CHARACTERISATION AND EVALUATION OF PULP AND PAPER FROM SELECTED UGANDAN GRASSES FOR PAPER INDUSTRY

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Non-wood fibrous materials and recycled fibres offer an opportunity to decrease or replace the use of wood fibres in the production of pulp and paper in countries with insufficient forest resources. The aim of this study was to characterise and evaluate the pulp and paper derived from four Ugandan grasses, namely *Cymbopogon nardus*, *Paspalum notatum*, *Saccharum officinarum*, and *Digitaria scalarum*, obtained using Soda-AQ and Kraft pulping methods for their potential use in the paper industry. The fibre morphology, as well as the physical properties, of both pulp and handmade paper sheets was analysed. The pulp and paper were identified with reasonable yield, medium viscosity, high bleachability, short and narrow fibres, and moderate paper strength. *Saccharum officinarum* pulp was characterised with high weighted average fibre length (1.143 mm), moderately high fibre width (18 μm), slenderness ratio (68), brightness (71.27%) and low kappa number (11.9); and the paper sheets with a tear index of 7.05 mNm^2/g, while *Cymbopogon nardus* pulp was characterised with higher yield (44.20%), viscosity (915 cm^3/g), low kinked fibre (20%) and curl (6%). The pulps from the two grasses superseded the others. Nevertheless, all the four grasses were recommended for pulp and paper production.

Keywords: Soda-AQ and Kraft pulping, fibre morphology, paper sheets, strength properties, sustainability

INTRODUCTION

The consumption of paper worldwide has escalated by 400 percent in the last 4 decades and around 4 billion trees are cut across the globe for pulp and paper mills on every continent.[1] This has caused global deforestation and forest degradation, creating an ecological and climatic imbalance, in addition to making homeless 300 million people who consider forests their home around the globe.[2] Realizing such severe consequences, major pulp and paper producing companies worldwide have considered not to cut down natural forests any longer,[3] while groups of researchers in pulp and paper are working towards exploring non-wood lignocellulosic materials and recyclable fibres for assessment and expansion of their pulp and papermaking capability.[4] Non-wood fibrous materials and recycled fibres offer a great opportunity to decrease or even replace the use of wood fibres.[5] In recent years, the attention has been focused on g rasses[6] and the hope of many countries, including Uganda, with insufficient forest resources lies in grasses for production of any virgin pulp. Uganda, a country spread on 236,040 km^2 with a population of about 35 million, has a forest cover estimated at 14% of the land surface and it is decreasing at a rate of 2% per year due to increasing population, which relies on agriculture for survival and much on wood for energy.[7] Nevertheless, Uganda is blessed with conducive equatorial type climate, which is ideal for the growth of many types of grasses that stand as potential raw materials for paper industry. These highly prospective grasses need to be investigated. Currently, many grasses are regarded as bothersome weeds in gardens and as a burden to farmers during the planting seasons. In urban areas, grasses that are cleared from compounds burden municipal authorities, in terms of their disposal since they don't bring any economic benefits to most communities.

Grasses are herbaceous and monocotyledonous plants with small height stems, long and slender leaves without branches. There are various grasses, such as reed canary grass (*Phalaris arundinacea*), tall fescue (*Festuca arundinacea*),[6] dogtooth grass (*Chenopodium album*),[7] prairie sandreed (*Calmovilfa longifolia*), cord grass (*Spartina pectinata*), big bluestem (*Andropogon gerardii*), switch grass (*Panicum virgatum)*,[9] elephant grass (*Pennisetum* purpureum)[10] etc., that have been researched upon for pulping and papermaking. However, to the best of our knowledge, the pulping and papermaking potential of *Cymbopagon nardus*, *Paspalum notatum*, *Saccharum officinarum* and *Digitaria scalarum* from Uganda have not been investigated much.

The evaluation of the pulping and papermaking potential of a raw material basically involves the determination of its proximate chemical composition, the identification of a suitable pulping process and bleaching sequence, the evaluation of bleached and unbleached pulp, the morphological analysis of pulp fibre, as well as testing for the physical properties of handmade paper sheets. Hence, the aim of this study has been to characterise pulp and paper derived from some Ugandan grasses as to evaluate their potential use in the pulp and paper industry. This has been done by carrying out a comparative study of the characteristics of the pulp and paper derived from the selected grasses, using Soda-AQ and Kraft pulping in relation with other species already in use in papermaking.

