COMPLETE CHARACTERIZATION OF BAGASSE OF EARLY SPECIES OF *SACCHARUM OFFICINERUM*-CO 89003 FOR PULP AND PAPER MAKING

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Bagasse from early species of *Saccharum officinerum*-Co 89003 has 71.36% useful, long, and thick-walled fibers with good slenderness ratio, but the rigidity coefficient is less than that of *Eucalyptus tereticornis* and *Leucaena leucocephala*. The kink index and kink per mm length are lower in bagasse fiber than *E. terticornis*, which gives rise to fewer weak points in the fiber. Low alcohol–benzene soluble substances in bagasse induce less pitch problems and favor more homogeneity in the paper. Lignin content in bagasse is comparable to *Eucalyptus globulus* and *Leucaena leucocephala*, but α-cellulose, and pentosans are slightly lower. A higher proportion of carbon content compared to hydrogen and oxygen increases the energy value of bagasse. It produces 42.2% pulp yield of kappa number 28.2 at optimum cooking conditions, such as active alkali 12% (as Na_2O), temperature 150^{o}C, and time (at temperature) 60 min. An addition of 0.1% anthraquinone at the optimum condition improves pulp yield by 2.6% and mitigates kappa number by 3.9 units.

Keywords: Anatomy; Morphology; Proximate analysis, Ultimate analysis, Pulping, Paper properties

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INTRODUCTION

World demand for paper and paperboard is estimated to grow from 300 million tonnes (Hurter 1997) to over 490 million tonnes by the year 2020 (John 2006) with an average growth rate of 2.8% per annum (Hurter 1997). India currently produces about 5.6 million metric tonnes of paper and board per year, which accounts for about 1.6% of the world's production. In 2007, the total domestic demand for paper was at 7.6 million metric tonnes against a production of 6.7 million metric tonnes, and by 2015 demand may attain the level of 12.5 million metric tonnes. The annual paper consumption per capita in India is only approximately 8 kg, against world per capita paper consumption of 50 kg (Lindberg and Tuomi 2009). The forest cover in India is 67.8 million ha, or 20.6% of the country's surface area, which translates into a per capita forest area of only 0.8 ha per person, one of the lowest in the world (Flynn 2007). Total fiber consumption for the production of paper and paperboard in India will be nearly doubled between 2006 and 2016, growing from 7.4 to 13.7 million tonnes. India's total wood fiber deficit is forecasted to increase at an annual rate 11.3% through 2016 (Flynn 2007). Depleting forest resources are forcing the Indian pulp and paper industry to use various alternate fibrous resources, such as non-woody plants, agricultural residues, and waste paper. Bagasse, the sugarcane residue, is found to be one of the best alternatives because of its

low cost, longer fiber than straw, low refining energy consumption, and good sheet formation and paper smoothness, which enables the sugarcane bagasse to meet the quality requirements for newsprint and fine paper manufacture (Rajesh and Rao Mohan 1998). At present about 50 million tonnes of bagasse is generated in the country per annum, out of which only 10 million tonnes is available as surplus for the pulp and paper industry (Anon. 2005a). It is expected that even if only 20% of the total quantity can be made available to Indian pulp and paper industry, then, there should be no difficulty in meeting the targeted demand for paper and paper board products.

Keeping these objectives in view, and to ascertain supply of sugarcane bagasse for a longer period to pulp and paper industry, a complete characterization of bagasse from early species of *Saccharum officinerum*-Co 89003 was done, which covers (a) anatomical, morphological, and chemical characterizations, (b) optimization of soda pulping, and (c) optimization of mechanical action given to the fibers (^{o}SR) to get optimal mechanical strength.

MATERIALS AND METHODS

Raw Material Preparations

Bagasse from early species of *Saccharum officinerum*-Co 89003 was collected from U.P. Sugar Cooperative Factory, Bidwi, 15 km away from Indian Institute of Technology Roorkee, Saharanpur Campus, Saharanpur, located in the foothills of Shivalik in Western Uttar Pradesh (India). Dry depithing of bagasse was done in a dry depither (Bramco, BD 101, India). Further, the depithed bagasse was disintegrated in a hydrapulper (wet depithing) to remove the rest of the pith cells at 2.5% consistency, and screened in WEVERK vibratory screen of mesh size 150, an approach similar to that followed by Rajesh and Rao Mohan (1998).

Anatomy and Morphology

For fiber length determination, small slivers of sugarcane bagasse were macerated with 10 mL of 67% HNO_3 and boiled at 100^{o}C for 10 min (Ogbonnaya et al. 1997). The slivers were then washed, placed in small flasks with 50 mL distilled water, and the fiber bundles were separated into individual fibers using a small mixer with a plastic end to avoid fiber breaking. The macerated fiber suspension was finally placed on a slide (standard, 7.5cm×2.5cm) by means of a medicine dropper (Han et al. 1999). All fiber samples were viewed under a calibrated microscope. A total of 100 randomly chosen fibers were measured. The following derived values were also calculated using fiber dimensions: slenderness ratio as fiber length/fiber diameter, flexibility coefficient as (fiber lumen diameter/fiber diameter)×100, and Runkel ratio as (2×fibre cell wall thickness/lumen diameter) (Saikia et al. 1997; Ogbonnaya et al. 1997). For fiber diameter, lumen diameter, and cell wall thickness determination, cross sections of sugarcane were taken at base, middle, and top of its height/length respectively, an approach similar to that followed by Dutt (Lal et al. 2010), and were stained with 1:1 aniline sulphate–glycerin mixture to enhance cell wall visibility (cell walls retain a characteristic yellowish color). The morphological characteristics of sugarcane bagasse

were compared to those of *Eucalyptus tereticornis*, *Eucalyptus robusta*, *Leucaena leucocephala,* and Mexican sugarcane bagasse. A suspension of sugarcane bagasse fibers (0.02% consistency) was used for detailed anatomical features including fiber length, fiber width, curl index, and kink index by using Hi-Resolution Fiber Quality Analyzer (Optest Equipment Inc. model: LDA 2002).

