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Refiner Mechanical and Biomechanical Pulping of Jute

By Harmohinder S. Sabharwal[1], Masood Akhtar[2], Robert A. Blanchette[3], and Raymond A. Young[1]

[1]Department of Forestry, University of Wisconsin, Madison, U.S.A.
[2]University of Wisconsin, Biotechnology Center and Institute for Microbial and Biochemical Technology, USDA Forest Products Laboratory, Madison, U.S.A.
[3]Department of Plant Pathology. University of Minnesota, St. Paul, U.S.A.

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Summary

Atmospheric refiner mechanical pulping of untreated,, fungal and alkali treated jute bast has been explored In the present investigation. Hammermilled and cut jute bast strands were refined in a laboratory single disc refiner under atmospheric conditions. First stage refining was carried out to about 500ml, CSF and second stage refining was carried out at various clearance levels to varying degrees 0f freeness. Although the energy consumption was higher for cut jute, the resulting pulps had higher Strengh properties; significantly higher than my other conventional refiner mechanical or thermo-mechanical pulps. The energy consumption in refining was reduced by 33% for fungal treated jute and burst, tensile and tear strengths were enhanced by 39%, 22% and 33%, respectively. The treatment of cut jute with alkali prior to refining yielded pulps with higher strength, but the yields were lower compared to fungal treated jute. The energy consumption of 450 KWh/ton for biomechanical pulp from jute bast compared to an average 1600 KWh/ton for pulp produced from wood; thus a saving of 1150 KWh/ton of pulp could be realized if wood was replaced by jute bast.

Introduction

Jute *(Corchorus capsularis)* is primarily grown in Bangladesh, India, China and Thailand. The plant grows to 2.5–3.5 meter in height at maturity. The outer bark or bast comprises about 40% of the stem by weight and is mainly used for low value-added products such as rope, cordage and gunny sacks.

The inner woody core accounts for the remaining 60% ot the stem. Newly 2.2 million tons of jute bast alone (excluding core) are reported to he potentially available world wide (Atchison 1983). Jute has been traditionally a major source of foreign exchange earnings for the jute producing countries. However, the use of jute has been steadily decreasing in recent years mainly due to the substitution by synthetic fibers in the developed countries. India is a classic example, where exports of jute products dropped from 80% in 1960 to 19% in 1990. A similar trend has been observed for other jute producing countries. The major decline in jute exports from developing countries has accelerated research to diversify utiliztition for value-added products. We feel that the production of pulp for papermaking from jute on a large scale has great potential.

The limited use of jute for pulp and papermaking has been mostly confined to cuttings from burlap manufacture, washed sugar bagging and the tares used in wrapping cotton bales. Chemical pulping processes are primarily employed for the jute waste products (McGovern *(et al.* 1983a). Tribeni Tissues Limited (India) is the only mill to use raw jute for pulp manufacture where it is used in blends with other pulps to produce speciality paper. The 14.5 thousand tons of bast material used by this paper mill in India constituted just 1% of the total jute bast material available in India in 1990-91.

High energy cost and inferior pulp quality, in general, renders the mechanical pulping processes less attractive in spite of the obvious advantages of higher yields and less pollution. A number of other non-woody plants have been successfully used for the production of certain grades of pulp, such as newsprint by mechanical pulping processes.

Considerable efforts have been expended on reducing the energy consumption in mechanical pulping by treating the substrate with chemicals prior to or during refining. Energy consumption can be reduced by the chemical approach but it still offers only a partial solution to the problem of pollution and may not be cost effective (Mackie and Joyce 1987). However, in recent years the advantages of using fungal treatment prior to mechanical refining of wood have been demonstrated. Numerous investigations on the use of fungi for wood prior to mechanical refining have been reported (Bar-Lev *et al.* 1982: Akamatsu

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Table 1. Refining conditions for hammermilled and cut jute bast