EXPERIMENTAL

Raw material

Cymbopogon nardus, *Paspalum notatum*, *Saccharum officinarum* and *Digitaria scalarum* were collected from Central and Eastern Uganda. The collected samples were manually chopped in sizes of about 2-3 cm, screened to get rid of the fines, cleaned with distilled water to eliminate adhered soils, and dried under a shed. Some quantities of them were ground to powder with a mesh size of 40 using a laboratory grinder for determining their proximate chemical composition. The analyses of the chemical constituents, as well as the identification of suitable pulping techniques and optimal pulping conditions, were done in the previous studies.[11,12]

Pulping and bleaching

The dry materials were soaked in water at room temperature for 24 h in a solid to liquor ratio of 1:10 in order to reduce the cold water extractives. They were then transferred to hot water in an autoclave in a solid to liquor ratio of 1:8 and hydrolysed at 100 °C for 1 h. This was done to increase the permeability of the chemicals from the cooking liquor.[13] The hydrolysed materials were digested in a 15 l laboratory digester PL001 with a pressure and temperature control, in replicates of three to four. Soda-AQ pulping was done at a soda charge of 25% with 0.1% anthraquinone for 1 h at a temperature of 160 °C. The Kraft pulping was done at a sulphidity of 30% for *Cymbopogon nardus* and *Paspalum notatum*; and a sulphidity of 10% for *Saccharum officinarum* and *Digitaria scalarum*, at active alkali of 20% and a temperature of 160 °C for 1 h. The cooked materials were disintegrated in a wet pulper at 1200 rpm for 20 min and screened by sieving through a screen of 1 mm mesh size. The isolated pulps were pre-bleached with a two-step HP_E (H is hypochlorite, P_E is alkalised hydrogen peroxide) bleaching sequence using the easily available bleaching agents at the recommended dosages. The optimal conditions for Soda-AQ and Kraft pulping, as well as HP_E bleaching, had been identified in our previous study.[12]

Pulp characterisation

The pre-bleached yields of pulps obtained from the selected grasses using both Soda-AQ and Kraft pulping methods were determined gravimetrically in replicates of three to four. The other properties of the isolated pulp that were analysed are kappa number (TAPPI T236 om-99), viscosity (TAPPI T230 om-08) and brightness (TAPPI T525 cm92). The morphological characteristics of fibres, such as fibre length, fibre diameter, coarseness, kink percentage, curl percentage, fibre length distribution and fibre width distribution, were determined using a Morphi Fibre Analyser and an Olympus BX61 research microscope.

Evaluation of paper sheets

The Canadian Standard Freeness (CSF) of the unbeaten and beaten pulp samples was measured before paper sheet making (TAPPI T227 om-99). Some pulp was subjected to mechanical beating using the PFI mill (TAPPI T248 sp-00). The paper sheets of 60 GSM were made with a handmade sheet making machine (TAPPI T205 sp-95). The properties of the paper sheets, such as tensile index (TAPPI T494 om-96), burst index (TAPPI T403 om-97), tear index (TAPPI T414 om-98), apparent density (gravimetrically) and air resistance (TAPPI T460 om-96), were analysed.

RESULTS AND DISCUSSION

Properties of Soda-AQ and Kraft pulps

The results for the physical properties of the pulps isolated from the four fibrous materials are summarised in Table 1. The research findings reveal that there were some slight variations in pulp characteristics among the different fibrous materials obtained by the two pulping methods.

The kappa numbers of the pulps obtained by Soda-AQ pulping were lower than those of the Kraft pulps from the same fibrous materials. *Saccharum officinarum* pulp had the lowest kappa numbers – of 11.9 and 23.4 for both Soda-AQ pulping and Kraft pulping respectively, while *Digitaria scalarum* Soda-AQ pulp and *Cymbopogon nardus* Kraft pulp had the highest kappa numbers – of 29.5 and 31.2, respectively. This is explained by the low lignin content of *Saccharum officinarum* leaves in comparison with the other three grasses.[11] The kappa numbers and the yield of *Paspalum notatum* Kraft pulp were slightly lower than those of its Soda-AQ pulp, which implies that *Paspalum notatum* responds better to Kraft pulping than to Soda-AQ pulping.

Among the grasses, *Cymbopogon nardus* had the highest yield irrespective of the pulping method. With the exception of *Paspalum notatum*, Soda-AQ pulping gave slightly lower yields than Kraft pulping. This is possibly attributed to fibre peeling or dissolution of hemicelluloses. Remarkably high brightness of both Soda-AQ and Kraft pulps was achieved with a simple preliminary bleaching sequence. This high brightness implied easy bleachability of the pulps from the four fibrous grasses and hence, a reduction in the chemical charges required in bleaching. Brightness reciprocates the kappa number, which in turn is a measure of the level of delignification. This explains why Soda-AQ pulps were brighter than the corresponding Kraft pulps of the same fibrous grass material.

