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Optimization of Banana Stem Pulp to Substitute Softwood Pulp For High Quality Paper

Mamduh M. Nassar [1], Ibrahim I. Ibrahim[1]. Hisham M. Elsherif[1], Mohamed Abdallah[2]

[1]*Faculty of Engineering,Mania University, Egypt*
[2]*Techniacl Managing Director in Misr- Edfu for pulp and paper Co. Egypt.*

Abstract

This study deals with optimizing pulping conditions of the banana stem to substitute softwood pulp in writing and printing paper. Scanning micrograph and chemical composition of banana stem indicate that banana fibers are flat, flexible, long (2.24 mm) and the raw banana is characterized with high cellulose (65%) and low lignin (13.5%) contents. The banana stem was pulped using Kraft process (8.5 % alkali as Na_2O and 17% sulfidity cooked at 105°C for 3 hr. Detail mechanism of the pulping parameters was discussed. The obtained pulps were characterized with respect to yield (64%) and Kappa number (35%). Compared to imported softwood pulp, all strength properties and opacity are high. This is attributed to the long banana fibers and the high cellulose content. The effect of these two parameters on tensile, burst, and tear, strengths was discussed. High quality of writing and printing paper was obtained by a furnish blend ratio of 20%-80%, banana stem pulp, and commercial bagasse pulp respectively.

Keywords: Banana Stem, Fibre length, Sulfate pulp, writing and printing papers.

Introduction

The increased demand for raw fibrous materials than wood for pulp and paper industry directed the sight to the utilization of non-wood fibers (annual agricultural plants and residues) for pulp production. Different agricultural residues such as bamboo, rice straw, bagasse are currently used in commercial pulping operations [Hturter, 1988 and Fahmy et al,1972]. Pulping of non-wood fibers is more difficult than that of wood. The problem encountered the high percentages of non-cellulosic materials such as pith (35%) in bagasse [Nassar, 1975]and high ash (18%) in rice straw of which 90% is silica [El-Taraboulsi, and Nassar, 1980]. Wood (spruce) contains 95 % cells which are considered as fibers, only 65% of the cells in bagasse are useful fibers [Redholm, 1969].

Pulping of non-wood fibers has been carried out mostly by alkaline methods to make different grades of papers [El-Taraboulsi and Abosalem, 1963; Jafari-Petroudy, 2011]. But the acid process was also studied to produce paper from rice straw and bagasse pulps [Nassar, 2003, El-Taraboulsi et al. 1983].

Banana stem is characterized by high cellulose content, low lignin content and long fiber length [Khan et al., 2013]; therefore it can be considered as a good material for paper production. However, detailed studies of pulping banana stem; seems to have not adequately been studied in the literatures.

The present work, therefore, deals with detailed studies of pulping banana stem by Kraft process to produce pulp suitable for writing and printing paper. The study extended to make different blends of banana-bagasse pulp. The selection of banana stem for production of paper is not only as a new source for paper manufacture in Egypt to compensate the shortage of bagasse pulp, but also aimed mainly to substitute the imported wood pulp due to its long fiber.

Experimental

The banana stem used in this study was obtained from the farms located in north Luxor City-Egypt; its name is William Hybrid banana, the scientific name is Sp. Musa, nature height=8-10ft.

The raw material used (banana stem) was chipped to a length 2.5 - 4cm, and wet cleaned, and then air-dried to a uniform moisture content of 10%. The chemical analysis of banana stem was determined

*Corresponding author e-mail: mabdalla.meppco@yahoo.com.; (Mohamed Abdallah Ali).
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according to the corresponding TAPPI standards for different components, namely: water solubility (T-207), 1% sodium hydroxide solubility (T-212), ethanol-benzene solved extractives (T-204), lignin (T222), pentosanes (T-223) and ash (T-211). For cellulose and hollo-cellulose, analysis by Kurichner- Hoffner method (T249, cm-09).