Proximate Chemical Analysis

Depithed sugarcane bagasse was milled into powder in a laboratory Wiley mill (Weverk, A-47054, Sweden), and a fraction passing through 48 mesh size, but retained on +80 mesh size was used for analysis of water solubility (TAPPI method T207 cm-99), 1% caustic soda solubility (T212 om−98), alcohol-benzene solubility (T204 cm−97), holocellulose (T249 cm−00), lignin (T222 om−02), ash (T211 om−93), pentosan (T223−cm-01), iron (T242 wd-97), chloride (T256 cm-97), calcium (T247 wd-98) (Anon. 2007) and phosphorus (424 F), as per Standard Methods for the Examination of Water and Wastewater, American Public Health Association (1985).

The determination of carbon was done in a Leco SC-144DR instrument using direct combustion and infrared detection. In nitrogen determination the sample is dropped into a hot furnace and flushed with pure oxygen for very rapid combustion, and by-products of combustion are formed (CO_2, H_2O, NO_x, and N_2). The material then is passed through the furnace filter and thermoelectric cooler for subsequent collection in a ballast apparatus. These collected gases in the ballast are mixed, and a small aliquot dose is then used for further conversion of the gases. The remaining aliquot that has been reduced is measured by the thermal conductivity cell for nitrogen, in a Leco FP-528. Two determinations per sample were performed according to CEN/TS 15104 (Anon. 2005b) to the (C, N).

The Leco TruSpec TRSCHNC was used to determine hydrogen. The system is based on the Dumas method of combustion. There are three phases during an analysis cycle: purge, burn, and analyze. In the sample-drop purge phase, the encapsulated sample is placed in the loading head, sealed, and purged of any atmospheric gases that have entered during sample loading. The ballast volume (zero volume at this point) and gas lines are also purged. During the burn phase, the sample is dropped into the primary furnace (950^{o}C), and flushed with pure oxygen for very rapid combustion. The products of combustion are passed through the after-burner furnace, furnace filter, pre-cooler, and thermoelectric cooler before collecting in the ballast volume. In the analysis phase, the combustion gases in the ballast become homogeneous by means of passive mixing. A series of infrared detectors measure the evolved gases for hydrogen. In addition, a 3 cm^3 aliquot captured in a loop before the ballast piston is forced down to evacuate the ballast. An optimized detector was used for hydrogen. The final result was displayed as weight percentage, according to CEN/TS 15104 (2005).

Pulping Studies

Well depithed sugarcane bagasse was digested in a WEVERK electrically heated rotary digester of 0.02 m^3 capacity having four bombs of 1 L capacity each by soda pulping process at different cooking conditions, including maximum temperature 130 to 160^{o}C, cooking time 15 to 150 min, active alkali doses 10 to 14% (as Na_2O), and liquor

to raw material ratio of 4:1. 0.1% anthraquinone (AQ), a carbohydrate stabilizer, was added at optimum soda cooking conditions to bring further down the kappa number at different alkali doses. The cooked pulps were washed on a laboratory flat stationary screen having 300 mesh wire bottom, disintegrated, screened through a WEVERK vibratory flat screen with slot size of 0.15 mm, and evaluated for kappa number (T236 cm-85), screened pulp yield, lignin (T222 om−02), and screening rejects and viscosity (Anon. 2007).

Preparation of Laboratory Handsheets and Testing

The unbleached pulp was beaten in a PFI mill (T200 sp-96) at different beating levels. Laboratory hand sheets of 60 g/m^2 were prepared (T221 cm-99) on a British sheet-former, pressed, air-dried in atmospheric conditions, conditioned at 27±2^{o}C and 65±2% relative humidity, and tested for various physical strength properties such as tear index (T414 om-98), tensile index (T494 om-01), burst index (T403 om-97), and double folds (T403 om-97) (Anon. 2007).

Statistical Analysis

All the experiments were carried out in triplicate, and experimental results were represented as the mean ± standard deviation of three identical conditions.

RESULTS AND DISCUSSIONS

Anatomical and Morphological Studies

Table 1 reveals that even after dry and wet depithing, 15.48% pith was still associated with sugarcane bagasse fibers, while useful fibers were 71.36%, along with 13.14% of soluble matter (T207 cm-99) (Anon. 2007), which includes a part of extraneous components, such as inorganic compounds, tannins, gums, sugars, and coloring matter. A transverse section of *Saccharum officinarum*-Co 89003 showed that minor bundles are concentrated close to the epidermis and form an almost continuous ring of fibrous tissue. Inside this outer circle the most valuable vascular bundles are found. This peripheral part of the stem is called the rind (Plate1). The conducting system is built up by two major complex tissues, xylem and phloem. The vascular bundles of sugarcane are collateral, which means that phloem is external to xylem (Plate 1). The ground tissue is composed of different types of parenchymatous cells. These are primarily storage cells for solutes and food stuffs for the plant (Hegbom 1992). The parenchymatous cells can be divided into four main groups: collenchyma, chlorenchyma, rind, and pith parenchyma. The zone between the epidermis, and the vascular tissue is called the cortex. There is a typical difference between the rind and pith parenchyma cells. Rind parenchyma cells are long, wide, and quite thick-walled and are present to a great extent in the pulp, while pith parenchyma cells are barrel-like and thin-walled. The pith parenchyma is readily broken to flakes, but rind parenchyma is resistant to pulping, so they do not have a bonding effect and act as fillers. If rind parenchymatous cells are present on the paper surface, they cause linting problems during papermaking or printing (Dutt et al. 2008).

