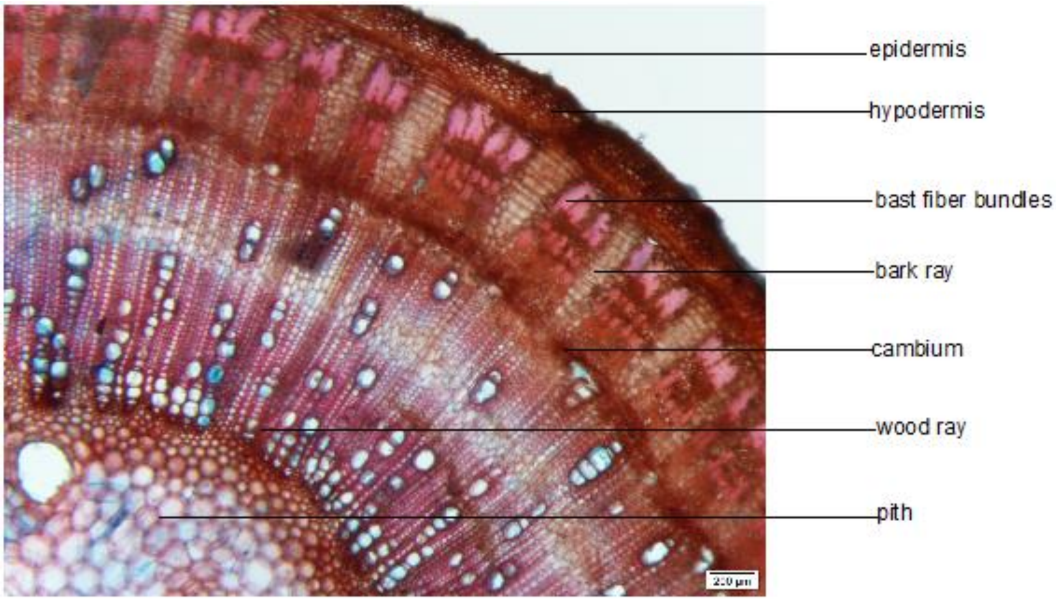

Fig. 2. Cross section of *T. cordifolia* stem (representative of all analyzed Malvaceae)

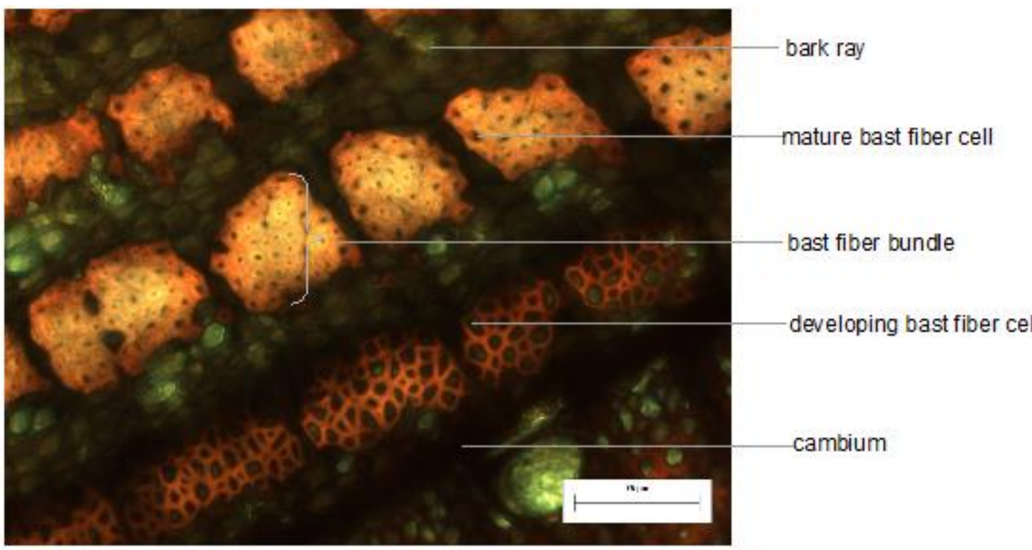

Fig. 3. Detailed view of fiber cells within the shoot axis

Chemical Composition

During retting, non-cellulosic materials such as pectin and hemicellulose are removed, and individual fibers are released (Tahir *et al.* 2011).

