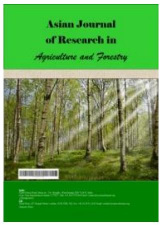

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Relationship between Leaf and Fibre Characteristics of *Agave sisalana*

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Authors' contributions

This work was carried out in collaboration among all authors. Author AOO conceived designed and supervised the research. Author TAA performed laboratory analysis. Author IO performed the statistical analysis and wrote the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

With decrease in wood from the forest, non-wood fibres have attracted interest in the production of pulp and paper products in recent times due to their short growth cycles, moderate irrigation and fertilizer requirements as well as their low lignin content. The use of these plants will aid sustainable development in the pulp and paper industry. This study investigated leaf dimensions and fibre characteristics of *Agave sisalana* and how the leaf dimensions relates to its fibre characteristics. Leaves were collected from three sisal plant stands in Oyo State, Nigeria. The plant whorl was divided systematically into bottom, middle and top from which five leaves were randomly collected from each whorl position. The fibres of the leaves were extracted from which 2cm of fibres were taken from three positions on the leaf (top, middle and base). Extracted fibres were macerated and 3375 fibres were measured. The result shows that *Agave sisalana* leaves collected at the top had the longest length and was also widest at the base and middle. The average fibre length was 1.69 mm, while the fibre diameter, lumen width and cell wall thickness of *Agave sisalana* were 16.98 μm, 12.33 μm and 2.32 μm respectively. The slenderness ratio averaged 99.4 while the coefficient of flexibility averaged 72.61. The highest value of the runkel ratio of *Agave*

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sisalana was 0.42. There was significant negative correlation between leaf characteristics and fibre characteristics. Young sisal (*Agave sisalana*) leaves produced the best fibre characteristics suitable for the production of high quality paper.

Keywords: Leaf dimensions; Agave sisalana; fibre characteristics; cell wall thickness.

1. INTRODUCTION

With the decrease in wood from the forest and the subsequent increase in the consumption of pulp and paper products, non-wood fibers are becoming important as a raw material in the pulp and paper industry [1]. The use of non-woody fibers from field crops and agricultural residues represent an alternative to woody raw materials for pulp and paper production in developing countries [2]. The main sources of non-woody raw materials are annuals and monocotyledonous plants which include cereal straw and bagasse, or plants grown specifically for the fiber, such as bamboo, reeds, and some other grass plants such as flax, hemp, kenaf, jute, sisal, or abaca [2,3]. Non-woody plants offer several advantages over woody biomass these include short growth cycles, moderate irrigation requirements and low lignin content, which in principle would result in reduced energy and chemicals consumption during pulping [4]. The use of fibre dimensions as well as other certain indices helps to predict the suitability of raw materials for pulp and paper making [5].

Sisal is native to the semi-arid regions of Mexico. It is a short plant growing to a height of 0.9 meters and 0.38 cm in diameters found in bushlands, roadsides, savanna and along drainage lines and was previously grown for horticultural purposes [6]. Sisal which is a hardy plant grows all year round and can be cultivated in all soil types except clay and has low tolerance to very moist and saline soil types [7]. Sisal can be harvested from 2-3 years after planting having a life span of up to 12 years producing 180-240 leaves depending on location, level of rainfall, altitude and variety of plant. The leaves are sword shaped that are fleshy and spiny measuring up to 2 meters long. Fibre obtained from sisal is coarse and strong and it's been use for production of composite materials for furniture, cars, construction and plastic as well as for paper production [7]. Higher grades sisal fibres are used to make yarn for carpet weaving while the moderate grade fibres are suitable for making marine, shipping, agricultural and industrial ropes and twine. The lower grades fibres are processed to make paper products [6,8].

The main focus of this study is to investigate the fibre characteristics of sisal with relation to its leaf dimensions and its potential utilization in the production of pulp and paper.

2. MATERIALS AND METHODS

Agave sisalana used for this study was harvested from Awotan area of Ido Local Government Area, Oyo State, Nigeria. It is located on latitude 8º00ˈN and longitude 4º00ˈE. The vegetation pattern of Oyo State is that of rain forest in the South and guinea savannah in the North.