Generally, the viscosities of the Soda-AQ pulps were lower than those of the Kraft pulps for the four grasses. This was attributed to the loss of the short chain carbohydrates during the Soda-AQ pulping, which is not the case with Kraft pulping. *Cymbopogon nardus* pulps had the highest viscosity; followed by *Saccharum officinarum* pulps, while *Digitaria scalarum* pulps had the least. The magnitude of viscosity is a precursor for fibre length and degree of polymerisation. This again revealed longer coarse fibres for *Cymbopogon nardus* and *Saccharum officinarum*, and the shortest ones for *Digitaria scalarum*, but this is not exclusive as other factors may also have influenced these results.

Fibre morphological analysis

The different morphological properties of fibres from both Soda-AQ and Kraft pulp samples for the four grasses are shown in Table 2. The results reveal that the pulp from different selected grasses contained fibres with intermediate fibre length, very close to those of hardwood, e.g. aspen (0.73 mm),[14] and also in a closer range to those of other grasses already investigated, e.g. *Chenopodium album* (0.60 mm),[14] alfalfa and switch grass (0.78 mm), but higher than those of two year old poplar (0.38 mm) and willow (0.34 mm).[15] The fibre length of the pulps obtained from the two pulping techniques did not differ significantly although the fibre lengths of Kraft pulps were slightly higher than those of Soda-AQ pulp, with the exception of *Saccharum officinarum*. This is attributed to some fibre peeling in the case of soda pulping. The *Saccharum officinarum* pulp was characterised by the longest fibres compared to the other three grasses, while *Digitaria scalarum* had the shortest ones. The observed *Saccharum officinarum* fibre length was in agreement with the earlier prediction, using viscosity as discussed in the previous section.

The distribution percentages of fibre lengths for both methods are presented in Figure 1. The largest proportions of fibres (28-43.7%) for all pulp samples were observed to be short (0.2-0.5 mm). There was even distribution of fibre lengths among the intermediate ranges of lengths (0.5-0.75 mm and 0.75-1.25 mm). Few fibres for all pulp samples were observed to have lengths in the range of 1.25 to 1.5 mm. Only *Saccharum officinarum* was observed having fibres with a length greater than 1.5 mm (25%). The fibre length distributions of the pulps obtained by the two pulping methods did not differ significantly.

The distribution percentage of fibre widths is presented in Figure 2. The fibre widths of all pulps from the four grasses varied between 11.6-18.5 µm, *Saccharum officinarum* pulp had the largest fibres compared to those of other three grasses. This explains the observed high coarseness of its fibres. *Paspalum notatum* had the smallest fibre width and intermediate fibre coarseness, which predict its high fibre flexibility. Fibre flexibility is a very important parameter due to its contribution towards the paper strength. Flexibility increases bonding abilities, thereby increasing the paper strength properties. The fibre widths of all the four grasses were close to those of *Eucalyptus tereticornis* (14.6 µm) and *Eucalyptus grandis* (19.2 µm) [16] and within the range of values of other grasses such as switch grass (13.90 µm) and elephant grass (15.14 µm).[10]

Table 1
Properties of pulp from the four grasses processed by Soda-AQ and Kraft pulping methods

Pulp property	Soda-AQ pulp				Kraft pulp			
	SOSP	DSSP	CNSP	PPSP	SOKP	DSKP	CNKP	PPKP
Kappa number	11.9±0.2	29.5±0.6	24.4±0.5	24.4±0.4	23.4±0.5	23.4±0.5	31.2±0.5	25.9±0.5
Pre-bleached yield (%)	40.48± 0.61	36.25± 0.73	42.83±0.64	31.10±1.01	41.54±0.83	35.50±0.78	44.20±0.69	31.58±0.67
Intrinsic viscosity (cm^3/g)	777.84±7.00	603.59±9.05	782.51±8.6	629.93±4.41	835.34±5.85	662.73±5.30	915.00±7.32	719.94±6.48
Brightness (%)	71.27± 1.07	59.61±0.83	69.65±0.91	60.90±0.91	63.33±1.08	56.62±0.85	57.71±0.92	48.60±0.73

SOSP: *Saccharum officinarum* Soda-AQ pulp; DSSP: *Digitaria scalarum* Soda-AQ pulp; CNSP: *Cymbopogon nardus* Soda-AQ pulp; PPSP: *Paspalum notatum* Soda-AQ pulp; SOKP: *Saccharum officinarum* Kraft pulp; DSKP: *Digitaria scalarum* Kraft pulp; CNKP: *Cymbopogon nardus* Kraft pulp; PPKP: *Paspalum notatum* Kraft pulp

