Fiber Properties of Some Non-Woods as Possible Reinforcement in Composite Making

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Abstract: **Natural fibers can serve as excellent and environmentally friendly renewable reinforcement materials in making a polymer, geopolymer and cement composites. The dimension of the fiber and its chemical composition is useful in selecting appropriate fiber suitable for enhancing the physical and mechanical properties of a given composite. In this study, the fiber dimension of eight plants was measured and their derived values (morphological indices) were calculated. The chemical compositions of the plants as well as their solubilities in aqueous and organic solvents were determined. The result showed that the fiber length of the samples was below 3 mm (1.20 to 2. 51 mm), characteristics of short to medium fiber length which is preferred for composite reinforcement. Other fiber dimensions varied as follows: fiber diameter (9.20-15.25 µm), lumen width (6.12 - 10.58 µm) and cell wall thickness (1.17 - 2.44µm). All the plant samples showed very good morphological indices: low Runkel ratios (0.24 – 0.63), high fiber slenderness (129 – 207) and flexibility coefficients (62-80). The ash content obtained for the selected sample ranged from 3% – 8 %. The content of cellulose was relatively low ranging from 19 to 45.5% while the lignin content varied from 14% to 33%. Thus, the plants can serve as viable natural fibers for the reinforcement of composites.**

Keywords: **Natural fibers, fiber dimensions, chemical composition composites, reinforcements**

I. INTRODUCTION

There is an increasing interest in the use and applications of composite materials for construction and engineering purposes. Composites are formed from the combination of two materials with different physical, chemical, and mechanical properties such that the desirable properties of the individual material are conserved and improved upon in favor of the undesirable properties. A good number of composite products are made from polymer, geopolymer, cement, ceramic, and wood reinforced with suitable fibers [1-3]. Composite, especially when reinforced with fibers, demonstrates superior properties when compared with conventional materials. The fibers function mainly to bear the load in a matrix and give appropriate structural attire to the composite. These make composites suitable for many applications, such as high specific strength and stiffness, long fatigue life, low coefficient of thermal expansion, good energy dissipation, texture attractiveness, and low thermal conductivity. Fibers used in reinforcing composites can be synthetic or natural. Natural fibers are gradually replacing synthetic fibers in polymer, geopolymer, and cement composites. That is because natural fibers are relatively abundant, biodegradable, and renewable, of low density, of low cost, sustainable, and non-abrasiveness. Indeed, their comparative advantages over synthetic fibers are overwhelming [4-10]. Their mechanical properties, tensile and flexural modulus compared favorably well with that of synthetic fibers. The major setback in the use of natural fibers is their high water absorption and poor adhesion to the matrix complex. This setback can, however, be easily be overcome either through fiber pretreatment and modification, the introduction of a compatibilizer, or the use of in-situ fiber matrix interactive adhesion [11, 12]. Some of the natural fibers commonly used as reinforcement in composites include cotton, jute bamboo sisal, hemp, pineapple, kenaf, flask, sugarcane, plantain, and coir [7, 13-16].

Apart from such factors as fiber volume, fiber-matrix interactions, processing techniques, and specific industrial applications, the potential utilization of natural fiber and its reinforcement characteristics is a function of its chemical constituents and fiber properties [17-19]. The physical and mechanical properties of fibrous composites are greatly affected by the chemical and fiber properties of the plant [17, 20-22. Natural fibers vary from plant to plant for the distribution of their chemical contents (cellulose, lignin, and extractives), fiber dimension (length, diameter, lumen width, cell wall thickness), and morphological indices (flexibility coefficient, Runkel and slenderness ratio). The variations depend on plant varieties, origins, geographical locations, and environmental factors [7]. A careful search of the literature revealed that the entrenched fiber dimension and chemical properties of the plant not only played essential roles in the mechanical properties of fiber during composite reinforcement [7, 16] but made them suitable for a variety of applications. It is highly crucial to examine natural fibers with regards to these properties to determine their usefulness or otherwise in reinforced composites.