Sugarcane bagasse fibers are long (1.51 mm), wide (21.4µm), and have a narrower lumen (6.27µm) with thicker cell wall (7.74 µm) compared to *E. tereticornis, E. robusta*, Mexican sugarcane bagasse, and *L. leucocephala*, but the lumen of *E. tereticornis* (3.4 µm) is narrower, and *L. leucocephala* fibers are wider (23.33) with a thicker wall (10.45 µm) (Table 1). Fiber length generally influences the tearing strength of paper. The greater the fiber length, the higher will be the tearing resistance of paper. Fiber diameter and wall thickness governs the fiber flexibility. Thick-walled fibers adversely affect the bursting strength, tensile strength, and folding endurance of paper. The paper manufactured from thick-walled fibers will be bulky with coarse surface texture, and containing a large amount of void volume. Fiber lumen width affects the beating of pulp. The shorter the fiber lumen width, the poorer will be the beating of pulp because of the penetration of liquids into empty spaces of the fibers. Sugarcane bagasse fibers have a high Runkel ratio (2.46) compared to hardwoods, which is expected to have an inevitably negative effect on tensile and bursting strengths, as well on folding endurance (Ogbonnaya et al. 1997). The fibers with Runkel ratio above 1.0 are considered as thick-walled fibers (Istek, 2006), which are stiffer, less flexible, and form bulky paper of lower bonded area (Dutt et al. 2005a). Runkel ratio is also related to paper conformability (DuPlooy 1980) and pulp yield (Ona et al. 2001). The fibers of sugarcane bagasse are less thick compared to *E. robusta* (3.18) and thicker than Mexican sugarcane bagasse fiber (1.65), while the fibers of *E. tereticornis* and *L. leucocephala* are considered as thin-walled fibers.

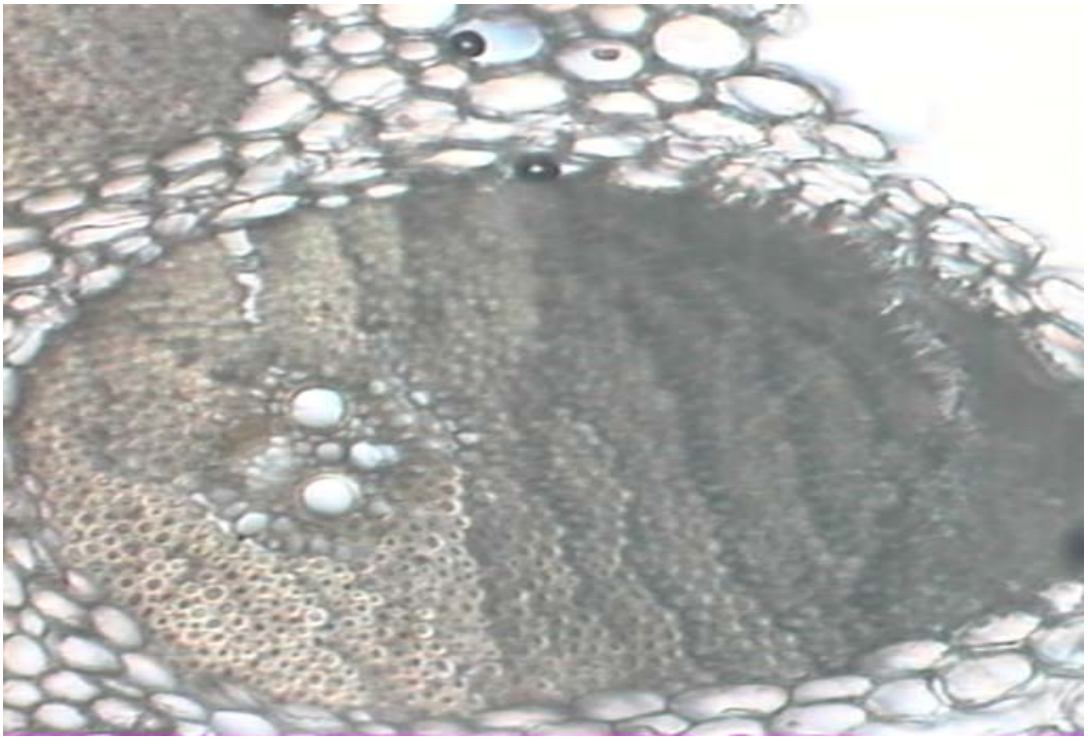

Plate 1. T.S. of *Saccharum officinerum*-Co 89003

Table 1. Morphological Characteristics of Depithed Sugarcane Bagasse (T 232 cm-01) (Anon. 2007)

Particulars	Sugarcane bagasse*	*Eucalyptus tereticornis* (Panwar 2001)	*Eucalyptus robusta* (Panwar 2001)	*Leucaena leucocephala* (Malik et al. 2004)	Mexicain sugarcane bagasse (Sunján et al. 2001)
Fiber length (L), mm	1.51±0.08	0.70	1.07	0.96	1.13
Fiber width (D), µm	21.4±1.6	14.2	19	23.33	20
Lumen diameter (d), µm	6.27±0.4	3.4	12.1	12.90	12
Cell wall thickness (w), µm	7.74±0.2	5.4	3.4	10.45	4.0
Runkel ratio (2w/d)	2.46	3.18	0.56	1.65	0.67
Flexibility coefficient (dX100/D)	29.29	23.94	63.68	55.29	60
Slenderness ratio (L/D)	70.56	49.29	56.31	41.14	56.50
Rigidity coefficient (2w/D)	0.72	0.76	0.36	0.89	0.40

± refers standard deviation, *Depithed

Table 2. Fiber Dimensions of Sugarcane Bagasse and Comparisons with Straw Fibers

Particulars	Bagasse	Wheat straw (T259OM-93)	Rice straw (T259OM-93)	Hardwood (Mittal et al. 1978)	Mexicain sugarcane bagasse (Sunján et al. 2001)
Parenchyma					
Length, µm	326.9±4.2	450	350	–	290
Width, µm	53.4±2.9	130	82	–	60.4
Lumen width, µm	48.5	–	–	–	57
Wall thickness, µm	4.9	–	–	–	1.7
%	–	30	–	3-21	–
Vessels Length, µm	152.3±2.5	100	650	–	123
Width, µm	28.1±1.0	60	40	–	80.4
Lumen width, µm	25.1	5	–	–	75
Wall thickness, µm	3.2	–	–	–	2.7
%	–	–	–	5-58	–

Dry and wet depithing of bagasse	Useful fiber, %	Pith, %	Solubles, %	
	71.36±1.5	15.48±0.8	13.14±1.0	–