Table 2
Fibre morphological features of grass pulps

Pulp fibre property	Soda-AQ pulp				Kraft pulp			
	SOSP	DSSP	CNSP	PPSP	SOKP	DSKP	CNKP	PPKP
Arithmetic avg. length (mm)	0.652	0.483	0.512	0.532	0.63	0.51	0.52	0.554
Weighted avg. length (mm)	1.143	0.661	0.744	0.709	1.133	0.718	0.771	0.748
Avg. width (µm)	16.7	13	14.4	12.2	18.5	14.8	13.7	11.6
Coarseness (mg/m)	0.1234	0.0388	0.0646	0.0564	0.1031	0.0440	0.0635	0.0584
Kinked fibre (%)	28.1	24.9	18.6	39.2	26.3	30	22.5	30.5
Curl (%)	10.4	8.1	6.1	10.9	8.2	9.3	6.6	8.2
Broken ends (%)	17.74	16.19	13.13	18.59	20.9	18.43	13.44	16.03
Fine elements (%)	35.8	23.86	31.7	37.42	34.04	17.61	29.18	37.41
Slenderness ratio	68.44	50.85	51.67	58.11	61.24	48.51	56.28	64.48

SOSP: *Saccharum officinarum* Soda-AQ pulp; DSSP: *Digitaria scalarum* Soda-AQ pulp; CNSP: *Cymbopogon nardus* Soda-AQ pulp; PPSP: *Paspalum notatum* Soda-AQ pulp; SOKP: *Saccharum officinarum* Kraft pulp; DSKP: *Digitaria scalarum* Kraft pulp; CNKP: *Cymbopogon nardus* Kraft pulp; PPKP: *Paspalum notatum* Kraft pulp

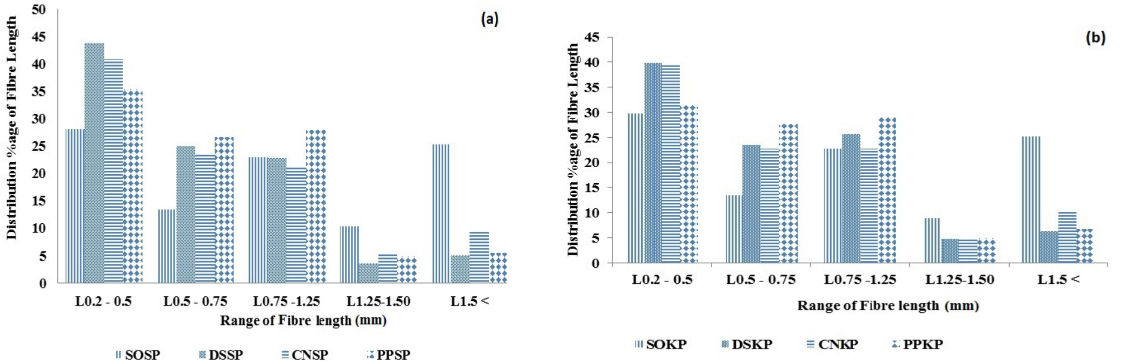

Figure 1: Fibre length distribution for (a) Soda-AQ pulp and (b) Kraft pulp (SOSP: *Saccharum officinarum* Soda- AQ pulp; DSSP: *Digitaria scalarum* Soda-AQ pulp; CNSP: *Cymbopogon nardus* Soda-AQ pulp; PPSP: *Paspalum notatum* Soda-AQ pulp; SOKP: *Saccharum officinarum* Kraft pulp; DSKP: *Digitaria scalarum* Kraft pulp; CNKP: *Cymbopogon nardus* Kraft pulp; PPKP: *Paspalum notatum* Kraft pulp)