Freeness of initial unrefined stock (Hammermilled):	750 ml CSF
Freeness of initial unrefined stock (Cut):	730 ml CSF
First pass through:	0.02" (Primary stage refining)
Feed consistency:	10%
Discharge consistency:	1–2%
Feed rate:	250 g/min. = 360 Kg/day
Stock received after 1st pass (Primary stage refining) was divided into various portions to pass through various clearance levels (For secondary stage refining) under indentical conditions as follows:	
Feed consistency:	10%
Feed rate:	600 g/mt = 864 Kg/day

et al. 1984; Yoshinori *et al.* 1993). Considerable energy savings and enhancement in strength properties of aspen and pine pulps were realized by the use of white-rot fungus *Ceriporiopsis subvermispora* (Akhtar *et al.* 1992 and 1993). The use of fungi for non-woody plants prior to mechanical refining has, however, received verly little attention. Efficient delignification of wheat straw by *Panus conchatus,* a white rot fungus, has been demonstrated. Up to 24.7% water soluble modified lignin was released from the wheat straw by this fungus after only three days inoculation (Yu and Eriksson 1985). Selective delignification of wheat straw by *pleurotus eryngii* has also been recently reported (Kuhn *et al.* 1992).

Studies on the atmospheric refiner mechanical pulping (RMP), bio-refiner mechanical pulping (BRMP) and chemi-refiner mechanical pulping (CRMP) were initiated to evaluate the potential of these processes for pulp production from jute bast.

Materials and Methods

Jute strands

The mature jute strands were obtained after the stalks attained maturity at a height of 2.5 to 3.0 meters. The bast fibers were liberated by rctting process. Hammer milled and cut (2-4cm long) jute strands were used in the present investigation.

Refining

Atmospheric refining was carried out in a 12" Sprout Waldron single disc refiner.Sprout Waldron D2A507 Ni Hard plates were used because of their wider range of applicability. The refiner was run with a 50 hp motor at 2600rpm. Primary stage refining of hammer milled and cut samples was carried out at a feed rate of 250 g/min (366 Kg/day) at 0.02" clearance with resulting freeness of 5.30m1. and 490ml, CSF. respectively. The discharge consistency was maintained at 1–2%. Sufficient pulp was obtained from primary stage refining for secondary stage refining at various clearance levels to obtain pulp at various freeness levels (Fig. 2) The second stage refining was carried out at 10% consistency and feed rate was maintained at 600g/min (864 Kg/day) (Table I). The energy consumption was measured by a watt meter attached to the power supply side of thc driving electric motor (Tablc 2). The energy consumption during hammer milling was not measured but it would constitute a small fraction of total energy requirement for the primary and secondary refining stages.

Table2. Energy consumption at various freeness ievels

	Clearance inch	Freeness ml. CSF	Energy consumption KWh/ton of pulp	Energy saving %	Cumulative energy saving %
Untreated					
Hammermilled					
Initial	–	750	–		
Primary stage	0.020	530	466		
Secondary stage:	0.005	300	494		
"	0.003	200	577		
"	0.0025	150	591		
"	0.002	100	604		
Cut					
Initial	–	730	–		
Primary stage	0.020	500	500		
Secondary stage:	0.005	250	600		
"	0.003	180	677		
"	0.002	80	710		
Fungal treated cut					
Initial	–	700	–		
Primary stage	0.020	470	390	22	22
Secondary stage:	0.005	330	450	40	25
"	0.003	200	565	Nil	16.5

Fungal strain

Ceriporiopsis subvermispora (Fil.) was selected for this study because of its greater lignin selectivity (Blanchette *et a1.* 1992) and superior biopulping performance than tbe other fungi (Akhtar *et al.* 1992 and 1993). Strain CZ-3 of this fungus was selected bused on its superior biopulping performance (Akhtar 1994). The strain was obtained from the Center for Mycology Research of the Forest Products Laboratory. Madison, WI.