All the pulping experiments were carried out in laboratory rotated thermostated stainless steel autoclave –digester of 3 litres capacity, equipped with a rotating unit and heated with oil bath. Temperature and pressure devices are available to control the required cooking conditions. A batch of 200gm moisture free raw material was cooked under different cooking conditions such as: Temperature, ranged from 85 to 150ºC, cooking time from 2hr to 7hr and active alkali from 7 to 14 % (as Na_2O). The liquor to the raw material ratio of 12:1 and sulfidity was kept constant at 17%. At the end of cooking, the digester (autoclave) was removed and quenched in cooled water to depressurize. The digested material was separated from black liquor, dispread in waster and disintegrated then washed with hot water to remove the remaining black liquor and dissolved substances. After thorough washing, the pulp was screened on a laboratory vibrating screen with a slot size of 0.14 mm. The cleaned pulps were evaluated for screen yields and the rejects content. The moisture content was determined as TAPPI test T236. The residual lignin content in pulp was assessed by determining Kappa number (TAPPI test T236 cm 13).

Freeness of pulp (Shopper Regular, SR^{o}) was determined as ISO 5267 method. Hand sheets of 60 gm were made on sheet former TAPPI method T 205 sp18. The physical strength properties of paper hand sheets were determined as TAPPI test (T 220 sp-16), tensile breaking strength-T404 wd-03, internal tearing resistance index-T 414om-12, burst strength-T 403 om-15 and folding endurance tester (MIT) T511 om-13. Tensile tester (Adamel Lhomargy, model No.596420, DY-30, France). Bursting strength tester (Tecnolab Company, model No. BS 20 E/SN.160.08, Austria). Tearing tester (FRANK-PTI GMBH, Elmendorf tear tester, digital Mod. 53984, Sr. 40551). Twin folding tester (Folding endurance, KOEGEl, LEIPIZG, DFP 6/60 9401). All the experiments were performed in duplicate and average values are reported herewith (TAPPI Test method. Atlanta, Georgia, USA, TAPPI Press; 2013).

Characterization of banana fiber surface dimensions was carried out using a Scanning Electron Microscope (SEM) model FEI Quanta 250 FEG.

Three types of pulp were used in this study namely banana stem pulp, bagasse pulp and soft wood pulp.

1- Banana stem pulp was experimentally prepared according to certain programmed (see discussion, tables 3, 4 and 5) to produce different pulp yields from 77% to 44%.

A selected banana pulp was bleached for paper manufacture (hand sheet) under the following conditions:

Pulping conditions of banana stem for manufacture hand sheet:

Temperature = 105ºC, % alkali as Na_2O = 8.5, Time = 3 hr.

Different cooking trials were carried out at different temperatures. It was found that at a higher temperature, the degradation of carbohydrate fractions of banana fiber increases, thereby resulting in a reduced pulp yield. Beyond a temperature of 105ºC degradation of carbohydrates contents occurs due to peeling reactions, and poor drainage (increasing pulp freeness SR°) led to problems in the filtration process and it is not economical to continue the cooking operation beyond this optimum temperature of 105ºC. Therefore, based on experimental data, a maximum cooking time of 3 hr. and a maximum cooking temperature of 105ºC was considered as an optimum cooking condition for the Kraft pulping of banana stem.

Bleaching:

1st stage: 1.6% NaOH, at 75ºC for 2 hrs.

2nd stage: 4% Sodium hypochlorite, at 35ºC, for 3hrs, pH = 11

2- Bagasse pulp used; was commercial pulp produced by Kraft process [Misr-Edfu for pulp and paper company, Egypt], using Pandia continuous digester under the following conditions:

Temperature = 162ºC, Time = 20 min, Alkali charge as Na_2O = 10%, liquor ratio = 1:4

Bleaching condition:

Input unbleached pulp with pH = 9 at 37ºC

1st stage (O_2 bleaching): pH = 11, temperature = 90ºC soda = 20 kg/T pulp as dry base (conc. 120 g/l) oxygen at 20 kg/T pulp), time = 90 min (inside oxygen tower).

2nd stage (hypochlorite stage):Hypo- charge = 35 kg/T pulp as active chlorine, hypo. Conc. = 120 g/l, time = 3hr, pH = 10.