Lignin and holocellulose content increased with retting time, which was clearly visible in *T. cordifolia*. UT fibers revealed lignin contents of 9.90 ± 0.14% and holocellulose contents of 72.26 ± 0.09%; in 3W fibers, these values rose to 12.73 ± 0.05% and 82.72 ± 0.17%, respectively. 6W fibers showed the highest values (13.67 ± 0.16% lignin and 87.90 ± 0.07% holocellulose). *U. lobata* and *D. burgessiae* showed similar trends (Table 2 and Fig. 4).

Table 2. Chemical Composition of Bast Fibers from All Analyzed Plant Species

Bast Fiber	Extract Content (%)	Lignin Content (%)	Holocellulose Content (%)
T. cordifolia (UT)	3.10	9.90 ± 0.14	72.26 ± 0.09
T. cordifolia (3W)	0.85	12.73 ± 0.05	82.72 ± 0.17
T. cordifolia (6W)	0.70	13.67 ± 0.16	87.90 ± 0.07
U. lobata (UT)	2.20	8.87 ± 0.66	81.35 ± 0.03
U. lobata (3W)	0.74	9.90 ± 0.03	79.61 ± 0.09
U. lobata (6W)	0.55	10.08 ± 0.23	89.27 ± 0.93
D. burgessiae (UT)	5.26	12.51 ± 0.17	71.13 ± 0.07
D. burgessiae (3W)	0.87	14.11 ± 0.65	78.05 ± 0.26
D. burgessiae (6W)	0.82	16.23 ± 0.06	82.12 ± 1.24
UT, untreated; 3W, fibers retted for three weeks; 6W, fibers retted for six weeks			

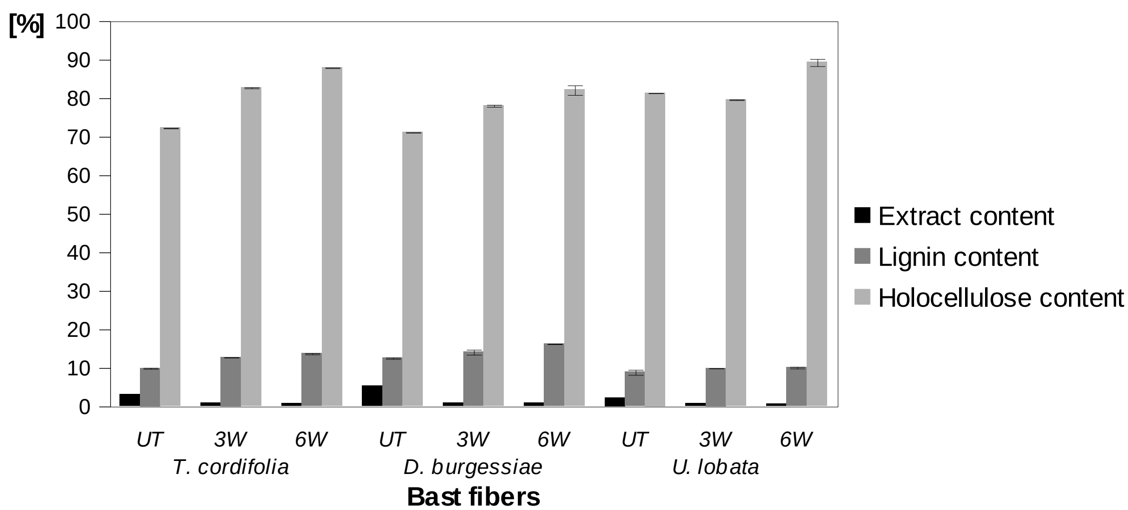

Fig. 4. Chemical composition of all plant species. UT, untreated; 3W, fibers retted for three weeks; 6W, fibers retted for six weeks

Density

The fiber density increased with retting time. For *T. cordifolia*, the density of UT fibers was 1.16 ± 0.07 g/cm^3, 3W fibers revealed 1.26 ± 0.13 g/cm^3, and 6W fibers averaged 1.41 ± 0.06 g/cm^3. *U. lobata* and *D. burgessiae* showed similar trends (Table 3).