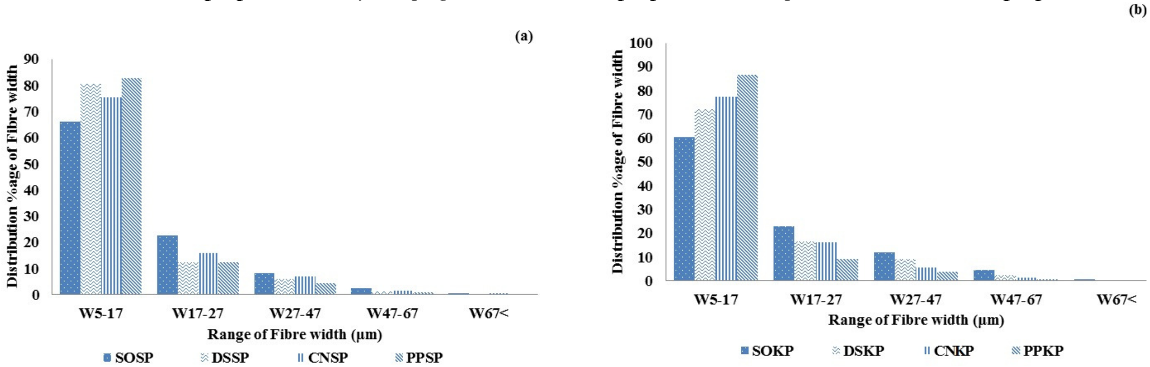

Figure 2: Fibre width distribution for (a) Soda-AQ pulp and (b) Kraft pulp (SOSP: *Saccharum officinarum* Soda-AQ pulp; DSSP: *Digitaria scalarum* Soda-AQ pulp; CNSP: *Cymbopogon nardus* Soda-AQ pulp; PPSP: *Paspalum notatum* Soda-AQ pulp; SOKP: *Saccharum officinarum* Kraft pulp; DSKP: *Digitaria scalarum* Kraft pulp; CNKP: *Cymbopogon nardus* Kraft pulp; PPKP: *Paspalum notatum* Kraft pulp)

These results reveal that fibre width distributions for both methods were skewed to the left for all the pulp samples, with the majority of their fibres (66.1-86.6%) being thin (5-17 µm). *Paspalum notatum* pulps were observed with the greatest kinked and curled fibres for both pulping techniques. The high magnitude of the two properties is attributed to the high flexibility of its fibres. *Saccharum officinarum* pulps had a high amount of kinked and curled fibres, whereas *Cymbopogon nardus* pulps had the least. The high value of kinked and curled fibres in *Saccharum officinarum* pulps is attributed to its long fibres. The low kinked and curled fibres of *Cymbopogon nardus* pulps indicated stiffer fibres.

Soda-AQ pulps of all the grass species, with the exception of *Paspalum notatum*, had fewer broken ends than the Kraft pulps. This is due to the fact that Soda-AQ pulping produces polished and more flexible pulps, which do not break easily. The fine element percentages for all samples were high and did not differ significantly for the two methods. The fines are thought to be derived from non-fibre cellular tissues, which exist in the pulp. *Paspalum notatum* pulps had the highest fine elements and also an appreciable amount of fibres with broken ends. This is attributed to its weak fibres. *Saccharum officinarum* Soda-AQ pulp exhibited a high slenderness value and this again explains its high tear index value. It is followed by *Paspalum notatum* Kraft pulp, while the Kraft and Soda-AQ pulps of *Digitaria scalarum* had the least slenderness ratio, which explains its low tear indices. The slenderness ratio of all pulp samples were close to those of other non-wood materials already recommended for paper production such as sugarcane bagasse (70.56),[17] lemon grass (66.9) and Sofia grass (59.2).[18]

Photomicrographs of the pulp fibres obtained by both Soda-AQ and Kraft pulping were taken using an Olympus BX61 computer aided microscope at different magnifications, as shown in Figs. 3, 4 and 5. These findings display that all the grasses, like many non-wood materials, contain other non-fibrous cellular materials, such as parenchyma tissues, vessel elements and epidermal tissues, in addition to cellulose fibres, which do not have any paper making properties. Their presence in large numbers tends to hamper inter-fibre bonding. The parenchyma tissues in these photomicrographs are seen as large, barrel-shaped, iso-diametric and thin-walled. When these thin walled and poorly lignified parenchymas are plugged into sheets, they impair drainage and easily flatten during refining causing further drainage problems[18]. The presence of these epidermal cells, parenchyma tissues and vessel elements explains the presence of high fractions of fines in the pulp, which are formed during the pulping and beating of pulp. Fines are the most undesirable elements in stock for paper making, since their presence reduces freeness and increases water retention by the pulp. Critical observation of the photomicrographs reveals that the fibre morphology of the pulps of the same plant species obtained by the two pulping methods does not differ significantly.