The leaf was the plant part used for this study was collected from three sisal plant stands. The plant whorl was divided systematically into bottom, middle and top from which five leaves were randomly collected from each whorl position. The fibres of the leaves were extracted by mechanical means through beating of the leaves, scrapping and washing. Extracted fibres were dried from which 2 cm of fibres were taken from three positions on the leaf (top, middle and base). For fibre characteristics determination, extracted fibres were macerated with 30% hydrogen peroxide and 10% glacial acetic acid in a 1:1 ratio and placed in a boiling water for 2hrs [10]. After boiling, the fibres were decanted and rinsed with water. Fibres were then separated into individual fibres by vigorously shaking the solution. The resultant fibre suspension was place on a slide and stained with safranin solution. The fibre length, lumen width, fibre diameter and cell wall thickness were then measured using a calibrated microscope. A total of 25 randomly selected fibres were measured giving a total of 3375 measured fibres (3plants x 3positions on the branch x 3positions on the leaf x 5leaves x 25fibres). Derived values were obtained using the values obtained from measured fibre dimensions according to [5].:

$$Slenderness\ ratio = \frac{FL}{FD} \quad (1)$$

$$Flexibility\ coefficient = \frac{\frac{LW}{FD}}{100} \quad (2)$$

$$Runkel\ ratio = \frac{2 \times CWT}{LW} \quad (3)$$

$$F - factor = \frac{FL}{CWT} \quad (4)$$

$$Muhlsteph\ ratio = \frac{FD^2 - LW^2}{FD \times 100} \quad (5)$$

Where FL = Fibre length; FD = Fibre diameter; LW = Lumen width; CWT = Cell wall thickness

Data collected was subjected to analysis of variance (ANOVA, $p<0.05$) with the sources of variation being the plant as the source of variation.

3. RESULTS

3.1 Leaf Characteristics of *Agave sisalana*

The leaf characteristics of *Agave sisalana* collected from three different plants are shown in Table 1. The leaf length ranged from 32.84-52.66 cm while the width at the base, middle and top of the plant ranged from 3.04-4.01 cm, 4.94-7.20 cm and 1.90-2.22 cm respectively. Leaves at the top had the longest length and was also widest at the base and middle however, leaves collected from the middle was widest at the top. Leaves collected from plant C was longer and wider than those collected from plant A and B

3.2 Fibre Characteristics of *Agave sisalana*

The fibre dimensions of *Agave sisalana* are presented in Table 2 showing values obtained for fibre length, fibre diameter, lumen width and cell wall thickness. Plant B had the highest fibre length (1.70 mm) of the three sampled plants while plant A had the highest value for fibre diameter (17.61 µm), lumen width (12.93 µm) and cell wall thickness (2.34 µm). The average fibre length, fibre diameter, lumen width and cell wall thickness of *Agave sisalana* as observed from this study were 1.69 mm, 16.98 µm, 12.33 µm and 2.32 µm respectively (Table 2)