Other calculated derived properties of importance are the flexibility co-efficient (29.29) and rigidity co-efficient (0.72) (Table 1). The rigidity coefficients of *E. tereticornis* (0.72) and *L. leucocephala* (0.89) are slightly on the higher side, but very much on the lower side in case of *E. robusta* (0.39), and Mexican sugarcane bagasse fiber (0.40) compared to sugarcane fibers. An increase in the rigidity of fibers results in a decrease in fiber bonding. The slenderness ratio of sugarcane bagasse fibers is more than that of *E. tereticornis*, *L. leucocephala*, *E. robusta*, and Mexican sugarcane bagasse fiber. The lower the value of length/width ratio, the lower will be the fiber flexibility, and the poorer the chance of forming well bonded paper. The long and thick walled fibers of sugarcane baggase produce a good slenderness ratio (70.56), which is related to paper sheet density and to pulp digestibility (Ona et al. 2001) and, in turn, increases tearing resistance. The properties of such type of fibers can successfully be used for manufacturing of writing and printing paper, base paper for printed circuit board (Dutt et al. 2003), seed germination paper (Dutt et al. 2005b), and tea bag paper (Dutt et al. 2007), etc.

Table 2 reveals that the length of parenchyma varies up to 900 μm, with an average length of about 326.9 μm. The width is up to 180 μm with an average of 53.4 μm. The parenchyma cells are small to medium sized, narrow rectangular, and numerous. Vessels range from 120 to 1600 μm (average 152.3 μm), which is fairly long and narrow. The length and width of parenchyma are much lower than those of wheat and rice straw, while the length of vessels is higher than that of wheat straw, but much lower than that of rice straw. Compared to this, parenchyma cells of Mexican sugarcane bagasse have length and width of 290 and 60.4 μm and vessels 123 and 80.4 μm respectively. The slenderness ratio of parenchyma (6.12) and vessel cells (5.54) of sugarcane bagasse are much higher compared to slenderness ratio of parenchyma (4.80) and vessel cells (1.52) of Mexican sugarcane bagasse. This indicates that sugarcane bagasse cells do not readily collapse and form porous and opaque sheet, while cells of Mexican sugarcane bagasse are easily collapsing to form a very dense sheet with few pores. Parenchyma and vessel cells of sugarcane bagasse have a smaller cell diameter that that of Mexican sugarcane bagasse. Therefore, its small cell diameter and thin wall form a tissue component that contributes to strength (Table 2). Slot size of the screen for depithing should be selected according to the morphology of sugarcane bagasse, and the same cannot be used for rice and wheat straws. Pith cells are non-fibrous, have large surface area, and adversely affect the mechanical strength properties of paper (Dutt et al. 2008).

The mean fiber curl index in sugarcane bagasse (0.151) is more than that of *E. terticornis* (0.141) (Table 3). Kink index and kink per mm length of fiber are on the lower side compared to *E. terticornis*, but kink angle is more in sugarcane bagasse compared to *E. terticornis.* Kink is an abrupt change in the curvature of a fiber. It may give rise to dislocations, which is a type of deformation described as micro-compressions and misaligned zones Hakanen et al. (1995), where the alignment of the micro fibrils is locally disturbed and, according to Hartler (1963), they develop after the fiber structure has been subjected to a compressive strain above the elastic limit. Savolainen (2003) suggested that dislocated regions in the fibers enhance polysaccharide degradation by enhanced diffusion of harmful radicals into fiber wall segments, eventually leading to reduced fiber strength. Defects such as kinks and curls in fibers reduce paper strength

because they give rise to weak points in of the fiber structure that will reduce fiber strength. Introduction of curls and kinks reduces the modulus of elasticity of fiber (Page et al. 1979). Fiber swelling, as well as internal and external fibrillation renders the fibers more flexible as a result of beating, and refining removes kinks and curls to some extent (Mohlin et al. 1996).

Proximate Chemical Analysis

Water soluble substances in sugarcane bagasse (7.42%) are higher than those of *E. globulus* (2.21%), *L. leucocephala* (5.98%), and Mexican sugarcane bagasse (1.1%), and alcohol-benzene solubles (1.8%) is lower compared to *E. globulus* (2.30%) and *L. leucocephala* (2.55%), but higher compared to Mexican sugarcane bagasse (1.1%) (Table 3).

Table 3. Fiber Dimensions of Sugarcane Bagasse Using Hi-resolution Fiber Quality Analyzer and Comparison with *Eucalyptus tereticornis*

Sl. No.	Dimensions	Depithed sugarcane bagasse	*Eucalyptus tereticornis* (Panwar 2001)
1	Mean fiber length, mm (weight weighed) (L = 0.20-4.50 mm)	1.461	0.651
2	Mean fiber width, µm (w = 7-80 µm) (L = 0.30-6.0 mm)	20.8	14.2
3	Mean fiber curl index (Length weighed) (L = 0.20-4.5mm)	0.151	0.141
4	Mean fiber kink index (L = 0.5-5mm) Kink index, 1/mm Total kink angle, degrees Kink, 1/mm	 1.89 37.9 0.93	 2.15 29.93 0.98
5	Fines (L = 0.07-0.20) Arithmetic,% Length weighed, %	 30.29 7.58	 25.59 5.34

All of the soluble materials come under the category of extractives, and these are totally undesirable in pulp and paper making. The water and alcohol-benzene soluble substances affect the pulp yield, paper quality, and drainage characteristics of paper machine. Sugarcane bagasse is comparatively less resinous than Mexican sugarcane bagasse (1.1%), as evidenced by the alcohol–benzene solubility. Therefore, it will create lesser pitch problems and also provide more homogeneity in the paper sheet (Kasiviswanathan 1998). 1% NaOH solubility, which measures low molecular weight carbohydrates, is higher in sugarcane bagasse (32.29%) compared to *E. globulus* (14.58%) and *L. leucocephala* (13.26%), but comparable with Mexican sugarcane bagasse (31.8%). This indicates that degradation of sugarcane bagasse due to light, heat, and fungal decay is greater, hence adequate precaution for sugarcane bagasse should be taken during its storage. Pentosan content indicates the retention or loss of

hemicelluloses, in general, during pulping and bleaching processes, and since hemicelluloses contributes to the strength of paper pulps, high pentosan content is desirable (Wilson and Mandel 1960). Pentosan content is on the higher side in sugarcane bagasse (23.90%) compared to *E. globulus* (17.64%) and *L. leucocephala* (17.21%) but less than Mexican sugarcane bagasse (28.8%).