Unlike the non-woods, most wood species widely cultivated in Nigeria have been examined with respect to their fiber potentials and chemical constituents [23,24].The present study is an evaluation of the fiber and chemical properties of some selected fibrous non-wood plants from Nigeria with regards to their potential ability for composite reinforcements. Eight plants were selected and some of their botanical details are briefly summarized in Table 1 [25-41]. The plants are *Combretumplatypetalum, Distemonanthusbenthamianus, Fagarazanthoxyloides, Musa paradisiaca, Sidaacuta, Serindeiawarneckei. Terminaliaglaucescens and Urenalobata.*Apart from *Musa paradisiaca*, *Urenalobata*and *Sidaacuta*, [42-44], not much work has been done on the fiber, chemical, and the reinforcement properties of the other plants for composites making.

II. MATERIALS AND METHODS

Sample collection, identification, and preparation

Combretumplatypetalum, Sidaacuta, and *Urenalobata* were collected at a farm in Apata Ibadan, Nigeria. *Musa paradisiaca* was obtained at the Institute of Agricultural Research Technology farm, Moor plantation, Apata, Ibadan while *Distemonanthusbenthamianus, Fagarazanthoxyloides, Serindeiawarneckei*, and *Terminaliaglaucescens* were purchased from local herbs seller at Agbekoya market Apata, Ibadan Nigeria. Identification and authentication of the plant samples were done at the herbarium section of Botany Department, University of Ibadan, Nigeria. The plants were carefully cut into stems after removing their leaves (Fig. 1).

Chemical Composition

Ground samples of the various plant parts were used to determine its chemical constituents. The following extractive contents of the plant were determined using ASTM standards [45]: cold and hot water solubilities (ASTM D 1110-56), alcohol-benzene solubility (ASTM D 1107) and 1 % caustic soda solubility (ASTM D 1109). The lignin content was determine based on ethanol- benzene (1:2) extracted samples by TAPPI standard designated T222 OM -98 (Klason lignin) [46]. Kurschner-Hoffer cellulose method was used for the cellulose content as adopted by Ogunsile and Uwajeh 2009 [47] while the ash content was determined as the percentage of residue remaining after ignition in a muffle furnace at 600^0C [45].

Basic Density and Fiber Dimensions

The basis density was determined using a representative sample from each plant following the ASTM standard procedure designated D 2395-89 method B [45]. To measure the fiber dimension, fibers were randomly selected from the species and reduced to splints of about 20mm to 40mm long with the aid of a sharp knife. Some of the fibers were chosen again at random and macerated in a mixture of equal volume (1:1) of glacial acetic acid and 48% hydrogen peroxide in a covered bottle. The macerated samples were left for about a month with intermittent shaking at room temperature to liberate the fibers. The liberated fibers were prepared on a slide and the fiber length (L), fiber diameter (D), Lumen Width (d), and cell wall thickness (CWT) were measured with the following magnification: fiber length x4, fiber wall thickness, fiber lumen width and fiber diameter x100. Photomicrographs of the slides were taken using Accu-scope trinocular microscope (ACCU-scope 33001 LED Trinocular microscope) with a 3.2 MP CMOS digital camera. The following morphological indices were determined from these measurements as follows:

i. Felting power (slenderness ratio) $= L \,/\, D$
ii. Elasticity coefficient (%) $= (d \,/\, D) \times 100$
iii. Rigidity coefficient (%) $= \{(CWT)/D\} \times 100$
iv. Runkel index: $= \{(2CWT) \,/\, d\} \times 100$
v. F. factor $= (L/CWT) \times 100$

III. RESULTS AND DISCUSSION

Moisture and Ash Contents

The results of the moisture and ash contents are shown in Fig. 2. The mean value of moisture obtained for the plant species ranged from 6.0 % to 8.25% based on air-dried samples. The values were low and acceptable, and compare favourably well with that of woven kenaf and within the values reported for other natural fibers [21, 48-50]. The moisture content of natural fiber is an important criterion in choosing fibers for reinforcement of composites. Moisture content was reported to affect the electrical resistivity, dimensional stability, tensile strength, and porosity of the composite [20]. Low moisture content improves the tensile and flexural strength of composites. [50].

The values obtained for the ash contents were similar to those reported for annual plants. *B. benthaminus* had the least (3.80%) while *M. paradisiaca* had the highest (8.05%). High contents of inorganic minerals such as calcium,Potassium, and magnesium in addition to manganese and silica are not desirable as they affect chemical consumption and recovery during fiber pretreatment and modification.