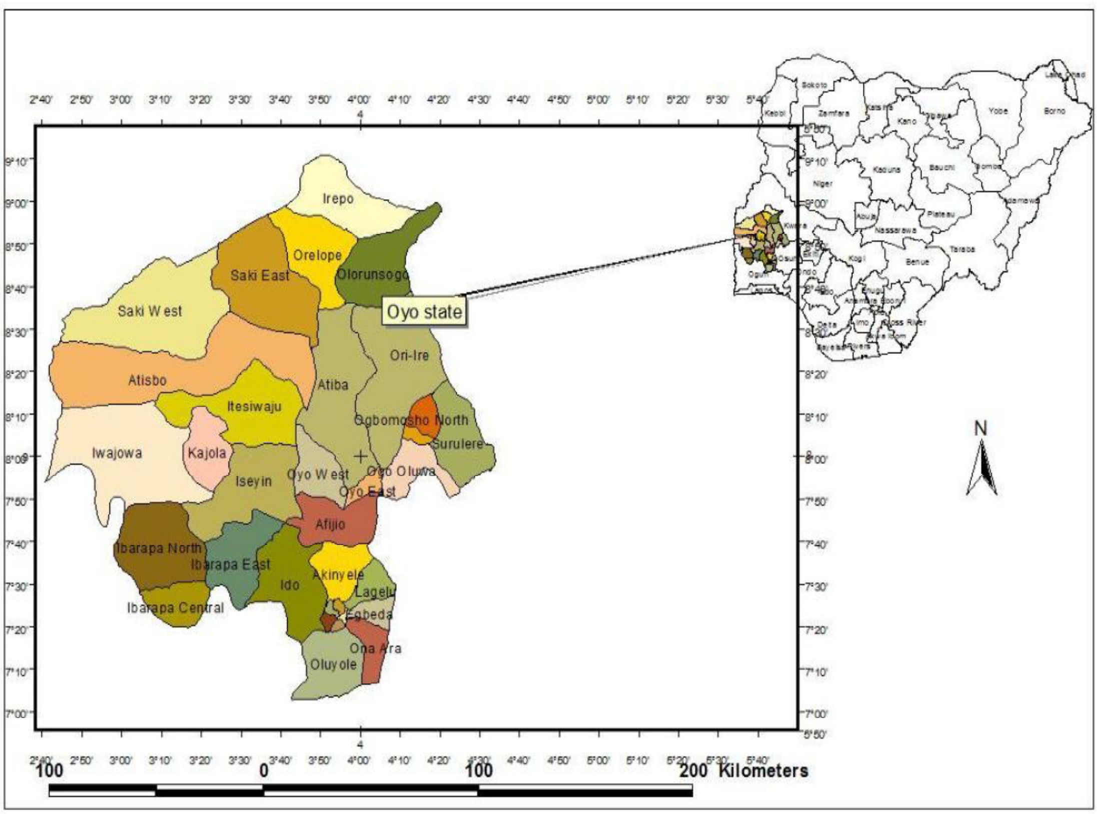

Fig. 1. Map of Oyo State showing study area [9]

3.3 Derived Fibre Characteristics of *Agave sisalana*

The derived fibre dimensions of *Agave sisalana* are presented in Table 4. Plant B had the highest felting power (101.33) and F factor (741.63). The highest elasticity coefficient was obtained by plant A (73.40) while pant C had the highest runkel ratio (0.39) and Mulsteph ratio (48.30). The average felting power, elasticity coefficient, runkel ratio, F factor and Mulsteph ratio of *Agave sisalana* as observed from this study were 99.4, 72.61, 0.38, 727.55 mad 47.27 respectively (Table 3).

3.4 Correlation between Leaf and Fibre Characteristics of *Agave sisalana*

There was significant positive correlation between leaf length and basal leaf width and middle leaf width with correlation value of 0.95. However, negative correlation was observed between leaf length and fibre characteristics (Table 4). The result of the correlation analysis showed negative correlation was also observed between basal leaf width and fibre characteristics as well as middle leaf width and fibre characteristics. There was however positive correlation between top leaf width and fibre characteristics. There was a positive correlation between leaf width and fibre derived charactiestics except for elasticity coefficient that showed a negative correlation.

4. DISCUSSION

The average fibre length of sisal leaf of 1.69 compares favourably with other non-wood fibres. It is shorter than that of kenaf bast and miraculous berry stalk. It is however higher than many other researched non-wood fibres such as tobacco stalk, maize stalk, reed, rice straw, cotton stalk, wheat and sun flower stalk etc. It is also higher than the maximum value for hardwood as reported by [3] to be 0.7 to 1.6mm. Fibre length has been reported to affect paper

Table 1. Leaf dimensions of *Agave sisalana* harvested from Awotan, Oyo State, Nigeria