Table 4. Proximate Chemical Analysis of Depithed Sugarcane Bagasse

Sl. No.	Particulars	Depithed Bagasse	*Eucalyptus globulus* (Panwar, 2001)	*Leucaena leucocephala* (Malik et al., 2004)	Mexicain sugarcane bagasse (Sunján et al.,2001)
1	Cold water solubility, %	3.02±0.02	1.61	3.45	–
2	Hot water solubility, %	7.42±0.05	2.21	5.98	1.1
3	1% NaOH solubility	32.29±0.1	14.58	13.26	31.8
4	Alcohol: benzene solubility, %	1.85±0.01	2.30	2.55	2.50
5	Ash content, %	2.10±0.03	0.30	0.85	1.1
6	Silica content, %	0.98±0.007	–	0.55	–
7	Lignin (acid insoluble), %	21.7±0.35	21.18	19.55	17.7
8	Pentosan, %	23.9±0.21	17.64	17.21	28.8
9	Holocellulose, %	71.03±0.5	73.27	76.58	78.6
10	α-cellulose, %	42.34±0.36	48.66	58.70	45.0
11	Hemicellulose, %	28.60±0.42	–	–	–
12	Phosphorus, %	0.44±0.007	–	–	–
13	Iron, %	0.013±0.001	–	–	–
14	Chloride, %	0.00	–	–	–
15	Hydrogen, %	6.51±0.2	–	–	–
16	Nitrogen, %	0.41±0.005	–	–	–
17	Carbon, %	46.12±0.3	46.2	–	–
18	Oxygen, %	45.96±0.3	–	–	–
18	Calcium, %	0.46±0.003	–	–	–

± refers standard deviation, all values on extractive free basis, Sl. No. 15-18 % by weight

Carbohydrate composition is important in determining its response to processing conditions and the development of physical properties (Crowell and Burnett 1967). Holocellulose in sugarcane bagasse is slightly lower than *E. globulus, L. leucocephala*, and Mexican sugarcane bagasse. Other authors (Goyal et al. 1991; Ramaswamy et al. 1991) reported levels of 76.6 and 74.4% for holocellulose in depithed bagasse and 67.1% for the pith fraction (Upadhyaya et al. 1991) based on the total bagasse material. α-

cellulose is comparatively less in sugarcane bagasse than that of *E. globulus* and *L. leucocephala*, but more than Mexican sugarcane bagasse (45%). According to the rating system as suggested by Nieschlag et al. (1960), plant materials with 34%, and higher α-cellulose content are characterized as promising for pulp and paper manufacture from a chemical composition point of view. Lignin content (21.70%) is comparable to other hardwoods, for example *E. globulus* (21.70%) and *L. leucocephala* (19.55%), but less than Mexican sugarcane bagasse (17.7%). Of significance is the fact that the structure of lignin in sugarcane bagasse is more open and looser. This means that sugarcane bagasse needs, in general, milder pulping conditions (lower temperatures and chemical charges) to reach a satisfactory kappa number with improved tensile, burst, and tear strengths and double folds and sheet density. Lal et al. (2010) report such conditions for *Anthocephalus cadamba*, López et al. (2010) for *Leucaena diversifolia*, and Jahan et al. (2009) for *Trema orientalis.* High ash contents are undesirable for pulping, as they affect normal alkali consumption, give problems at recovery of the cooking chemicals (evaporation, combustion, and lime mud reburning), and result in operational problems in material handling, pulp washing, and pulp beating. In this case, the high quantity of ashes (2.10%) cannot be considered as problematic, in the context of pulping and papermaking processes, since the silica-based salts are negligible (0.98%). Trace elements (Fe, 0.013%), which interfere with H_2O_2 and O_2 bleaching, can be removed effectively from the pulp by treatment with chelating agents such as DTPA/EDTA and $NaHSO_3$ (Q stage) (Gellerstedt and Pettersson 1982). Chlorine content in sugarcane bagasse is 0.00%. The main effect of Cl^- is the corrosive effect of chloride salts and HCl on metal parts in the furnace and boiler (Salmenoja and Makela 2000), as well as HCl and particulate (KCl, NaCl, $ZnCl_2$ and $PbCl_2$) emissions. The concentration of N in sugarcane bagasse is 0.41%. The main environmental impact is the generation of NOx in the chemical recovery furnace (Nussbaumer 2002). Calcium and phosphorous contents in sugarcane bagasse are 0.46 and 0.44% respectively, and they are especially important for any thermo-chemical conversion process. The major elemental constituents of sugarcane bagasse are carbon (46.12%), oxygen (45.96%), and hydrogen (6.51%). The biomass contains higher proportion of carbon content compared to hydrogen and oxygen, which increases the energy value. Ultimate analysis is very important in order to determine the theoretical air–fuel ratio in thermo-conversion systems, to calculate the heating values and also to have knowledge of the pollution potential.