Inoculum preparation

The fungal culture was maintained on potato dextrose agar (PDA) (Difco Laboratories, Detroit, Ml) slants and kept refrigerated until used. PDA plate cultures were inoculated from these slants and incubated at 27°C and 65% relative humidity for 10 days, A culture medium was made with 330ml of water containing potato dextrose broth [(7.2g) Difco Laboratories, Detroit, Ml)] and yeast extract [(2.18g) (Amberex 1003, Universal Foods Corporation, Milwaukee, WI)], This medium was poured into one 2.8 liter flask. The Fernbatch flask containing medium was closed with aluminium foil and autoclaved for 20 min. 121°C and 15 psi. After cooling to room temperature, the flask was inoculated with 30 plugs (9 mm diameter) from the 10-day old petri plate cultures. The flask was then incubated at 27°C and 65% relative humidity for 10 days without agitation. The spent medium in the flask containing the fungal biomass was then decanted. the mycelium washed with stelile distilled water, and then blended aseptically in a Waring blender. Sterile water was then added to the blended mycelium to make the total vlume of the suspension to 100ml. Twenty five grams of this suspension (0.1% fungus on dry weight basis) was added to the medium prior to inoculation.

Medium Preparation

A glucose-containing medium described previously (Leatham et al. 1990) was used to increase the fungal biomass and supplress cellulose degradation. The medium was added in four bioreactors (two conrols and two treatments each with hammer milled jute and cut jute) in sufficient quantity to bring the moisture content to about 80% on wet weight basis. Each bioreactor contained about 350g of jute on dry weight basis Thc hammer milled sample formed large lumps on adding the medium thus making the treatment heterogenous. The biotreated hammer milled sample was not processed for further refining. The refining experiments were carried out only for fungal treated cut jute sample after 14 days of incubation. The bioreactor used in this study has been described in a previous publication (Akhtar *et al.* 1993).

.Alkali treatment

The cut sample was treated with 5% and *10%* (based on o.d. jute) sodium hydroxide at 100°C for 1 hour prior to refining. The liquor to wood ratio was 10:1.

Pulp testing

Tappi standards Were emplolyed for the evaluation of all the pulps after removing the latency.

Scanning electron microscopy

Inoculated and noninoculated jute bast samples were sectioned in a cryo-cut freezing microtome to provide a transverse cut surface through the fibers. Sectioned material was allowed to air dry and mounted for scanning electron microscopy. Samples were coated with 40% gold and 60% palladium and examined using a Hitachi 450 scanning electron microscope.

Results and Discussion

Refining involves the repeated compression and relaxation fo the plant material and fibers in water provided by the bars and groves of refiner disc. This results in both energy consumption and mechanical disruption of the bonds holding the lamellae together-that make up the secondary wall. The refining process can be augmented by pressure and temperature known as pressurized refiner mechanical pulping and thermo-mechanical pulping processes. Low density, long fibers (1.5-5.0mm) and large lumen size enhance the compressibility of the material in mechanical refining (Leask 1983a.).

Jute bast material has these qualities and should be expected to respond better than wood to refiner mechanical pulping. Three factors which distinguish jute bast from woody plants are the orientation of the fibrils, lignin distribution in the cell wall and lignin content. The fibrils of bast fibers lie more or less parallel to the fiber axis, unlike wood fibers whose fibrils are spirally wound. The jute bast fibers can therefore be split length-wise by mechanical action to yield fine, relatively long fibrous threads (Clark 1978).

Scanning electron micrographs of sectioned jute bast show separated bundles of fibers containing cells of varying thickness (Fig. 1a). Fungal pretreated fibers are modified by hyphae that colonize the exposed edges of the fiber bundles (Fig. 1b). Previous investigations of wood chips treated with *Ceriporiopsis subvermispora* for four weeks and examined by scanning electron microscopy showed cell wall swelling, softening and a collapse of cell structure (Sachs *et al.* 1991).Although variations in cell with thickness were apparent in jute Fibers, differences were not easy to differentiate from cell walls of untreated samples. Additional study on the ultrastructural changes that occur within middle lamellae and secondary Walls of treated bast fibers should provide important information on the mechanism involved and distinct changes occurring within the modified cell walls.