		LL (cm)	BW (cm)	MW (cm)	TW (cm)
Plant A	Base	34.14	3.04	4.94	2.10
	Middle	42.40	3.32	5.88	2.16
	Top	48.82	3.58	6.16	1.92
	Mean	41.72	3.31	5.66	2.06
Plant B	Base	32.84	3.08	5.00	2.08
	Middle	39.68	3.18	5.50	2.22
	Top	48.20	3.68	6.20	1.90
	Mean	40.24	3.31	5.57	2.07
Plant C	Base	41.24	3.54	6.10	2.12
	Middle	51.16	3.90	7.14	2.14
	Top	52.66	4.10	7.20	1.96
	Mean	48.35	3.85	6.81	2.07

Where LL= Leaf length, BW= Basal width, MW= Middle width, TW= Top Width

Table 2. Fibre characteristics of *Agave sisalana* harvested from awotan, oyo state, Nigeria

	FL mm	FD μm	LW μm	CWT μm
Plant A	1.68	17.61	12.93	2.34
Plant B	1.70	16.71	12.11	2.30
Plant C	1.68	16.63	11.96	2.33
Mean	1.69	16.98	12.33	2.32

FL= Fibre length, FD= Fibre diameter, LW= Lumen width, CWT= Cell wall thickness

Table 3. Derived fibre characteristics of *Agave sisalana* harvested from awotan, oyo state, Nigeria

	FP	EC	RR	Ff	MR
Plant A	96.35	73.40	0.36	723.94	46.12
Plant B	101.33	72.53	0.38	741.63	47.38
Plant C	100.52	71.90	0.39	717.07	48.30
Mean	99.40	72.61	0.38	727.55	47.27

Where FP= Felting power, EC= Elasticity coefficient, RR= Runkel ratio, Ff= F-factor, MR= Mulsteph ratio

Table 4. Correlation matrix of leaf dimensions and fibre characteristics of *Agave sisalana*

	Leaf length	Basal width	Middle width	Top width	Fibre length	Fibre diameter	Lumen width	Cell wall thickness	Felting power	Elasticity coefficient	Runkel ratio	F factor	Muhlsteph ratio
Leaf length	1												
Basal width	0.95	1											
Middle width	0.95	1	1										
Top width	-0.283	-0.35	-0.35	1									
Fibre length	-0.39	-0.312	-0.312	0.607	1								
Fibre diameter	-0.46	-0.636	-0.636	0.142	-0.17	1							
Lumen width	-0.317	-0.533	-0.533	0	-0.295	0.904	1						
Cell wall thickness	-0.6	-0.6	-0.6	0.467	0.043	0.527	0.2	1					
Felting power	-0.017	0.1	0.1	0.417	0.78	-0.678	-0.633	-0.333	1				
Elasticity coefficient	0.083	-0.033	-0.033	-0.45	-0.208	0	0.383	-0.683	0.017	1			
Runkel ratio	0	0.149	0.149	0.483	0.374	-0.247	-0.58	0.501	0.237	-0.949	1		
F factor	-0.017	0.05	0.05	-0.05	0.65	-0.46	-0.317	-0.633	0.767	0.467	-0.246	1	
Muhlsteph ratio	-0.083	0.033	0.033	0.45	0.208	0	-0.383	0.683	-0.017	1	0.949	-0.467	1

Table 5. Mean value of sisal leaf fibre dimensions compared with other non-wood paper making fibres

Non-wood Plant	FL (mm)	FD (μm)	LW (μm)	CWT (μm)	Source
Sisal	1.69	16.98	12.33	2.32	Present study
Kenaf (Bast)	2.9	28.16	6.08	11.04	[13]
Kenaf (Whole)	1.29	22.1	12.70	4.30	[5]
Tobacco stalk	1.23	24.31	15.38	8.93	[3]
Maize stalk	1.52	30.19	13.67	8.82	[14]
Canola stalk	1.17	23.02	12.5	5.26	[15]
Reed	1.39	13.50	7.00	3.20	[16]
Rice straw	0.89	14.80	6.40	6.36	[17]
Switch grass	1.15	13.10	5.80	4.60	[5]
Cotton stalk	0.83	19.60	12.80	3.40	[5]
Sugarcane bagasse	1.15	21.40	6.27	7.74	[18]
Wheat straw	0.74	13.20	4.00	4.60	[19]
Sunflower stalk	1.28	22.10	15.60	3.30	[20]
Miraculous berry	2.68	15.61	10.11	2.75	[21]