Pulping Studies

Table 5 and Fig. 1A present the curves plotted between lignin and reaction time at temperatures varying from 130 to160^{o}C. The curves can be approximated by two straight lines at each temperature investigated. The curves with steeper slopes are related to rapid solubilization of bulk of lignin (bulk delignification), whereas the part of curves with gentler slopes are related to the slow solubilization of the residual lignin (residual delignification). The bulk delignification corresponds to the removal of easily assessable lignin present in the middle lamella, and the residual delignification corresponds to the removal of lignin present in the primary wall, secondary wall layers, and the central inter-connections cavities. The delignification of wood in alkaline pulping is also associated with the solubilization of significant amounts of hemicelluloses (Kleinert 1965). These

curves also indicate that as the temperature decreases from 160 to 130°C, the time to reach transition from bulk to residual delignification and the lignin content of the pulp, corresponding to this transition point, increases. Figure 1A also reveals that in a lower temperature range the residual lignin decreases sharply, while at higher temperature, the magnitude of decrease in lignin is insignificant. Moreover, at higher temperature, the degradation of carbohydrates also increases, thereby reducing the pulp yield (Kleinert 1965). In other words, at the transition point, lower pulp lignin content is obtained at 150°C. Beyond a temperature of 150°C, in addition to the peeling reaction, alkaline hydrolysis (depolymerization) of the polysaccharide chains occurs and the cellulose is subjected to further degradation reactions (secondary peeling) (Hinrichs 1967). The shapes of curves after the transition points are almost horizontal lines, clearly indicating that the bulk delignification is completed up to these transition points and it is not economical to continue the cooking operation beyond a temperature of 150°C. The curves plotted between residual lignin and reaction time (Fig. 1A) and cooking time and kappa number (Fig. 1B) reveal that the drop in kappa number beyond a cooking time of 1.0 h is found to be insignificant, and pulp yield decreases sharply (Fig. 1B). Therefore, based on the experimental data, a cooking time of 1.0 h and cooking temperature 150°C may be considered as optimum for sugarcane bagasse (Table 5).

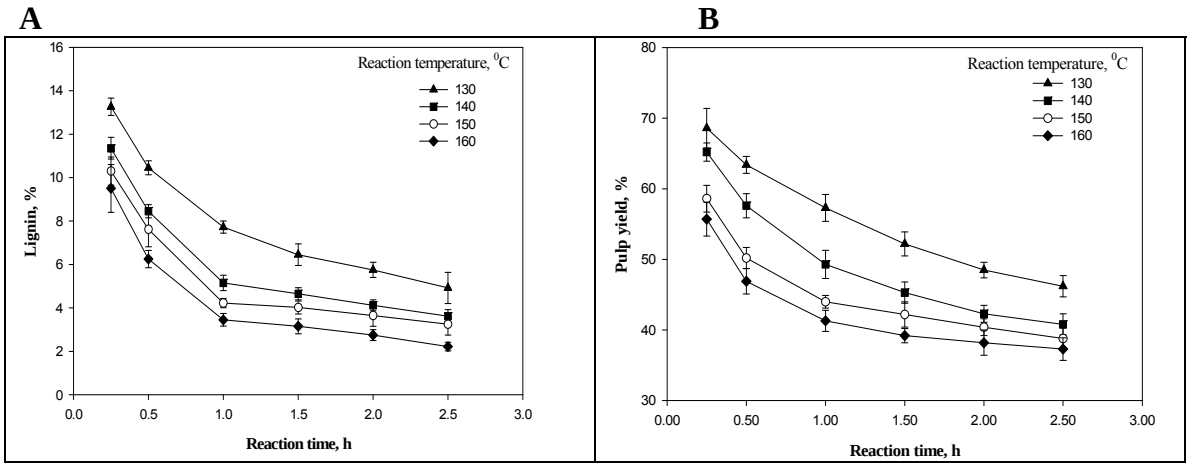

Fig. 1. Curves of different reaction times *vs* (A) lignin, and (B) pulp yield at different cooking temperature during soda pulping of sugarcane bagasse

Figure 2A reveals that screened pulp yield increases with increasing active alkali from 10 to 12% (as Na_2O) and then tends to decline sharply, whereas both kappa number and screening rejects decline sharply up to an alkali dose of 12%, and beyond that both of these parameters practically remain constant. The screened pulp yield of sugarcane bagasse is found to be 42.2% at kappa number of 28.2 and an active alkali charge of 12% (as Na_2O), which may be considered as optimum for sugarcane bagasse.

Figure 2B shows the effect of maximum cooking time on screened pulp yield, screening rejects, and kappa number during soda pulping of sugarcane bagasse, while keeping other variables constant, including alkali dose 12% (as Na_2O), liquor to raw material ratio 4:1, digester pressure 5 kg/cm^2, and maximum cooking temperature 150°C,

when cooking time is increased from 30 to 60 min, the screened pulp yield increases from 40.4 to 42.2%, and kappa number drops from 41.4 to 28.2. Beyond that, screened pulp yield drops sharply, while kappa number remains almost constant. Therefore, a maximum cooking time of 60 min may be considered as an optimum cooking time for soda pulping of sugarcane bagasse.