In woody and non-woody plants lignin is typically concentrated toward the outer ceil wall and middle lamella whereas in jute bast the lignin is more evenly distributed, however, the inner layers of the cell wall contain the higher proportion of lignin after retting (Preston 1963). The lignin content of jute ranges From 12–14% (McGovern 1990) and is comparatively lower than conventional woody and non-woody materials used for mechanical pulping processes. All these factors suggest that jute should require it less drastic refining approach for mechanical pulping. The present investigation wits undertaken to determine if these special characteristics would prove to be advantageous in atmospheric refiner mechanical pulping of jute bast, and also if the same features would render jute more susceptible to fungal treatment by known fungus strains. The main focus was on energy consumption at various stages of refining, before and after fungal treatment. and the effect on the strength properties.

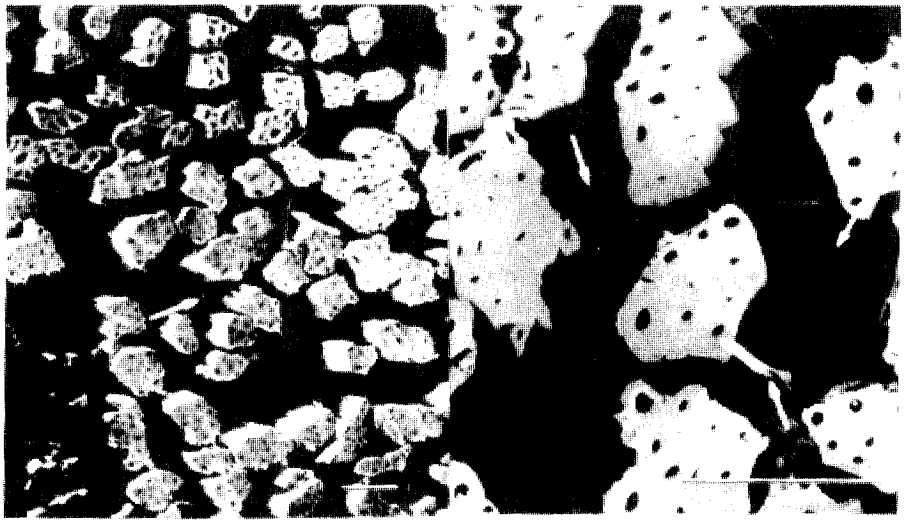

Fig. 1a and b. Scanning electron micrographs of transverse sections showing jute fibers that have been pretreated with CZ-3 strain of white-rot fungus *Ceriporiopsis subvermispora.*