FL= Fibre length, FD= Fibre diameter, LW= Lumen width, CWT= Cell wall thickness

Table 6. Mean value of sisal leaf fibre derived dimensions of other non-wood paper making fibres

Non-wood Plant	FP	EC	RR	Source
Sisal	99.4	72.61	0.38	Present study
Kenaf (Bast)	105	57	0.76	[13]
Kenaf (Whole)	58.3	57.5	0.67	[5]
Switch grass	87.7	44.2	1.5	[5]
Cotton stalk	42.97	65.3	0.5	[5]
Maize stalk	50.34	45.3	1.23	[14]
Tobacco stalk	50.9	63.28	1.16	[3]
Canola stalk	50.83	54.3	0.84	[15]
Reed	102.98	51.93	0.91	[16]
Rice straw	60.13	43.24	1.98	[17]
Sugarcane bagasse	70.58	29.29	2.46	[18]
Wheat straw	53.13	33.04	2.23	[19]
Sunflower stalk	57.9	70.6	0.42	[20]
Miraculous berry	174.1	64.54	0.57	[21]

FP= Felting power, EC= Elasticity coefficient, RR= Runkel ratio

quality as a long fibre will produce paper with a good strength property such as a higher tear resistance with a more open but less uniform sheet structure provided there is no concomitant increase in other cell parameters most notably the cell wall thickness [3,10,11]. The fibre diameter and lumen width compares favourably with other non-wood fibres but was lower when compared to hardwood fibre (20.2-40.0) [3]. The cell wall thickness was also found to be lower when compared with other non-wood fibres (Table 5). Apart from the fibre length, the thickness of the cell wall also has an important bearing on most paper properties as a thin walled fibre would be compact with a high tensile strength, burst resistance and folding endurance but with low tearing strength and vice versa for a thick walled fibre.

The fibre length and thin cell wall obtained from this study was responsible for the good indices observed with regards to the derived characteristics thus having a positive impact on paper mechanical strength. A short and thick cell wall results in fibres with poor felting power. Fibrous materials with low felting power below 70 are not suitable for pulp and paper production. Felting power otherwise known as slenderness ratio has been reported to be positively correlated with paper strength properties [3]. The felting power of sisal is lower than that of kenaf bast, reed and miraculous berry stalk. It is however higher than many other researched non-wood fibres such as tobacco stalk, maize stalk, rice straw, cotton stalk, wheat and sun flower stalk etc. (Table 6). The runkel ratio is below the accepted value of 1 which implies that fibres from sisal leaf are flexible and interfibre bonding is easily achievable [5]. The runkel ratio (0.38) is lower when also compared with other reported non-wood fibres. However, the coefficient of elasticity obtained from sisal which is higher than most reported non-wood plants invariably impacts the tensile strength, burst strength and folding endurance positively [5]. The felting power, coefficient of elasticity and runkel ratio compares favourably with the report of [12] for hardwoods and softwoods. He reported felting power, coefficient of elasticity and runkel ratio of hardwoods to be 55-75, 55-70, and 0.4-0.7 respectively while that of softwoods were 95-120, 75 and 0.35 for felting power, coefficient of elasticity and runkel ratio respectively.

5. CONCLUSION

This study has shown that leaf of sisal (*Agave sisalana*) possesses good fibre dimensions as well as their derived characteristics. Portions obtained from the top of the leaves possesses better fibre characteristics than those from the base leaves which is a similar occurrence in both hardwoods and softwoods species. To make a wide range of paper grades, fibres from sisal can be mixed with conventional softwood and other long fibre pulps.

6. FUNDING

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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