Mechanical Properties

From tension tests, the Young's modulus, tensile strength, and breaking strain of the specimens were calculated (Table 3). Not surprisingly, a strong gradient of biomechanical properties within the fibers became apparent: Young's modulus and tensile strength increased proportionally to the duration of retting, while breaking strain decreased at the same time.

Untreated fibers of *T. cordifolia* and *U. lobata* revealed relatively low Young's moduli of 12.5 ± 3.3 GPa and 16.5 ± 4.0 GPa, respectively, whereas samples after three weeks of retting showed considerably increased values (53.4 ± 10.3 GPa or 51.7 ±

9.7 GPa). In *D. burgessiae* the increase was less pronounced since UT-fibers showed 12.7 ± 3.8 GPa, whereas 3W-fibers revealed 21.3 ± 4.9 GPa (Fig. 5).

Young's moduli of six weeks retted fibers were even higher than the respective 3W-fibers, but the difference was low in relation to the doubled time of treatment. After six weeks of retting, the values for *T. cordifolia* accounted for 59.8 ± 9.7 GPa and those of *D. burgessiae* for 24.0 ± 6.1 GPa, respectively (Fig. 5).

After three weeks of retting, the tensile strengths of the bast fibers were higher for all species while breaking strains decreased. (Table 3).

Table 3. Material Properties of Bast Fibers from All Plant Species

Bast Fiber	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Breaking Strain (%)
T. cordifolia (UT)	1.16 ± 0.07	12.5 ± 3.3	209.1 ± 64.1	2.55 ± 0.61
T. cordifolia (3W)	1.26 ± 0.13	53.4 ± 10.3	916.3 ± 370.3	1.75 ± 0.62
T. cordifolia (6W)	1.41 ± 0.06	59.8 ± 9.7	890.6 ± 293.6	1.56 ± 0.43
U. lobata (UT)	0.94 ± 0.06	16.5 ± 4.0	309.3 ± 88.5	3.07 ± 0.76
U. lobata (3W)	1.47 ± 0.09	51.7 ± 9.7	760.1 ± 264.8	1.53 ± 0.47
D. burgessiae (UT)	1.08 ± 0.04	12.7 ± 3.8	236.4 ± 75.4	2.63 ± 0.65
D. burgessiae (3W)	1.22 ± 0.05	21.3 ± 4.9	342.5 ± 110.7	2.06 ± 0.55
D. burgessiae (6W)	1.26 ± 0.08	24.0 ± 6.1	351.9 ± 140.6	1.85 ± 0.66
UT, untreated; 3W, fibers retted for three weeks; 6W, fibers retted for six weeks				

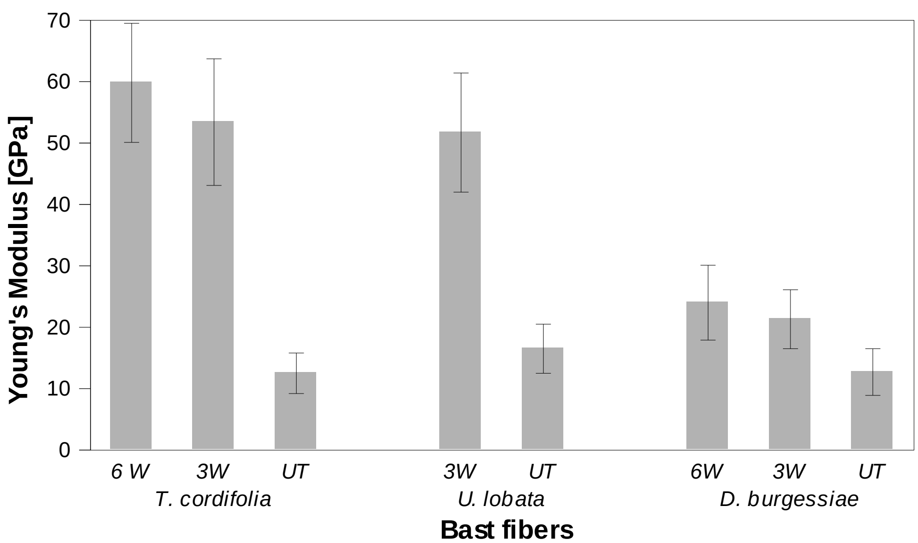

Fig. 5. Young's moduli of bast fibers from all analyzed plant species. UT, untreated; 3W, fibers retted for three weeks; 6W, fibers retted for six weeks