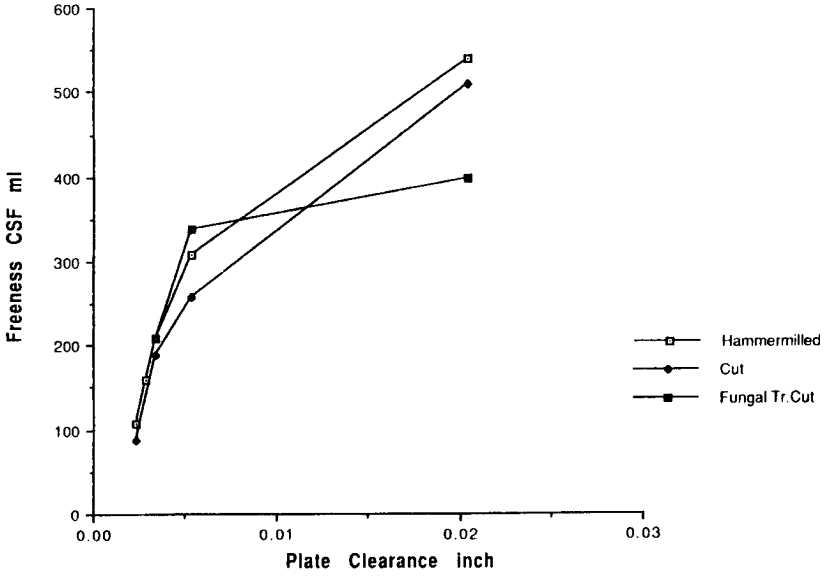

Fig. 2. Plate Clearance versus freeness

Energy consumption

The energy consumption of hammer milled, cut and fungal treated cut jute strands as seen in Figure 3 shows that though energy consumption for refining of cut sample is higher than hammer milled sample however considerable reduction in bio-treated cut sample has been realized. The energy consumption data (Table 2) shows that nearly 77.2% of the total energy required to obtain jute refiner mechanical pulp at 100ml. CSF was consumed in the primary stage for the hammer milled sample. The energy consumption in the primary stage for the cut sample was 70.0% of the total energy required to obtain pulp at 80ml. CSF. This is in contrast to the thermo-mechanical pulping of wood where only one third of the total refining energy is consumed during fiberization stage (Kano *et al.* 1982). This appears to be related to presteaming and refining in the thermomechanical pulping process. The low lignin content and large lumen size have a more beneficial effect during the second stage refining of jute bast. However the overall energy consumption for hammermilled, as well as cut jute, was considerably less than for TMP or CTMP reported for other nonwoody plant materials (Hodgson *et al. 1980).*

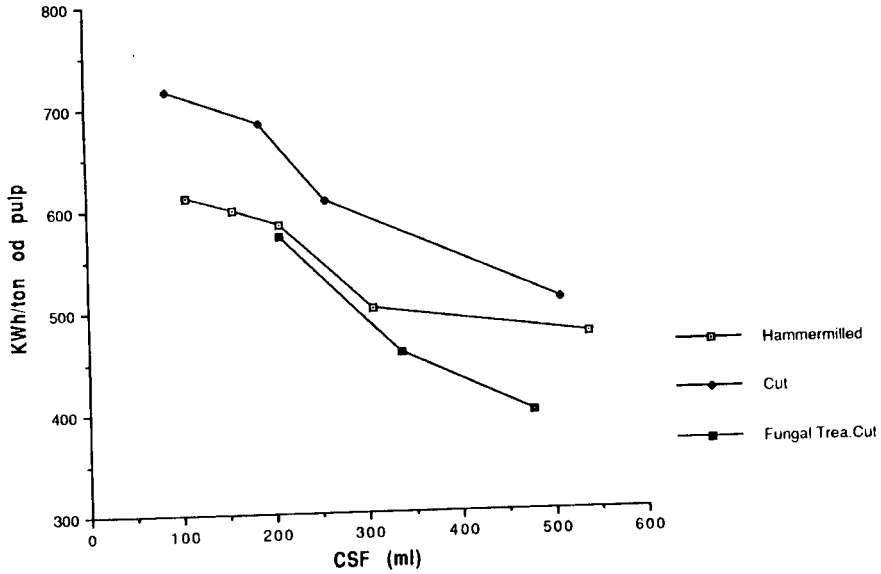

Fig. 3. Energy consumption versus freeness.

The energy consumption of fungal treated cut jute bast at the primary stage refining was 69% of the total refining energy required to obtain the pulp at 200 ml. CSF. The energy savings of 22% at primary stage (0.02" clearance) and 40% at secondary stage (0.005" clearance) is in contrast to kenaf bast (Sabharwal *et al.* 1994) where maximum energy saving was realized during primary stage (defiberization) and early stages of secondary refining indicating softening effect on the lignin by fungal attack was mainly confined in the region of middle lamella. This distinction in the case of jute bast can be explained by the fact that the softening of lignin by fungal attack was not only restricted to middle lamella but perhaps extended to the inner layers where higher proportion of lignin is dispersed after retting of jute plant. Higher energy saving during secondary stage (Fibrillation) of refining compared with kenaf is perhaps a combined effect of softening of lignin by fungal attack in the inner layers of cell wall in addition to large lumen size of the fibers. The cumulative energy saving with fungal treated jute bast at a level of 330ml. CSF. where optimum strength properties were obtained, was 25%. However, the overall energy consumption for fungal treated jute bast at 330ml. CSF was one-half of that obtained for thermo-mechanical Pulping of mesta (Kulkarni *et al.* 1989) and 60% less than that obtained from fungal treated aspen (Akhtar 1994) at 100ml. CSF as shown in (Fig. 4).