Table 1: Botanical Details of the Plant Species

Botanical (Common) name; Family	Picture	General Description	Location /Distribution	Local /Medicinal uses	References
Combretumplatypetalum, (bush willows), Combretaceae family		A dwarf shrub with annual stems, typically less than 30 cm, growing from a woody rootstock	Widely distributed in some part of Africa especially Tanzania, Malawi, Mozambique, Zambia and Zimbabwe	Medicinal uses includes treatment of pneumonia, relief of sore throats, cold, fever and chest cough associated with tuberculosis, and various forms of swelling. It has Cytotoxic Effects	Chirambaand Mukanganyama, 2016 [25].

Distemonanthusbenthaminus; Leguminosae family		The tree reaches a height of 90-125ft	Widely distributed throughout the high forest of West Africa	As chewing stick for oral-dental hygiene; rich in flavonoids. Locally use as a dye and source of wood.	Nguelefack*et al.,* 2005 [26], Aiyegoro*et al.,* 2008 [27]. Adeniyiand Odumosu, 2012 [28].
FagaraZanthoxyloides; Rubiaceae family		It is a spreading shrub, growing to 7m (23ft) tall	Widely distributed in Uganda and other African countries	Commonly used as chew-sticks, in treating dental diseases; antisickling and anticancer agents.	Messmer*et al.,* 1972 [29], Odebiyi and Sofowora, 1979 [30], Itemire, 2013 [31].
Musa paradisiaca(plantain or edible banana);*Musaceae family*		Herbicious plant that springs from an underground stem, or rhizome. Most varieties are 3–10 metres	Originated from Southeast Asia but now found in every tropical country	A good source of carbohydrates; Fruit are eaten raw, fried, roasted ,cooked or made into flour.	Adeniji*et al.,* 2007 [32], Mohammed and Saleha, 2011 [33], Oviri, 2014 [34].
Sidaacuta (broom grass; broomweeds, wire weed); Malvaceae family		Perenial shrub of about 30 to 150cm in height, stem are fibrous to almost woody, with a stringy bark	Originated from Mexico and central American but presently found in the tropic and subtropics region	Exhibit the following medicinal properties: antibacterial, antifugal, antiplasmodial, antioxidant and neuropharmacological effects. Traditional use to treat fever, headache, skin diseases, diarrhea and dysentery.	Holm *et al.,* 1977 [35, Simplice*et al.,* 2007 [36]
Sorindeiawarneckei(*S. grandifolia*); Anacardiaceae Family		It is an evergreen climbing shrub or a small tree of about 50 ft. high	Found in west tropical Africa – Sierra Leone to southern Nigeria	Harvested for local use as food, medicine and dye Used as chewing stick	Rotimi and Mosadomi, 1987 [37].

Terminaliaglaucescens; Combretaceae family		It is a dediduos, multipurpose perennial tree. The tree is up to 20m high.	Commonly found in Savannah regions	Highly medicinal: used in the treatment of many diseases e.gAIDS, Amenorrhoea, scrofulous infections, syphilis, sores and nervous disease	Aiyelaagbe*et al.*, 2014 [38].
Urenalobata (Caesar weed); Malvaceae family		Erect shrub or perennial herb usually around 1.5 m tall. Stems and leaves are covered with star-shaped (stellate) hairs. Describe as an aggressive invasive plant	Origin not certain but widely distributed in the tropics/sub-tropics region	Cultivated in some regions as a fiber crop used for making carpets and ropes. Leaves, roots, and flowers are reportedly used in traditional medicine. Seeds and parts sometimes eaten as famine food.	Langeland and Burk, 2008 [39], Ong 2001 [40], Muhammad and Muhammad,2017 [41].