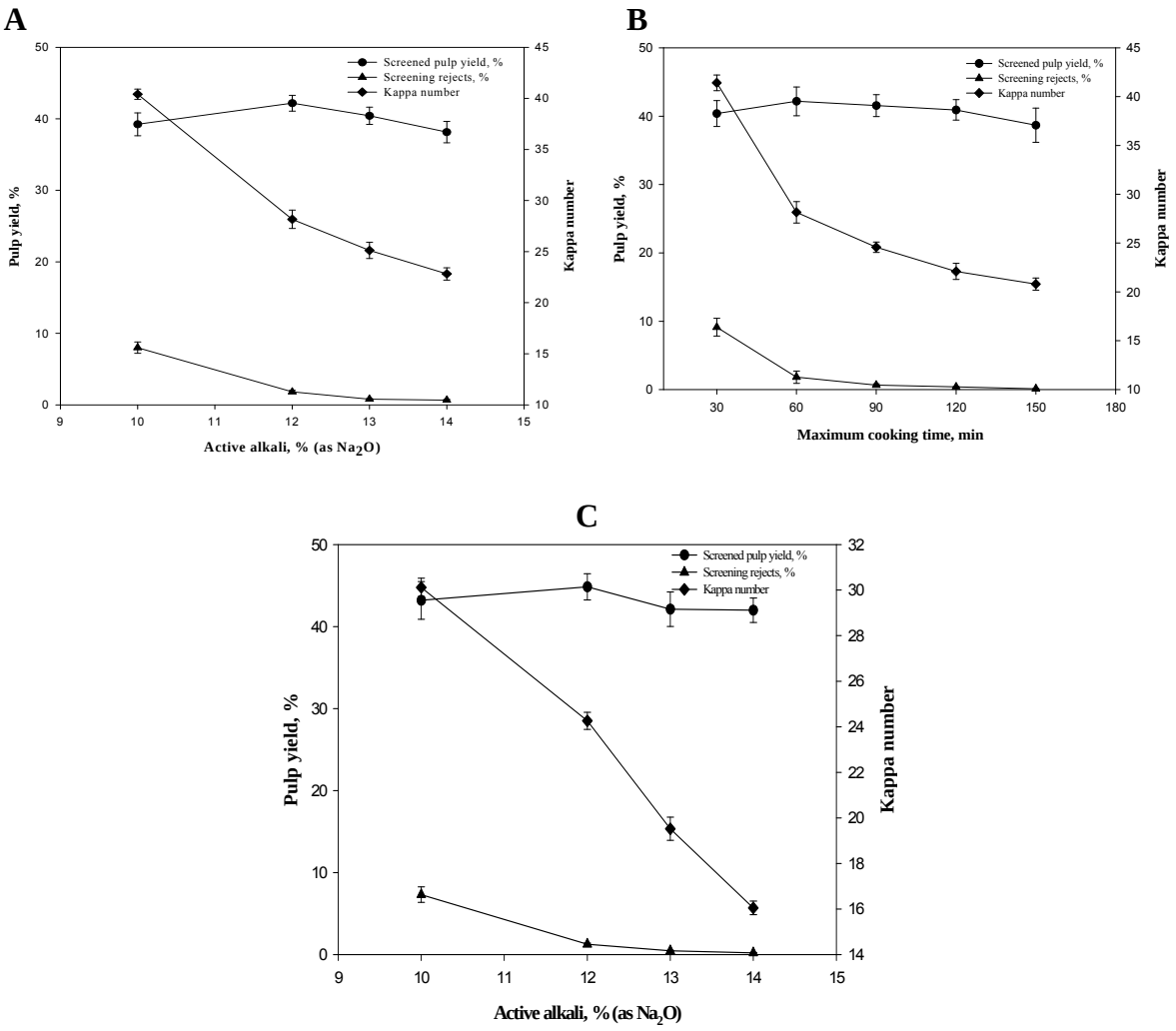

Fig. 2. Effect of (A) active alkali, (B) maximum cooking time, and (C) AQ dose at different alkali doses on screened pulp yield, screening rejects, and kappa number during soda pulping of sugarcane bagasse

Soda pulping of bagasse (collected from White Nile Province) at mild cooking condition with an active alkali level of 12.4% (as Na_2O) on oven dry raw material, 60 min heating up time to the maximum temperature of 160°C and 60 min cooking time, produces screened pulp yield of 55.8% at kappa number of 14.3. Under harsher conditions (90 min cooking time at 165°C) the kappa number can only marginally be reduced, and the screened yield dropps to 53.2%, but the pulp shows much higher tear strength (Khristova et. al. 2006). The effect of AQ at different alkali doses i.e. 10-14% (as Na_2O) while keeping other conditions constant during soda pulping of sugarcane

bagasse is presented in Fig. 2C and Table 6. The addition of 0.1% AQ dose at active alkali doses 10 and 12% (as Na_2O) improves the pulp yield by 10.1 and 2.7% respectively, while keeping other parameters constant. On the other hand, 0.1% AQ reduces kappa number of sugarcane bagasse pulp by 10.3 and 3.9 units at active alkali doses of 10 and 12% (as Na_2O), respectively.

Table 5. Effect of Maximum Cooking Temperature on Pulp Yield, Lignin, and Kappa Number of Sugarcane Bagasse

Temperature, ^{0}C	Time at temperature, h	Sugarcane bagasse		
		Yield, %	Kappa number	Lignin, %
130	0.25	68.6±2.8	-	13.26±0.4
	0.50	63.4±1.2	-	10.45±0.32
	1.00	57.3±1.9	45.2±1.7	7.72±0.28
	1.50	52.2±1.7	-	6.45±0.50
	2.00	48.5±1.1	-	5.75±0.35
	2.50	46.2±1.5	-	4.92±0.72
140	0.25	65.2±1.3	-	11.35±0.5
	0.50	57.6±1.7	-	8.45±0.30
	1.00	49.3±2.0	37.3±1.5	5.15±0.35
	1.50	45.3±1.5	-	4.65±0.28
	2.00	42.3±1.2	-	4.12±0.25
	2.50	40.8±1.5	-	3.62±0.30
150	0.25	58.6±1.9	-	10.30±0.65
	0.50	50.2±1.5	-	7.62±0.80
	1.00	44.0±0.9	28.2±0.9	4.22±0.21
	1.50	42.2±1.8	-	4.02±0.30
	2.00	40.4±1.2	-	3.65±0.50
	2.50	38.8±1.5	-	3.25±0.50
160	0.25	55.7±2.4	-	9.50±1.1
	0.50	46.9±1.8	-	6.25±0.4
	1.0	41.3±1.5	22.3±0.3	3.45±0.29
	1.5	39.2±1.0	-	3.15±0.34
	2.0	38.2±1.8	-	2.75±0.25
	2.5	37.3±1.6	-	2.22±0.20

± refers standard deviation; Cooking conditions: liquor to wood ratio: 4:1, active alkali: 12% (as Na_2O), digester pressure: 5.0 kg/cm^2, time from room temperature to 105±2^{0}C: 30 min and time from 105 to 150±2 ^{0}C: 30 min.

Table 6. Effect of AQ and Alkali Charges on Pulp Yield, Kappa Number and Screening Rejects

Active alkali, % (as Na_2O)	Total pulp yield, %	Screened pulp yield, %	Screening rejects, %	Kappa number	Spent liquor pH
10	50.5±3.0	43.2±2.3	7.3±0.95	30.1±0.40	8.9
12	46.1±2.5	44.9±1.6	1.3±0.12	24.3±0.38	10.0
13	43.0±1.9	42.1±2.1	0.5±0.05	19.5±0.51	10.4
14	42.2±2.9	42.0±1.5	0.2±0.02	16.1±0.30	10.6

± refers standard deviation; Cooking conditions: liquor to wood ratio: 4:1, digester pressure: 5.0 kg/cm^2, time from room temperature to 105±2°C: 30 min, time from 105°C to maximum temperature 150±2°C : 30 min, time at maximum temperature 150±2°C: 60 min and AQ dose (on oven dry raw materials basis): 0.1%

Mechanical strength properties such as burst and tear indexes and double fold increase with increasing alkali dose up to 12%, and beyond that these mechanical strength properties decline (Table 7).