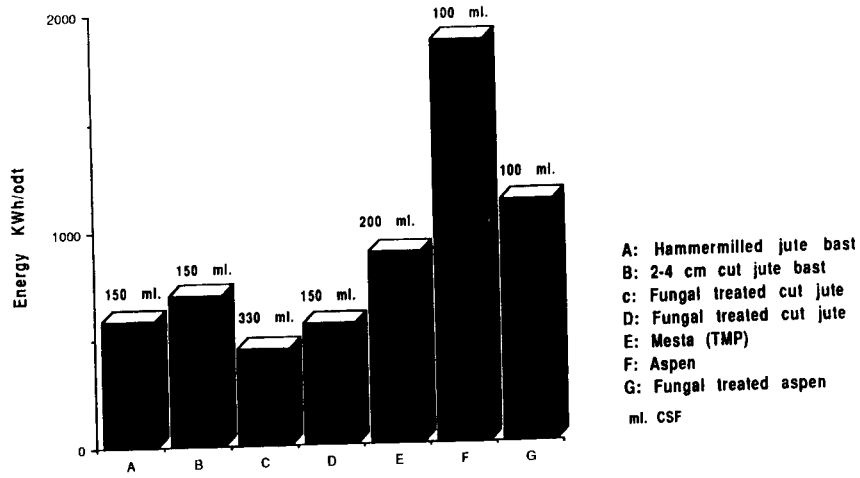

Fig 4. Specific energy consumption by various untreated and fungal treated wood and non-wood materials.

Table 3. Properties of refiner mechanical pulps from hammer milled and cut jute bast*

Freeness ml. CSF	Energy KWh/odt	Caliper µ	Bulk cm^3/g	Apparent density g/cm^3	Burst index K Pa m^2/g	Tensile index N. m/g	Tear index m. Nm^2/g
Hammermilled							
100	604	68	1.09	0.75	1.89	50.25	5.64
150	591	81	1.28	0.78	1.90	43.78	6.97
200	577	85	1.33	0.92	1.65	38.3	5.99
Cut							
80	710	151	2.36	0.42	1.29	37.13	4.29
150	677	148	2.37	0.42	2.54	59.50	7.80
250	600	157	2.40	0.40	2.37	57.90	9.19

* All 60gsm sheets.

Table 4. Properties of untreated and fungal treated refined pulps from jute bast

Sample	Freeness ml. CSF	Energy Wh/odt	Basis weight GSM	Caliper µ	Bulk cm^3/g	App. density g/cm^3	Burst index K. Pam^2/g	Tensile index N. m/g	Tear index m. Nm^2/g
A	100	604	63	68	1.09	0.92	1.89	50.25	5.64
B	150	677	62	148	2.37	0.42	2.54	59.50	4.29
C	200	565	59	131	2.24	0.45	2.97	72.36	7.46
D	330	450	62	149	2.38	0.42	3.54	72.60	10.37

A: Best case hammermilled jute bast refiner mechanical pulp. B: Best case cut jute bast refiner mechanical pulp. C: Fungal treated cut jute refiner mechanical pulp. D: Best case fungal treated cut jute refiner mechanical pulp.

Strength properties

The strength properties of pulps from cut jute samples were comparatively higher as is evident from Table 3. It is noteworthy that the cut samples yielded sufficiently strong pulps at higher freeness levels whereas the strength was progressively reduced at higher freeness levels for the hammer milled jute bast. A comparison of pulps from hammermilled and cut samples of jute bast at 150ml. CSF clearly demonstrates the advantage of cut over hammer-milled samples.

The pulps obtained from fungal treated cut jute bast at two freeness (CSF) levels of 200ml. and 330ml. had considerably enhanced strength properties compared to both untreated hammermilled and cut jute bast. The burst, tensile and tear strengths increased by 39%, 22% and 33%. respectively. in the case of fungal treated cut jute at 330m1. CSF and compared with cut jute at 150ml. CSF as is evident from Table 4.