Fig. 1: The plant samples (stems) after removing their leaves

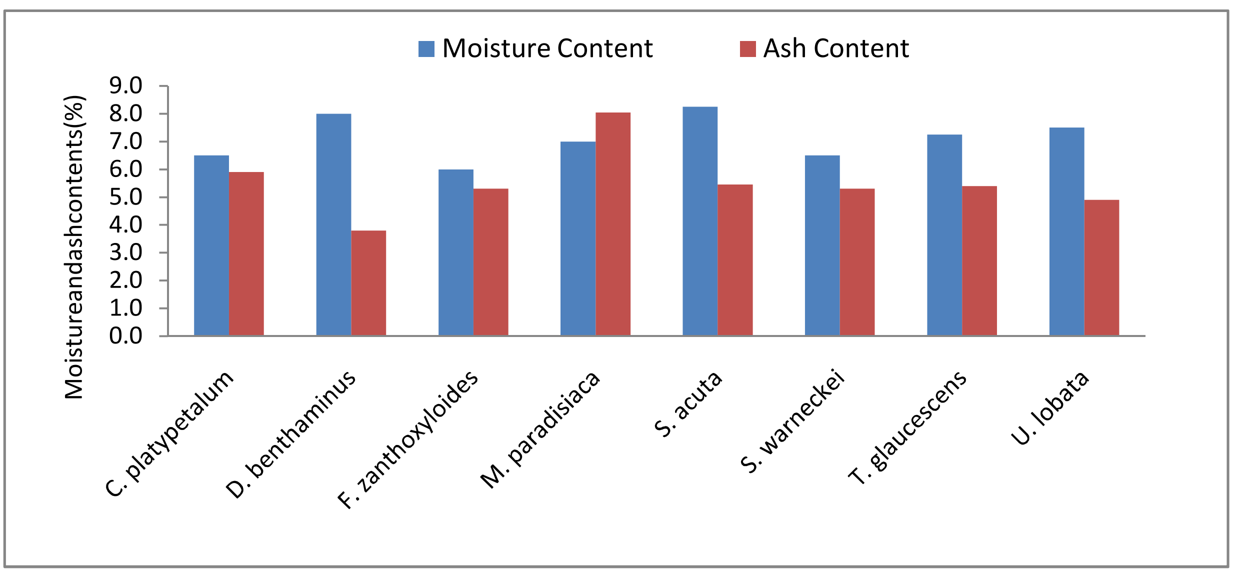

Fig. 2: Moisture and ash contents of the plant samples

Cellulose and Lignin Contents

The variation of the cellulose and lignin among the plant was depicted in Fig. 4. The mean value of cellulose obtained for the sample in this study was relatively low ranging from 19.00% to 45.50%. *S. acuta, U. lobata and C. platypetalum* exhibit average but tolerable cellulose content of 45.50%, 45.50%, and 43.00%, respectively. These plants are expected to give the highest mechanical strength in reinforcing composite than others. High cellulose contents are desirable in selecting candidate plants for reinforcement of composites and structural applications as they contribute to the strength of the fiber and mechanical properties of the composites [17, 18]. The cellulose content is also a measure of the fiber yield of the plant, thus *B. benthaminus, S. warneckei,* and *F. zanthoxyloides* are expected to yield a lower value of the fiber, hence more of the plants would be required for industrial application as reinforcement.

The lignin contents of the plant samples ranged from 14% to 33%. These were within the range of 3 to 24% reported for annual plants except for *C. platypetalum* and *D. benthamianus* which were similar to that of coniferous and leaf trees [51]. A decrease in the lignin content is desirable to increase the mechanical properties of the reinforced composite. Chemical treatment of the plants would be necessary to reduce their lignin contents. These will greatly improve the interfacial bonding between the fiber and the composite matrix [52].

A comparison of the cellulose and lignin contents of *U. lobata* obtained in this study was compared with that of Agu *et al*., 2014 [53]. The cellulose content of 46% reported here for *U. lobata* (from South-West Nigeria) was lower than 59% reported for the same plant (from South-East Nigeria) in 2014 [53]. The variation in values may be due to the different locations of the plant within the country. However, the values of the lignin contents were similar: 21% in this study while Agu *et al*. reported a value of 22% [53].

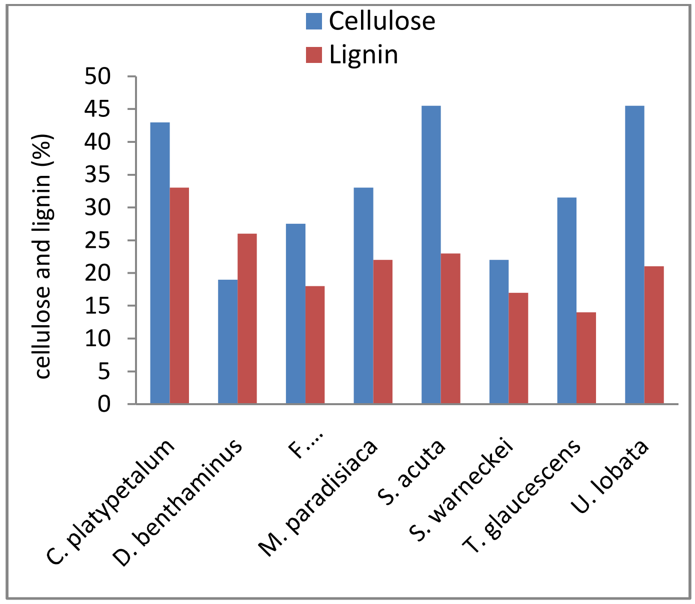

Fig. 3: Cellulose and Lignin contents of the plant samples

Extractive Contents

The results of the extractive contents of the plant species were illustrated in Fig. 3. The values obtained were slightly higher (especially for *B. benthaminus*) than those reported for wood species, though within the range recorded for some non-woods such as rice and wheat straw [54, 55].