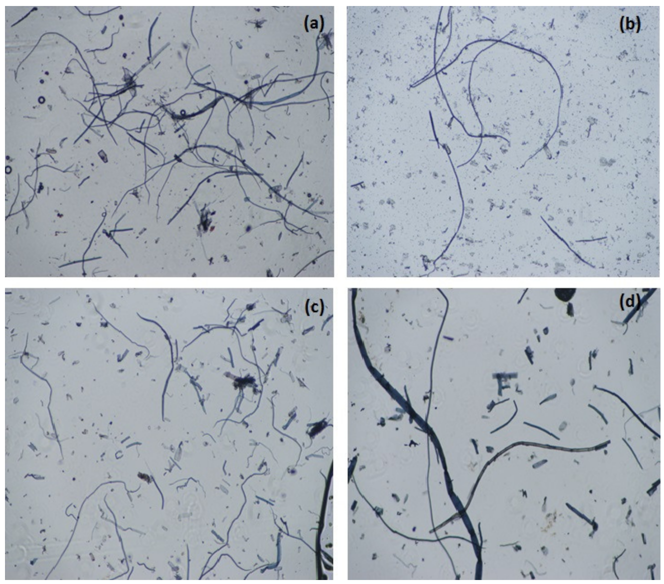

Figure 3: Photomicrographs for Soda-AQ pulp from (a) *Digitaria scalarum*; (b) *Cymbopogon nardus*; (c) *Paspalum notatum*; and (d) *Saccharum officinarum* at a magnification of 40X

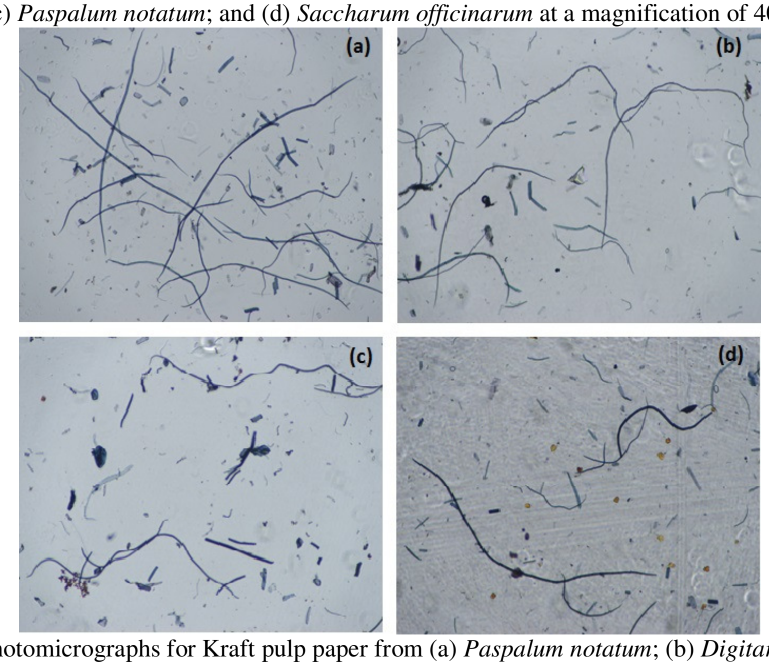

Figure 4: Photomicrographs for Kraft pulp paper from (a) *Paspalum notatum*; (b) *Digitaria scalarum*; (c) *Saccharum officinarum*; (d) *Cymbopogon nardus* at a magnification of 40X

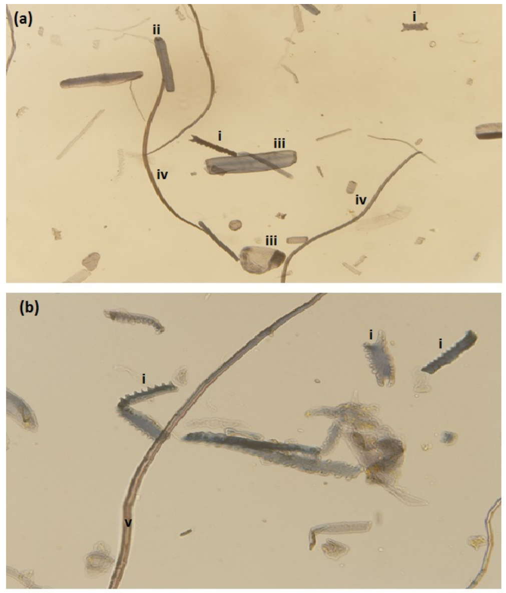

Figure 5: Photomicrographs showing: i. Epidermal tissues; ii. Vessel elements; iii. Parenchyma tissues; iv. Fibres; v. Fibre lumen for (a) *Cymbopogon nardus* Kraft pulp at a magnification of 100X and (b) *Paspalum notatum* Soda-AQ pulp at a magnification of 200X