3- Imported bleached softwood pulp (southern Soft wood, spruce) from two mills:

1stmill: SUN Stora Enso Biomaterials, Sunila Mill Kotka, Finland

2nd mill: Panasoft, Rock Tenn's mill in Panama City, Florida, USA.

Results and Discussion

1- Fiber characterization:

The most important factor in pulp-paper quality is fiber morphology, fiber structure and the fiber dimensions. On examining the fiber micrograph given in Figures 1a to 1d, it appears that banana fibers are flat and flexible leading to high strength paper. This observation is confirmed on studying banana fiber dimensions given Table 1

For comparison, dimensions of softwood, hardwood and bagasse fibers are given. It can be noticed that banana stem fiber has a fiber length comparable to softwood fiber and the aspect ratio of both are nearly in the same range.

Compared to annual plants, banana stem fibers have unique fiber dimensions: large fiber length (2.3 mm) and high aspect ratio (92); this finding was also found by others [Khan and Sakar, 2013]. Therefore, the banana pulp can successfully substitute softwood pulp as a reinforcing material in paper manufacture.

2- Chemical composition of banana stem:

The chemical composition of the banana stem is shown in table 2. The following remarks can be drawn out from studying the data: Banana stem has high cellulose (65%), low lignin (13.5%) and high ash (8.6%). The high percentage of cellulose has the advantage over softwood with respect to pulp yield and paper strength. The ratio of cellulose to pentosane (hemicellulose) is 5.16 for the banana stem comparable to softwood (5.2). This ratio is important when considering the role which hemicelluloses play in paper strength. Therefore, it is expected that the paper produced from banana stem pulp be strong as that from softwood pulp. The low lignin content (13.5%) compared to wood (27%) is advantageous, making easy pulping with a short amount of active chemicals.

Agricultural residues are characterized by high ash content which is the same in case of the banana stem (8.6% ash, and 4.7% silica). Such high value is not dramatic in terms of the chemical recovery process from black liquor since the silica base salts are negligible [Cordeiro et al., 2003]. This assumption was supported from experiences gained during recovery of chemicals in Edfu Mills-Egypt (Mill manager, 2019) when blending black liquor from Kraft banana stem pulp (3.8% silica) blended with Kraft bagasse black liquor (1.7% silica), the average silica content was only 2.36% in the mixed black liquor, this amount is very safe in the recovery system.

Table 1: Fiber dimensions of banana stem, bagasse, hardwood and softwood

Item	Banana stem Present work	Bagasse [1]	Hardwood [2]	Softwood [2]
Fiber length (L) mm	2.21-2.24	1.7	1.7	2.2-3.3
Fiber diameter, (D) µm	24	20	20	34
Aspect ratio (L/D)	92-93	85	85	64-97

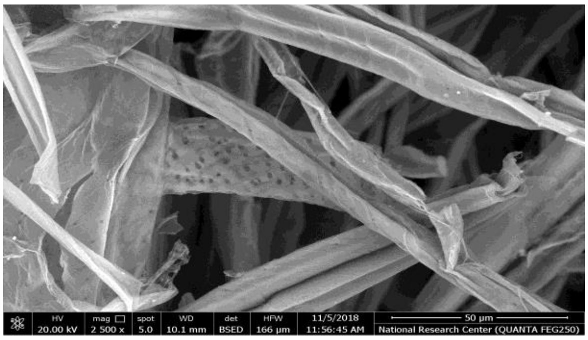

Figure 1a: SEM scan of banana stem fiber, magnification, 2500 X

Figure 1b: SEM scan of banana stem fiber, magnification, 2500X.