High water and solvent extractives can lead to a reduction in mechanical properties and a high rate of water absorption in the composites. It is therefore highly necessary to subject these plants to water and solvent extraction for their maximum beneficial use as composite reinforcement. Of all the extractive contents, one percent caustic soda was the highest. The relatively high values of microbial decay as indicated by the 1% NaOH extractives necessitates that the plants must be technically dried before storage to reduce the microbial attack.

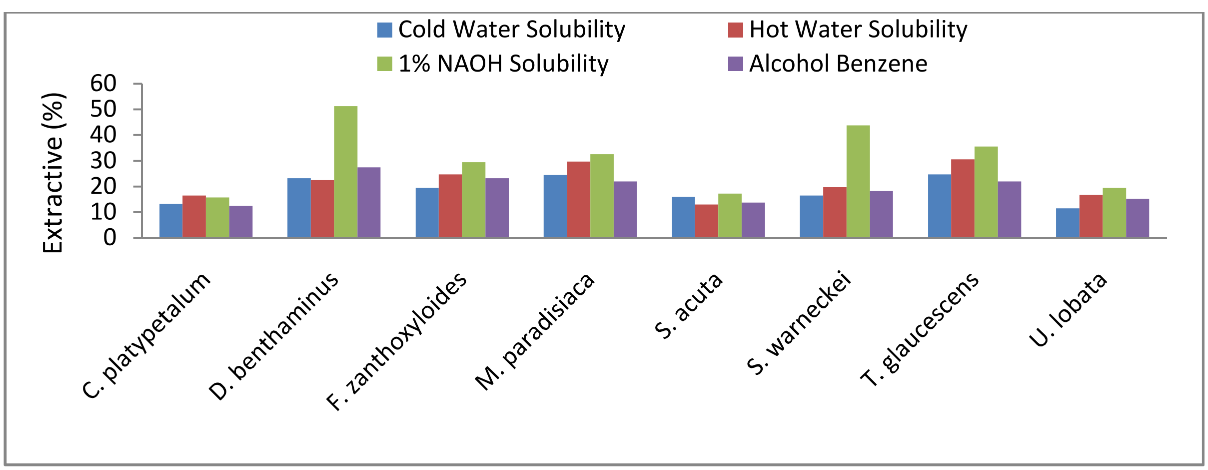

Fig. 4: Extractive contents of the plant samples

Basic Density and Fiber Length

The average specific gravity of the plants was shown in Table 2 and it varied from 0.352 for *U. lobata* to 0.722 for *S. warneckei* with an overall mean of 0.548. These values were within the range of 0.3 to 0.8 reported for some tropical rainforest on Borneo Island [56]. However, a range of 0.51 to 1.09 g/cm3 was reported for native trees and shrubs from Mexico [57], while relatively higher values were recorded for most commonly used natural fibers such as Sisal (1.33-1.5 g/cm3), Kenaf (1.2-1.24 g/cm3), Coir (1.2 g/cm3) and Jute (1.3 – 1.46 g/cm3) [58]. Wood density varies from plant to plant, and within plant species depending on age or growth, diameter, height, radial growth, geographical location, site, and growing conditions. The relatively low to medium values of density obtained here implied that solvent pretreatment and penetration of the sample would not be difficult leading to low chemical consumption. Besides, problems associated with the tearing or wearing of machine knives will be minimal with the use of these plants. However, unlike sisal, kenaf, and jute, a large volume of plant materials may be required because of their bulkiness.