Both *Paspalum notatum* and *Digitaria scalarum* micrographs showed thinner, end taped and more flexible fibres compared to those of *Saccharum officinarum* and *Cymbopogon nardus*. *Saccharum officinarum* had more non-fibre cellular tissues and thicker long fibres compared to the other three fibrous materials

Physical properties of handmade paper sheets

The physical properties of handmade paper sheets from Soda-AQ and Kraft pulp extracted from the four fibrous materials are summarised in Table 3. The results show that the CSF values (240-470 ml) for all the unbeaten pulp samples are generally low compared to those of hardwoods. This shows high interactions of grass pulp fibres with water molecules. Upon beating, the CSF decreased tremendously, due to the fact that more fibrils were opened, thereby the area for water adsorption was increased. The CSF values dropped very readily even below 200 on slight beating of the pulp. Generally, all pulp samples from all fibrous materials attained CSF values of about 200 at PFI beating of around 500 revolutions. Beating of pulp samples caused substantial improvement in the strength properties, which implies minimal energy requirements. The maximum tear strength is easily reached at 500 PFI revolutions for all paper samples although apparent density, burst index and tensile index continued to increase up to 1000 PFI revolutions. This implies that 500 PFI revolutions beating is optimum for all pulp samples before sheet making. Unlike wood pulp, whose beating may go up from 5000 to 6000 PFI revolutions in order to acquire the recommended CSF value, the energy required by any of the grass pulp samples for 500 PFI revolutions is very low, which implies saving energy and cost of production.

The apparent densities of all the paper sheets from all the four grass materials obtained by the two pulping methods are of medium values, but slightly higher than those of switch grass (0.35-0.57 g/cm^3),[14] cotton stalks (0.37-0.63 g/cm^3)[19] and are of the same magnitude as that of the dog tooth grass (0.62-0.73 g/cm^3).[8] The apparent density of the paper samples also increased with the increase in the beating level, which is due to the increased proportions of short fibres, which increase the fibre packing efficiency.

The burst indices for paper sheets from beaten pulps right from 500 to 1000 PFI revolutions are in normal ranges for most paper uses (News print 0.65 kN/g, Rag bond 2.29 kN/g)[20] and from most fibrous materials. The paper sheets from *Paspalum notatum* and *Digitaria scalarum* had higher burst indices than the two other grass species, which implies that they can be employed in special cases where high burst indices are required, for example in packaging bags. Both the apparent density and burst indices for all the paper samples could be ideal for writing paper and their magnitude could be increased with additives during the production processes.

Table 3
Physical properties of paper handsheets from pulps of different Ugandan raw materials

Property	PFI Rev	Soda pulp paper				Kraft pulp paper			
		SOSP	DSSP	CNSP	PPSP	SOKP	DSKP	CNKP	PPKP
Freeness CSF	0	375.00	395.00	345.00	240.00	470.00	315.00	360.00	240.00
	500	260.00	195.00	205.00	165.00	220.00	200.00	255.00	210.00
	1000	200.00	160.00	165.00	150.00	215.00	200.00	175.00	200.00
Apparent density	0	0.62	0.53	0.56	0.65	0.60	0.55	0.49	0.44
(g/cm^3)	500	0.72	0.67	0.65	0.74	0.71	0.57	0.61	0.51
	1000	0.73	0.71	0.68	0.76	0.75	0.63	0.62	0.57
Burst index	0	0.51	1.23	2.01	2.26	0.98	1.50	1.27	1.76
(Nm/g)	500	2.21	3.10	2.90	3.69	2.85	3.70	2.78	3.35
	1000	2.44	3.50	3.07	3.75	3.24	4.17	2.98	3.60
Tensile index	0	6.06	24.24	28.95	20.57	15.33	22.61	16.78	27.46
(kNm/g)	500	21.23	34.54	32.70	31.69	26.75	36.98	36.00	32.23
	1000	33.82	38.60	34.50	35.8	35.25	39.98	40.40	36.77
Tear index	0	6.90	4.61	5.23	4.84	5.76	5.20	4.12	3.57
(mNm^2/g)	500	7.05	4.70	5.09	5.54	6.34	5.81	6.44	6.12
	1000	6.5	4.45	5.01	5.32	5.53	5.40	5.54	5.80
Porosity	0	2933.6	1564.00	1880.00	238	2600.00	526.50	2495.00	180.00
Air resistance)	500	658.7	394.70	757.50	75.5	224.90	62.80	780.00	144.00
(ml/min)	1000	114.5	20.00	299.80	50.00	141.00	40.90	447.00	60.52