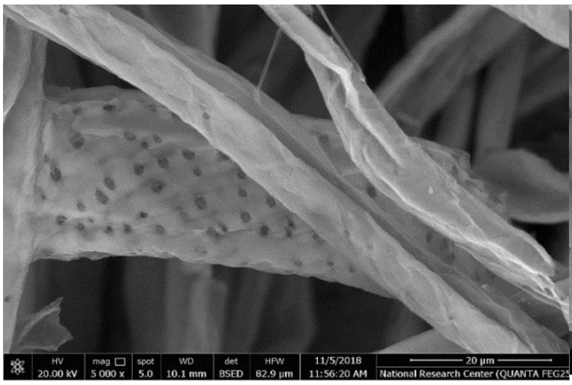

Figure 1c: SEM scan of banana stem fiber, magnification, 5000X

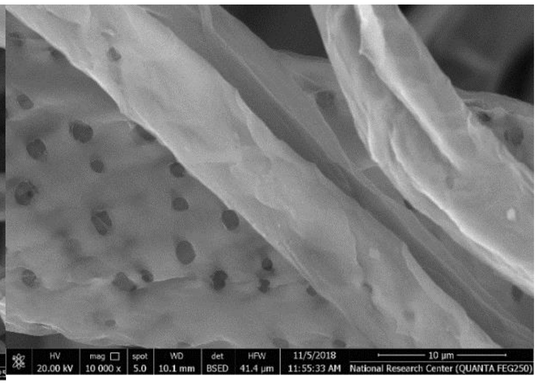

Figure 1d: SEM scan of banana stem fiber, magnification, 10000X.

Table 2: Chemical composition of banana stem, bagasse, and wood (hard and soft)

Items, %	Banana Stem Present work	Bagasse [1]	Hardwood [2]	Softwood [2]
Cellulose	65	48.4	60	58.3
Lignin	13.5	21.3	22	27.4
Ash	8.6	2.9	0.4	0.2
Silica	4.7	2	< 1	< 1
Extractive Pentosane	12.6	26.6	22	11
Extractive (Benzene-Alcohol	15.3	1.7	3.2	4.2
Solubility in cold water	11.6	4.0	-	-
Solubility in hot water	17.1	9.3	2.7	2.7
Cellulose/hemicellulose Ratio	5.16	2.23	2.7	5.2

[1] Nassar, 1975 [2] Rydholm, 1969

3- Pulping and Pulp Characterization:

Three variables were studied (temperature, percentage of alkali and time) on the degree of delignification of banana stem. Each variable was studied while keeping the other two constant.

Table 3 shows the effect of temperature on the pulp yield, percentage of rest alkali in black liquor and Kappa number. As the temperature increased from 85 to 150°C, pulp yield decreased from 76% to 44%. This is attributed to the fact that as temperature increased the rate of mass transfer of active chemicals increased consequently reaction between lignin (the cementing material between fibers) and alkali is increased. Thus enhancing the solubility of lignin and finally the yield is decreased. At the same time both, rejects and the rest alkali in black liquor are decreased. Kappa number which indicates the amount of residual lignin left in pulp is also reduced. However, the yield of banana pulp relatively high, (compared to other agricultural residues) due to the high cellulose in the raw banana stem (65 % cellulose).

Table 4 shows the effect of increasing the percentage of alkali on yield, percent of rejects, rest alkali and Kappa number. As the percentage of alkali increased, the rate of delignification increased and yield decreased. This is attributed to; the increased diffusion rate of alkali due to increased driving force between bulks of solution to banana fiber surface. Consequently, enhancing the alkali movement to enter fiber lumen then diffuses through fiber pits to reach middle lamella between fibers (where lignin is concentrated) causing a faster rate of delignification. The amount of reject decreased and Kappa number of the produced pulp is eventually reduced. However, the rest alkali's high value is due to the more alkali added than that needed for delignification.

Table 5 shows the effect of time on yield, rejects, rest alkali and Kappa number. As time increased, the delignification rate increased. This may be attributed to; as the time increased, the active chemicals will have time to pass through fiber lumen to the middle lamella where lignin is concentrated and dissolve the lignin and finely the dissolved lignin will be passed to solution as black liquor. Consequently, all other parameters (residue, rest alkali and Kappa number) are decreased.

Table 3: Effect of temperature on pulping of banana stem

T (℃)	YI (%)	R (%)	R A (gm/l)	Kappa No.
85	76	35	1.85	45
105	64	14	1.50	35
120	53	9.5	1.25	24
130	49	5.5	1.10	20
140	45	4.0	0.80	18
150	44	2.8	0.50	17

T, YI temperature and yield; R, Reject; RA, residual alkali. The values of time, %Alkali and liquor ratio are fixed and they were 3 hr., 8.5, 1:12 respectively.