The obtained results serve as a first characterization of the mechanical properties of bast fibers extracted from *Urena lobata*, *Triumfetta cordifolia*, and *Dombeya burgessiae*. The different pretreatments of the fibers (untreated, three or six weeks of retting) considerably influenced the biomechanical properties. The longer the fibers have been immersed in water, the more low-density and non-cellulosic material, such as pectin, was degraded and removed from the fibers. As a result, the density and the lignin and holocellulose contents of the 3W and 6W fibers increased, and as a consequence the stiffness and tensile strength of the fiber increased. Breaking strain decreased simultaneously (Tables 2 and 3). In a study by Thygesen *et al.* (2007), high cellulose content was correlated with increased Young's modulus and tensile strength. In the present study, untreated fibers showed overall lower relative holocellulose contents than retted fibers. The altered chemical composition is thus responsible for improved biomechanical properties. After three weeks of retting, Young's moduli increased by 213.3% in *U. lobata*, 327.2% in *T. cordifolia*, and 67.7% in *D. burgessiae*. However, 6W fibers did not show much higher Young's moduli than 3W fibers. The difference accounted for increases of 12.0% in *T. cordifolia* and 12.7% in *D. burgessiae.* With regard to the doubled time of treatment, the increase, however, was only moderate. As a result, removing a considerable quantity of pectin and hemicellulose by retting results in noticeably improved fiber stiffness and strength. After three weeks of retting, this threshold was reached, and additional degradation of non-cellulosic material did not result in further considerable enhancement of the properties. It is crucial to know this effect for the efficient production and commercial use of the fibers, as an unnecessarily long retting process would cause higher costs.

A comparison of the analyzed 3W fibers with those of other plant-derived fibers shows that Young's moduli of fiber samples from *T. cordifolia* (53.4 GPa) and *U. lobata* (51.7 GPa) were in range of kenaf (53 GPa), while *D. burgessiae* (21.3 GPa) exhibited a stiffness comparable to sisal (9.4 to 22 GPa) or ramie (24.5 GPa) (Faruk *et al.* 2012).

U. lobata is also called “Congo jute”, and its fibers are morphologically very similar to those of jute (Brink and Achigan-Dako 2012). However, the Young's modulus of *U. lobata* is actually higher than that of jute (26.5 GPa) (Faruk *et al.* 2012). The similarity between the two becomes clear when comparing tensile strength and breaking strain, which are 760 MPa and 1.53% for *U. lobata* and 393 to 773 MPa and 1.5 to 1.8% for jute (Faruk *et al.* 2012).

The tensile strength of *T. cordifolia* fibers (916 MPa) corresponds to kenaf (930 MPa) or flax (345 to 1035 MPa), while the breaking strain (1.75%) is similar to jute (1.5 to 1.8%) (Faruk *et al.* 2012). Although *T. cordifolia* (1.26 g/cm^3) and jute (1.3 g/cm^3) show similar density values, the Young's modulus of *T. cordifolia* fibers is much higher. The *D. burgessiae* averaged a breaking strain of 2.06%, which is in the range of sisal (2.0%) (Faruk *et al.* 2012). The tensile strength of 343 MPa is rather low in comparison to *T. cordifolia* or *U. lobata.* Similar values, however, were reported for abaca (400 MPa) or bagasse (290 MPa) (Faruk *et al.* 2012).

The most important mechanical properties of fibers as reinforcing components in composites are stiffness and strength in the axial direction. In this direction, the fibers carry most of the load of the composite, which is influenced by cellulose content, lumen size, and microfibril angle (Madsen and Gamstedt 2013).