The photomicrographs of the fibers were presented in Fig. 2. The mean value of average fiber length as shown in Table 3 ranged from 1.20mm to 2.51mm. *M. paradisiacal* has the highest fiber length of 2.51mm while *D. benthamianus* has the least fiber length of 1.20mm. For purposes of convenience the fiber length obtained in this study can be classified into two:

1. Fiber length less than 2mm (i.e. 1.20 -1.78mm). These are "short-fiber plants" The plants in this category include: *D. benthamianus, S. acuta,. T. glaucescens and S. warneckei*
2. Fiber length greater than 2mm (i.e 2.01 – 2.51mm). These are "short-to-medium fiber plants". They include *F. zanthoxyloides, U. lobata, C. platypetalum and M. paradisiacal*.

In general, short fiber plants are preferred for composite reinforcement because the fibers are easily dispersed in the matrix, thus improving their mechanical properties [59]. This makes the fibers obtained in this study quite suitable.

Fiber Diameter, Lumen Width, and Cell Wall Thickness (CWT)

The results of the fiber diameter are contained in Table 3. It ranged from 9.20 to 15.25 µm with *T. glausecene, U. lobata and M. paradisiaca* having close values of 12.68, 12.72, and 12.80µm respectively. The diameters were similar to the range of 10 - 15 µm reported for hemp fibers corresponding to a tensile strength of 2767 - 1695 MPa, respectively [60]. This indicated that the lower the fiber diameter, the higher the tensile strength. By implication, *D. benthamianus* is expected to show higher tensile strength than the other plant species.

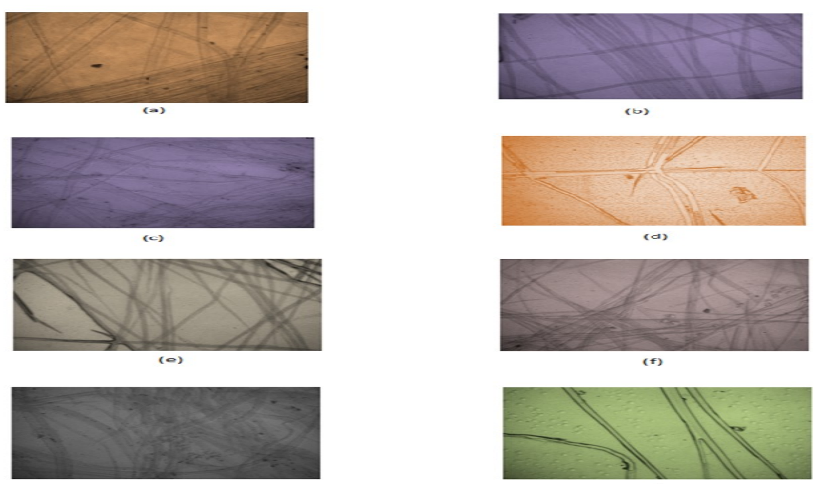

Fig. 5: The photomicrographs of the fibers (magnification x40): (a) *Combretumplatypetalum,* (b)*Distemomsnthusbenthamianus,* (c) *Fagarazan*thoxyloides, (d) *Musa* paradisiacal, (e) *Sidaacuta,,* (f)*Serindeiawarneckei,* (g) *Terminaliaglaucescens*and (h) *Urenalobata*

Table 2: Descriptive results of the basic densities of the plants

Plant species	N	Mean	Standard Deviation	Maximum	Minimum
Combretumplatypetalum	7	0.606	0.052	0.672	0.554
Distemomsnthusbenthamianus	7	0.411	0.050	0.484	0.360
Fagarazan-thoxyloides	7	0.461	0.049	0.520	0.389
Musa paradisiaca	7	0.638	0.022	0.670	0.607

Sidaacuta	9	0.580	0.034	0.617	0.531
Serindeiawarneckei	3	0.459	0.068	0.537	0.416
Terminaliaglaucescens	7	0.313	0.092	0.503	0.197
Urenalobata	6	0.791	0.025	0.840	0.773

Table 3: Descriptive results of the fiber lengths of the plants

Plant species	N	Mean	Standard Deviation	Maximum	Minimum
Combretumplatypetalum	15	2.47	0.46	3.13	1.40
Distemomsnthusbenthamianus	25	1.20	0.15	1.75	1.03
Fagarazan-thoxyloides	12	2.01	0.44	3.10	1.43
Musa paradisiaca	15	2.51	0.69	3.75	1.70
Sidaacuta	25	1.59	0.22	2.13	1.18
Serindeiawarneckei	25	1.75	0.45	2.85	0.90
Terminaliaglaucescens	25	1.64	0.16	1.98	1.45
Urenalobata	25	2.36	0.45	3.50	1.63