Table 4: Effect of alkali on pulping of banana stem fiber

Alkali (%)	YI (%)	R (%)	R A (gm/l)	Kappa No.
7	72	29	1.2	41
8.5	64	14	1.5	35
10	56	9	1.6	30
11	53	6.8	2.5	28
12.5	49	3.5	3.1	27
14	45	1.0	4.18	21

The values of time, liquor ratio and temperature are fixed and they were 3 hr., 1:12 and 105ºC respectively

Table (5) effect of time on pulping of banana stem fiber

Time (hr.)	YI (%)	R (%)	R A (gm/l)	Kappa No.
2	79	33	1.65	40
3	64	14	1.5	35
4	60.8	8.8	1.3	30
5	57.4	7.4	1.27	28
6	55	6.6	1.18	26
7	53.2	4.8	0.7	23

YI, Yield; R, Reject; RA, residual alkali, the values of temp., % Alkali, and liquor ratio consumption are fixed and they were 105ºC, 8.5, 1:12 respectively.

4- Yield-Kappa Number Relationship:

The degree of delignification is a function of residual lignin in the produced pulp. The residual lignin can be assessed by determining Kappa number. Figure2 shows the relationship of the yield versus Kappa number for different pulping parameters such as temperature, time, and amount of active chemicals. The relationship is linear and the following equation can be given: Equation (1) is valid for Kraft banana stem pulp covering a wide range of yield (45%-79%) and a wide range of Kappa number (17 – 45). This equation helps to estimate the amount of chemicals to be used for bleaching operation. Mikkail and Adriaan, (2011) accomplished comprehensive research and found that the relationship between residual lignin and Kappa number is linear. Rydholm, 1969, stated that Kappa number is related to lignin content in percent by a factor of 0.13.

Evaluation of banana pulp, bagasse pulp, and softwood pulp:

The furnish of pulp used in making hand sheet-paper was a blend of experimentally prepared Kraft banana pulp, commercial Kraft bagasse pulp and imported wood pulp. Table 6 shows the characterization of pulp and strength results of the hand sheet-paper.