SOSP: *Saccharum officinarum* Soda-AQ pulp; DSSP: *Digitaria scalarum* Soda-AQ pulp; CNSP: *Cymbopogon nardus* Soda-AQ pulp; PPSP: *Paspalum notatum* Soda-AQ pulp; SOKP: *Saccharum officinarum* Kraft pulp; DSKP: *Digitaria scalarum* Kraft pulp; CNKP: *Cymbopogon nardus* Kraft pulp; PPKP: *Paspalum notatum* Kraft pulp

The burst indices of all samples when beaten to 1000 revolutions were very close to those of spruce wood pulp (3.09-3.64 kPam^2/g)[21] and tobacco stalk pulp (3.98-4.36 kN/g),[22] while higher than that of banana tree residue (0.64-2.79 kN/g).[23]

The tensile indices of all the paper sheets from the four grasses were generally slightly lower than those of hardwood, e.g. *Eucalyptus globulus* (110.21 Nm/g),[24] and some non-wood materials, e.g. *Chenopodium album* (56.70 Nm/g).[8] As expected, the tensile indices of the Kraft paper sheets were higher than those of the corresponding Soda-AQ paper. The handmade sheets from *Digitaria scalarum* pulp had the highest tensile index, followed by those from *Cymbopogon nardus*, while those of *Saccharum officinarum* had the least values for both pulping methods. The low value of the tensile index of the *Saccharum officinarum* paper sheet is attributed to the high coarseness of its fibre and hence low flexibility, which does not allow good formation of a bonded network. Although *Paspalum notatum* and *Digitaria scalarum* paper sheets had good burst and tensile indices, these were overshadowed by the short fibres, which are poor in water drainage, causing problems in paper pressing during production. This can be improved by blending with long softwood fibres, especially for printing/writing paper.

The tear indices of all the paper sheet samples from the four grasses were moderately high compared to that of *Chenopodium album* (4.9 mN m^2/g),[8] but lower than that of *Eucalyptus globulus* (8.6 mNm^2/g).[24] *Saccharum officinarum* paper sheets from both pulping methods had the highest values of tear indices for the two, which is directly explained by its long fibres. Longer fibres have more bonding points, requiring more energy to be separated, hence the high tear strength/index. The unbeaten Soda-AQ paper has greater tear indices than the respective Kraft paper, with the exception of *Digitaria scalarum.* Upon beating, Kraft pulp gains more tear strength, which is credited to the opening up of the fibrils during the beating.

The paper sheets obtained from the unbeaten pulp samples of all fibrous materials had high porosity with the exception of those of *Paspalum notatum*, and decreased with pulp beating. The paper sheets from *Saccharum officinarum* had the highest porosity, followed by *Cymbopogon nardus*, whereas those of *Paspalum notatum* had the least porosity. The high porosity observed for *Saccharum officinarum* and *Cymbopogon nardus* paper sheets is explained by the high portions of longer fibres. The network of longer fibres leaves many open structures through which air can percolate. From a morphological point of view, pulp beating produces recognisable changes in the fibre structures, increasing fibre bonding. The beating process causes the outer primary wall and the first secondary layers to loosen and separate. The exposed area of fibrils forms potential bonding sites during sheet formation.[24,25] These changes are manifested in an increase of some physical properties of pulps and paper, such as apparent density, burst index, tensile index, and a decrease in CSF, porosity and tear index.

CONCLUSION

The properties of the pulp and paper from the four grasses were found very close to those of agricultural crops and residues already identified. The viscosity, kappa number and pre-bleached yield of Kraft pulp from different grasses were higher than those of Soda-AQ pulps. Soda-AQ pulps of all the four grasses were brighter than the Kraft pulps.

Saccharum officinarum pulp presented the highest brightness and longer fibres close to those of bagasse, but many non-fibre tissues, while *Cymbopogon nardus* had the highest yield and viscosity. There were no significant differences in the fibre morphology of the Soda-AQ and Kraft pulps for the corresponding grasses. Like many non-wood material, the four grasses contained a number of non-fibre materials and great percentages of fines.

The physical properties of the handmade sheets from the four grasses were at the lower ends of the ranges for hardwood, which implies that pulp from these grasses can replace hardwood pulp to a low or moderate extent, especially in writing, newspaper, toilet papers etc.

Beating pulp at up to 500 revolutions significantly improves paper properties and gives the optimal properties.

The choice of any of the four grasses and of the pulping method for paper production depends on the end uses of the paper being manufactured. The four grasses are recommended for pulp and paper production, although *Saccharum officinarum* and *Cymbopogon nardus* supersede others in a number of features.

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