Table 7. Mechanical Strength Properties of Unbleached Sugarcane Bagasse Soda-AQ Pulp at Different Alkali Doses

Active alkali, % (as Na_2O)	Beating level, °SR	Tensile index, Nm/g	Tear index, mNm^2/g	Burst index, $kPam^2/g$	Double fold, number
10	16	18.23±1.20	4.35±0.22	0.89±0.09	4±2.56
	35	38.74±1.60	5.15±0.18	2.82±0.11	68±5.3
	45	57.56±2.20	4.22±0.20	4.22±0.15	91±2.6
	55	54.83±1.90	2.88±0.21	3.87±0.12	88±4.4
12	16	23.64±1.30	4.85±0.15	1.03±0.08	7±1.30
	35	57.64±2.10	5.45±0.20	3.56±0.20	86±3.5
	45	69.98±3.30	4.55±0.16	4.66±0.06	110±4.0
	55	66.72±1.80	3.12±0.30	4.34±0.18	100±6.3
13	16	22.91±0.76	4.65±0.25	0.96±0.03	6±1.9
	35	53.11±1.40	5.25±0.11	3.32±0.21	82±2.1
	45	66.47±3.60	4.35±0.14	4.49±0.17	102±8.0
	55	62.36±1.93	3.05±0.33	4.1±0.16	97±5.4
14	16	25.55±0.50	4.52±0.29	0.94±0.10	5±1.3
	35	55.32±1.66	5.02±0.16	3.14±0.22	77±5.3
	45	68.44±2.91	4.16±0.22	4.35±0.25	95±7.3
	55	65.05±3.03	2.76±0.13	3.75±0.15	95±4.0

± refers standard deviation

It is found that the excessive active alkali dose, which remains unconsumed during the course of pulping, adversely affects the pulp mechanical strength properties due to peeling reactions and alkaline hydrolysis. Similarly, burst index, tensile index, and double fold increase with increasing beating level up to 45 ^{o}SR, and beyond that they decline, except for tear index. Removal of primary walls exposes secondary wall layers, which results in hydrogen bonding. Therefore, tearing energy required to pull the fibers from the mesh will increase slightly. Further, cutting action, external and internal fibrillations, and brushing action bring the tear index down, whereas all other properties depending upon hydrogen bonding improve with pulp beating. Hence, a beating level of 45 ^{o}SR may be taken as an optimum for sugarcane bagasse. Mechanical strength properties such as tensile index, burst index and double fold numbers improve with beating level (^{o}SR), except tear index. The mechanical strength properties of depithed sugarcane bagasse obtained from a sugar mill in Jalisco (Mexico), cooked at 14.5% NaOH (as Na_2O), kappa number 12, and beaten at 35 ^{o}SR, produces handsheets of tensile index 58 Nm/g, tear index 5.8 mNm^2/g, burst index 4.2 kPam^2/g and unbleached pulp brightness 48% (ISO) (Ramos et al. 2001). The tensile index (57.64 Nm/g) and burst index (5.45kPam^2/g) of sugarcane bagasse are comparable to those of sugarcane bagasse from Mexico, except for tear index (3.56 mNm^2/g), which is slightly on the lower side

CONCLUSIONS

For Indian paper industries, which face an acute shortage of cellulosic fibers, sugarcane bagasse from early species of *Saccharum officinerum*-Co 89003, a fibrous raw material widely available in Northern India, may be a viable fibrous source for them. Sugarcane bagasse contains 71.36% useful fibers for papermaking, and 15.48% pith that can be used for energy production in boilers or ethanol production. The fiber characteristics and morphological indices of the depithed bagasse reveal that it contains long and thick-walled fibers, which give rise to higher Runkal ratio, and slenderness ratio and lower flexibility coefficient, indicating suitability for producing higher tear index, bulk, and a more opaque sheet, which is suitable for manufacturing of writing and printing paper, and absorbent grade paper, base paper for pictorial circuit board, seed germination paper, and tea bag paper. The dimensions of sugarcane bagasse parenchyma and vessel cells lie between wheat and rice straws. Therefore, slot size intended for the depither's screen of bagasse cannot be used for wheat and rice straws. The kink index and kinks per mm length of fiber are lower compared to *E. terticornis*. Therefore, sugarcane bagasse is expected to produce strong paper. Kinks and curls can be removed by beating or refining to some extent as a result of increasing fiber flexibility. Solubles are slightly on the higher side, which affects pulp yield, but it induces less pitch problems and more homogeneity in the paper due to lower alcohol-benzene soluble substances. The levels of α-cellulose and pentosans are satisfactory in sugarcane bagasse, which are necessary for pulp and paper manufacture from a chemical composition point of view. Although the ash and extractives contents are on the high side, the very good carbohydrate content is favourable for alkaline pulping with moderate chemical charges, and good pulp yields can be expected.

Sugarcane bagasse requires milder pulping conditions to reach a satisfactory kappa number due to low lignin content and more open and loose structure. It contains a higher proportion of carbon content, compared with hydrogen and oxygen, which implies a relatively high energy value. This means that the pith can successfully be used for energy production. Depithed sugarcane bagasse produces screened pulp yield of 42.2% and kappa number 28.2 at optimized pulping conditions such as active alkali dose 12% (as Na_2O), maximum cooking temperature 150^oC, maximum cooking time 60 min, digester pressure 5 kg/cm^2, and liquor to wood ratio 4:1. The introduction of 0.1% AQ at optimized soda pulping conditions improves pulp yield by 2.7% and kappa number is reduced by 3.9 units. A beating level of 45 ^oSR is found to impart optimum effects on mechanical strength properties.

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