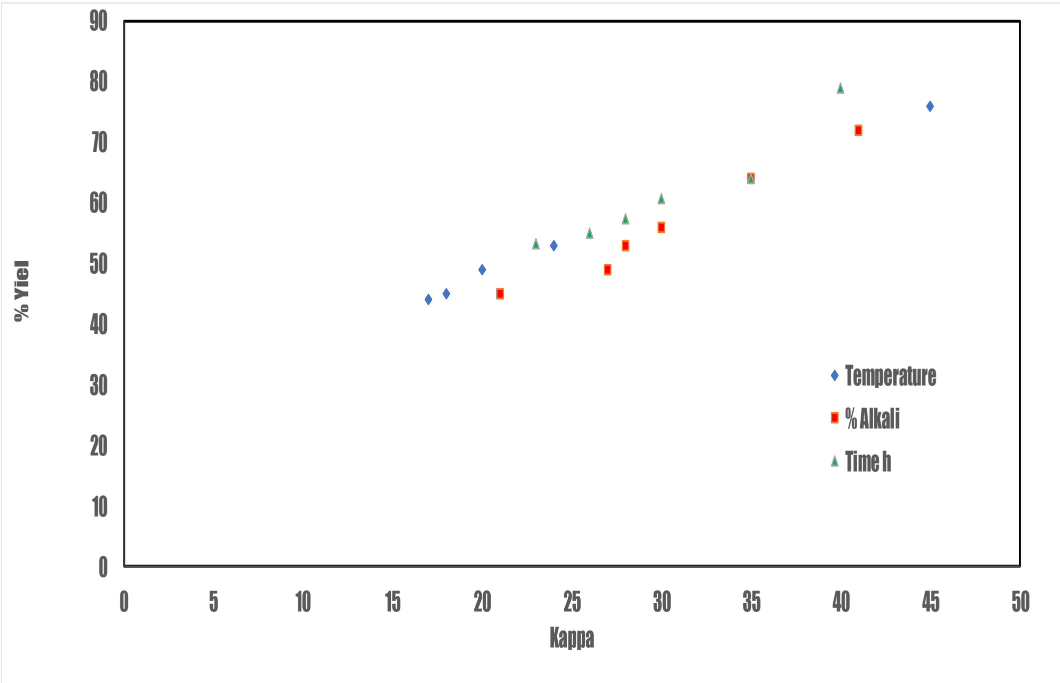

Figure 2: Relationship between Kappa number and % yield at different values of temperature, time and % alkali

Table 6: characterization of banana pulp, bagasse pulp and softwood pulp and paper strength properties.

Items	Experimentally prepared banana pulp		Commercial bagasse pulp		Imported wood pulp	
Pulp characterization						
	Unbleached	Bleached	Unbleached	Bleached	Bleached southern softwood pulp	
					Mill (1)*	Mill(2)*
Yield %	64		47			
Kappa Number	35		9.5			
Fiber Length of the raw material, mm	2.24		1.7		2.4	2.2
Paper characterization						
SR°	25	26	18	21	26	25
Bulk, cc/g	1.33	1.28	1.8	1.6	1.56	1.4
Burst Index, kPa m^2/g	6.66	7.35	4.2	3.53	5.5	-
Tear Index in mNm^2/g	6.08	5.58	3.53	3.24	12.4	11.7
Tensile index N.m/g	59.8	72.54	54.9	52.94	74.5	82.35
Opacity	99.5	94.6	98	84	57.9	59.8
Brightness% ISO	42	78	48	81	88	97

***Mill (1): Panasoft, Rock Tenn's mill in Panama City, Florida, USA.**
***Mill (2): SUN, Stora, ENSO Biomaterials, Sunila Mill, Katka, Finland.**

Data in table 6 depicted that bleached bagasse pulp has the lowest strength properties; this is attributed to the shorter fiber length (1.7 mm). The strength properties of bleached banana pulp match that of bleached softwood pulp, expect tear index. The similarity of breaking length and burst index of banana pulp and softwood pulp is attributed to fiber length similarity. The higher value of the tear index of softwood fiber may suggest that softwood fiber is stronger than that of banana stem fiber.

1- Blend Properties and Strength of Paper:

Effect of different blend levels of banana-bagasse pulp and strength properties of hand sheet-paper are shown in Table 7. Blend 80% commercial bagassepulp- 20% imported softwood pulp will be considered a standard blend (this blend is used in Misr-Edfu Mill-Egypt for production writing and printing paper).

Examining data in table 7 revealed that all mechanical strength properties of banana –bagasse blends are high compared to the bagasse-softwood pulp blend. This is attributed to the fact that, the mechanical properties of paper are a function of fiber length, number of fibers per unit weight of the material and fiber-fiber bond. Banana stem fiber used in this study is characterized by relatively long fiber (2.24mm), matching fiber length of softwood pulp (2.2 mm and 2.4 mm for softwood, mill No. 1 and No. 2, respectively). In addition, the percentage of cellulosic material, is high for banana stem (64%) which may suggest a larger number of fibers per unit weight of material compared to 58% in softwood pulp [Rydholm, 1969]. High cellulose content leads to a large number of hydroxyl groups on the fiber surface. The bond strength between fibers is due to the hydrogen bond between the hydroxyl groups on the fiber surface. High cellulose content means a larger number of hydroxyl groups and stronger paper. Also micrographs (Figures 1-3) show that banana fiber is flat and flexible, which can create a flat and flexible, stronger fiber-fiber bond.