The results of the lumen width and CWT are also shown in Table 3. Generally, fibers considered in this study were characterized by a large lumen and thin walls. Large lumen has a great tendency to absorb water which necessitates fiber pretreatment and modification [19]. However, fibers with thin walls such as *C. platypetalum* can readily collapse during processing to give good strength properties (stretch, tensile) while fibers with a low lumen and large walls (such as *T. glausecene*) tend to give poorer lateral conformation. Besides, the light cell wall is an indication of easy delignification. Thus, the fibers considered can easily be delignified and hence serve as a good material for reinforcement.

Morphological Indices

All the plant materials showed very good morphological indices (derived values) as shown in Table 4. The Runkel ratio (defined as the ratio of twice fiber thickness divided by lumen diameter) was less than one (< 1) for all the plant samples. This is an indication of good fibers especially for paper making [61]. It is also envisaged that the fibers would build a network of inter-fiber bonding within the matrix of the composite.

Table 4: Descriptive Results of the Fiber Diameter, Lumen Width and Cell Wall Thickness of the Plants

Parameter	*Combretumplatypetalum*	*Distemomsnthus-benthamianus*	*Fagarazan-thoxyloides*	*Musa paradisiaca*	*Sidaacuta*	*Serindeiawarneckei*	*Terminalia-glaucescens*	*Urenalobata*
N	15	25	12	15	25	25	25	25
Fiber Diameter (µm)								
Mean	11.93	9.20	15.25	12.80	10.10	13.04	12.68	12.72
Standard Deviation	2.87	1.32	2.38	1.82	2.34	3.97	3.09	3.08
Maximum	16.00	12.00	18.00	16.00	15.00	25.00	22.00	23.00
Minimum	7.00	6.00	10.00	9.00	7.00	9.00	9.00	10.00
Lumen Width (µm)								
Mean	9.60	6.12	11.42	9.53	7.04	9.28	7.80	10.00
Standard Deviation	2.69	1.30	2.31	1.68	2.11	3.66	2.61	2.96
Maximum	14.00	9.00	15.00	12.00	11.00	21.00	16.00	20.00
Minimum	6.00	4.00	7.00	6.00	4.00	4.00	5.00	7.00
Cell Wall Thickness (µm)								
Mean	1.17	1.54	1.92	1.63	1.54	1.88	2.44	1.36
Standard Deviation	0.36	0.48	0.47	0.61	0.50	0.68	0.67	0.31
Maximum	2.00	2.50	2.50	3.00	2.50	3.00	4.00	2.00
Minimum	0.50	1.00	1.00	1.00	1.00	1.00	1.50	1.00

Table 5: Morphological Indices of Plant Samples

Plant samples	Runkel ratio	Slenderness ratio	Flexibility coefficient
Combretumplatypetalum	0.27	185	79
Distemomsnthusbenthamianus	0.36	132	69
Fagarazan-thoxyloides	0.5	130	67
Musa paradisiaca	0.32	196	74
Sidaacuta	0.44	157	70
Serindeiawarneckei	0.41	137	71
Terminaliaglaucescens	0.63	129	62
Urenalobata	0.24	207	80

Similarly, the relative fiber length (i.e. the ratio of fiber length to fiber diameter) is significantly high ranging from 129 to 207. These values were higher than those of softwoods (100) and hardwoods (50), similar to a bamboo wide range of species (135-175), kenaf (135), rice straw (175), and sisal (180) but lower than abaca (300) [51]. The high slenderness ratio of the plant materials will increase tearing resistance and produce good surface contact within the matrix [61].

The values of the flexibility coefficient were quite above average (62-80) and are indicative of good burst strength and folding endurance. Of all the plant samples, *C. platypetalum* had the best-derived values.

IV. CONCLUSIONS

The industrial application of lignocellulose materials is influenced by their fiber dimension, chemical composition, and their extractives which dictate the difference in their mechanical properties when used as reinforcement in a matrix (either polymeric, ceramic, or metal). The fibers of the plant species examined in this study were characterized by short to medium average fiber length typical of fibers used in composite reinforcement. However, their field yields were relatively low. The fiber densities were lower than that of commercial fibers but may not pose problems associated with the tearing and wearing of machine knives to remove their lignin contents. All the plant samples have good morphological indices.

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