The high variability in mechanical properties can be explained in terms of several reasons. First, it may be a result of irregular cell geometry and fiber cross-sectional area (Bodros and Baley 2008). Natural fibers have a diverging lumen, which is usually not subtracted from the cross-sectional area. Indeed, only the cell wall sustains tensile stress. Fiber diameter and lumen size are linked, so that a higher fiber cross-sectional area results in a higher discrepancy in the calculation of Young's modulus and tensile strength (Kempe *et al.* 2015). Since cross-section shape is irregular along the fiber length, linear measurements of fiber dimensions and assumption of uniform cross-section further contribute to significant variation of key mechanical properties, such as moduli and strengths. However, this constitutes a problem for the whole composite sector and could be solved by the determination of a fiber area correction factor (Virk *et al.* 2012).

Secondly, morphological analyses of the shoot axes revealed that with increasing distance to the cambium or age of the fiber cells, the relative lumen size of the cells decreased. This result is crucial in terms of standard deviation of mechanical properties because in tensile tests the lumen size was not measured for each specimen. As a result, fully differentiated matured cells (located far from the cambium) showed higher stiffness and strength than young emergent fiber cells (located close to cambium).

A third important criterion is the microfibril angle (MFA). Higher MFAs lead to lower Young's moduli and larger breaking strains, whereas lower MFAs have the opposite effect (Reiterer *et al.* 1999; Gassan *et al.* 2001). MFAs were almost identical when comparing the investigated fibers. The obtained values for *U. lobata* averaged 6 ± 4° or 7 ± 5° for *D. burgessiae* and *T. cordifolia*, which are similar to hemp (6°), flax (6 to 10°), or jute (8°) (Gassan *et al.* 2001). In trees, fibers of young individuals, which need to be flexible, often have larger MFAs. Older plants need to be stiffer to stabilize shoots and branches and therefore possess fibers with smaller MFAs (Burgert 2006). Thus, the age of the plant influences the biomechanical properties.

Indeed, there is a high scattering of values such as Young's modulus, tensile strength, and breaking strain. However, biological materials characteristically show a broad variation in properties with regard to local growth conditions, such as temperature, wind exposure, or nutrient supply (Kempe *et al.* 2015).

The potential of these components in green composites was investigated only with regard to the mechanical properties of the fibers. Other factors such as processing, response to moisture changes, and thermal or insulating properties might be the subject of further investigations. In particular, the compatibility between fiber and matrix and the effect on the elastic and fracture behavior is crucial for a composite. The matrix (*e.g.*, PP, PE, and biodegradable PLA) determines the shape, surface appearance, environmental tolerance, and overall durability of composites, while the reinforcing fibers carry most of the structural loads, providing stiffness and strength (Faruk *et al.* 2012).

For composites, fibers like hemp, flax, kenaf, sisal, or jute are widely used (Faruk *et al.* 2012). However, the comparison of these already commercially applied fibers with the analyzed bast fibers showed that *U. lobata* and *T. cordifolia* could compete in terms of biomechanical properties due to their apparent high stiffness and tensile strength.

During the production of bio-composites by compression molding (the most frequently used method), various fiber types are mixed. Thin fibers (flax, kenaf, or jute) provide adhesion to the matrix due to their large surface, while coarse fibers (hemp, sisal) ensure the complete permeation of the polymer (Carus *et al.* 2008). Due to the very fine structure, the bast fibers of *T. cordifolia* and *U. lobata* could serve as an alternative to jute or flax, which show similar tensile strengths but apparently lower stiffness (Table 4). *T. cordifolia* fibers combine a high Young's modulus (53.4 GPa) and low density (1.27 g/cm^3), *i.e.*, a high specific stiffness, and they are promising for lightweight constructions. *D. burgessiae* fibers revealed considerably lower Young's moduli (21.3 GPa) and values for tensile strength (343 MPa). As the fibers are coarse, they have to compete with sisal or hemp, whose strength is much higher (511 to 635 MPa or 690 MPa, respectively (Faruk *et al.* 2012)). However, the density (1.21 g/cm^3) is lower than that of sisal (1.5 g/cm^3 (Faruk *et al.* 2012)) (Table 4).