The definition of mechanical strength of paper can shed light on the high strength of paper produced from banana- bagasse blends. Paper tensile strength is defined as the maximum force per unit width of paper strip that bears load before failure, when the force is applied perpendicular to the length of the tested sample. In this study as shown in table7, the comparison between blends (20% banana + 80% bagasse and 20% softwood + 80% bagasse at SR^0 33 for banana + bagasse blend and SR^0 27 for softwood and bagasse blend), the tensile index is relatively high, it is 57.7 compared to 46.57 for bagasse-softwood blend. Paper burst index is the maximum pressure (force) that a paper bears before breaking the paper surface, when the force is applied perpendicular to the tested sample. The value of the burst index for the banana-bagasse blend is 4.51, which is good for writing paper compared to 4.90 for bagasse-softwood blend in the standard sheet.

Paper double fold measures the number of folds a paper can stand before its tensile strength falls under standard condition. In this study, the values are 152 compared to 28 for bagasse-softwood in the standard sheet. The paper tear index represents the force required for further tearing of the paper from initial cut. In this work, the tear index is 5.1 compared to 5.94 for bagasse-softwood in the standard sheet. Tear strength is a function of the number of fibers per unit weight of material; higher cellulose content in banana may reflect the larger number of fiber per unit weight.

Optical properties (brightness and opacity) are important in writing and printing paper. The ISO brightness (82%) is high for the standard sheet (80% bagasse- 20% softwood) compared to the value of 79% for banana-bagasse blends. The lower brightness for banana-bagasse blends is due to lower brightness of bleached banana pulp. Opacity is high for banana-bagasse blends (90% - 88.6%) compared to bagasse –softwood blend (85%). The relation between brightness and opacity is physical phenomena; when brightness increased opacity decreased, according to Kubelka-MunK theory [Sixtaetal, 2006].

Table 7: Mechanical properties for blended bagasse pulp with banana pulp

Material Properties	60% bagasse + 40%Banana	75% Bagasse + 25% Banana	80% bagasse + 20% banana	80 % Bagasse + 20 % Softwood
Iso brightness %	76	78	79	82
Opacity %	90	89	88.6	85
Bulk cc/g	1.31	1.30	1.29	1.34
SR^0	42	36	33	27
Tensile index N.m/g	64.7	60.7	57.7	46.57
Burst index Kpa.m^2/g	5.98	4.9	4.51	4.90
Tear index mN.m^2/g	6.57	5.5	5.1	5.94
Double fold No	380	175	152	28

$$Bx\ 0.01 = 1 + k/s - \sqrt{(k/s)^2 + 2\ (k/s)} \quad (2)$$

Where B, k, and S, represents brightness degree (%), absorption coefficient and scattering coefficient of light (m^2/g), respectively; The scattering coefficient is an indication of opacity.

Strength properties as well as optical properties; prove that banana pulp can successfully replace the imported soft wood pulp for producing writing and printing paper.

The economical of using the banana stem as a substitute for softwood pulp:

Base of calculation: 80% bagasse pulp + 20% banana pulp compared with 80% bagasse pulp + 20% softwood pulp.

-Softwood pulp average price 2019 and 2018 = $750FOB

After adding taxes 14% and freight cost =$1026

- Cost of producing of banana stem pulp = $552/TP

-The gain from using banana stem pulp instead of softwood pulp =$474 /ton

-We are using 20% in the paper furnish = 200 kg pulp / ton of paper

- Gain per ton of paper = 474x 200/1000 = $94.8/ton of paper.

-Gain per month = 94.8 x 6000 ton/month = $568800/month

=$ 6.256 M/ year.

The economic return is estimated at 6.256 million dollars per year.

Conclusions

The morphology studies confirmed that the banana stem fibers are flat, flexible and long (2.24 mm), which reinforced fiber in writing and printing papers. Mechanical strength and optical properties of the sulfate banana stem pulp (64%; yield) are comparable to the softwood pulp. The high mechanical strength is attributed to the long fiber and high cellulose content of the banana stem, and the adequate opacity is due to the high pulp yield. The furnish blend ratio of 20% banana pulp with 80% commercial bagasse pulp produces high quality of writing and printing paper.

The study confirms that sulfate banana stem pulp can provide a new opportunity to produce writing and printing paper when mixed only with bagasse pulp without using the imported softwood pulp in addition to the economically and the environmental control for using banana in the pulp and paper industry.

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