Table 4. Material Properties of Various Bio-fibers

Fiber	Young's Modulus (GPa)	Tensile Strength (MPa)	Breaking Strain (%)	Density (g/cm^3)
T. cordifolia (3W)	53.4	916	1.75	1.26
U. lobata (3W)	51.7	760	1.53	1.47
D. burgessiae (3W)	21.3	343	2.06	1.21
Abaca*	12	400	3 – 10	1.5
Bagasse*	17	290	-	1.25
Flax*	27.6	345 – 1035	2.7 – 3.2	1.5
Jute*	26.5	393 – 773	1.5 – 1.8	1.3
Kenaf*	53	930	1.6	-
Hemp*	70	690	1.6	1.48
Sisal*	9.4 – 22	511 – 635	2 – 2.5	1.5
Ramie*	24.5	560	2.5	1.5

*Data republished from Faruk *et al.* 2012
3W, fibers retted for three weeks

Currently, no data about the production of *T. cordifolia*, *U. lobata* and *D. burgessiae* fibers are available because these species are cultivated only locally on a small scale. As bast fibers for technical applications are easily exchangeable, the competitive struggle in composite markets is very high. The price development for jute, which is most important in terms of revenue and production volume, has a great impact (Carus *et al.* 2008). Due to the lack of selection and breeding, the bast fiber content of the investigated plant species is rather low (9 to 10% in *U. lobata*, 9 to 12% in *T. cordifolia*, and 10 to 13% *D. burgessiae*), which compared to flax (15 to 35% (Barton *et al.* 2002)) may result in overall poorer fiber yields.

Because all three species grow abundantly in nearly every part of tropical Africa (Brink and Achigan-Dako 2012) and can be harvested for many years (Latham and Konda ku Mbuta 2014), there is great potential for commercial cultivation. However, research dealing with cultivation and targeted breeding, as well as fabrication and testing of first composite prototypes, is necessary.

CONCLUSIONS

1. Based on investigations of biomechanical properties, *T. cordifolia* and *U. lobata* may serve as a valuable source of fibers for green composites. Due to high stiffness and tensile strength, fibers of both species can seriously compete with commercially used fibers such as jute, kenaf, or flax. Regarding biomechanical performances, *D. burgessiae* performed less well.
2. A high variability in mechanical properties such as Young's modulus, tensile strength, and breaking strain was observed in other species. Growth conditions, plant age, and differences in cell geometry and lumen size most likely account for these differences.

3. The analyzed species may contribute to a larger diversity of natural fibers for technical applications, which becomes important in the case of crop failures or pest infestations in plantations. The fibers are already used for manifold purposes and daily life applications in Angola and have proven their reliability over centuries. Furthermore, these plants grow naturally in all parts of tropical Africa, which could facilitate their industrial commercialization.

ACKNOWLEDGMENTS

The authors acknowledge support by Markus Prehal, Hannah Schönmaier, and Dr. Oskar Paris from the Institute of Physics at Montanuniversität Leoben in Austria for conducting wide-angle X-ray diffraction measurements. Dr. Markus Rüggeberg from the Institute for Building Materials at the ETH Zürich calculated the MFAs. Furthermore, the authors thank Martin Hielscher and Karl Gähler from the Institute of Plant- and Wood-Chemistry at Technische Universität Dresden in Germany for performing chemical analyses of the bast fibers.

The authors also thank the administration and the staff of the University of Kimpa Vita in Uíge for logistical support during the fieldwork in Angola. The fieldwork in Angola was supported by a travel fund from the German Academic Exchange Service (DAAD). These published results were obtained in collaboration with the Instituto Nacional da Biodiversidade e Áreas de Conservação (INBAC) of the Ministério do Ambiente da República de Angola.

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Article submitted: March 23, 2016; Peer review completed: June 12, 2016; Revised version received: June 21, 2016; Accepted: July 11, 2016; Published: July 21, 2016.
DOI: 10.15376/biores.11.3.7595-7607