A comparison of burst and tear strengths of some non-wood. wood and fungus *Ceriporiopsis subver-*

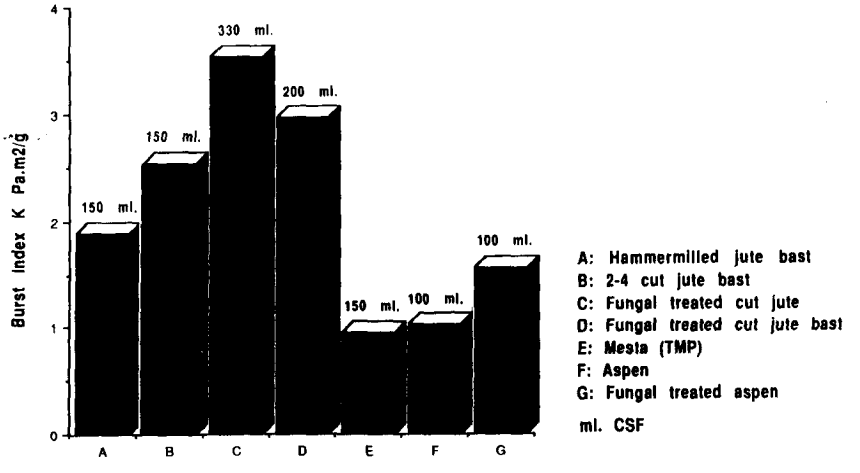

Fig. 5. Burst index of pulps from untreated and fungal treated wood and non-wood materials.

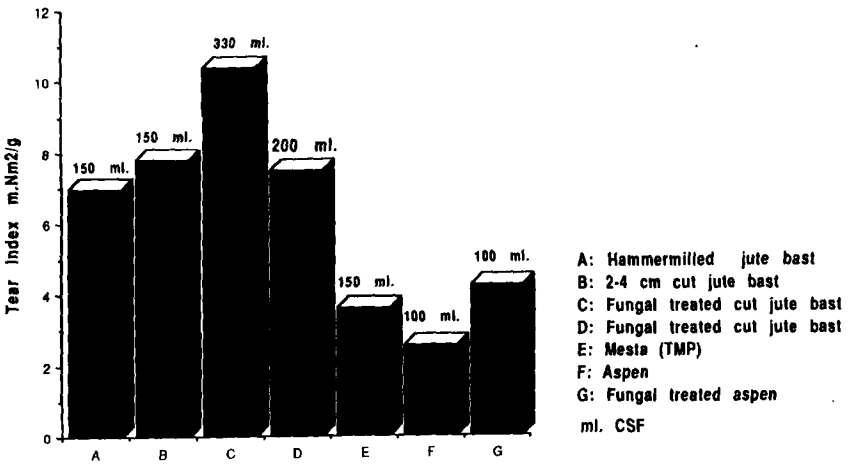

Fig. 6. Tear index of pulps from untreated and fungal treated wood and non-wood materials

mispora, treated wood (Figs. 5 and 6) indicates the specificity of this fungal strain for jute bast. The unique phenomenon of obtaining stronger pulps at higher freeness levels in the case of fungal treated cut jute bast can be explained by an earlier finding (Prommier *et al.* 1989) which demonstrated that many enzymatic cocktails of cellulases and hemicellulases, irrespective of their origin, had the ability to reverse the detrimental decrease in drainage properties inherent in recycled fibers. They speculated that the enzymes act on the surface of fibers producing a "peeling effect" as described by (Lee and Kim 1983).

Table 5. Optical properties of untreated and fungal treated refined pulps from jute bast

Sample	Freeness CSF ml	Brightness %	Printing opacity %	Light scattering coefficient m^2/Kg
Hammermilled	150	39.4	99.2	50.9
Cut	150	44.7	98.9	53.2
Fungal treated cut	200	33.2	97.5	36.4
Fungal treated cut	330	32.9	97.6	32.8

According to Pommier (Pommier *et al.* 1989), if the peeling effect is controlled, the enzyme will remove only small amount of components that have the greatest affinity for water, but do not contribute to the hydrogen bonding potential of the fibers. Thus. better dainage of the pulp is allowed without affecting the mechanical properties. The fungus strain used in our investigation possesses all these enzymes, that is cellulases, hemicellulases and ligninase. The activity of the cellulase enzyme was, however, suppressed in our investigation by adding small amount of glucose to the reaction mixture to avoid cellulose degradation. The other enzymes apparently were not repressed. A loss in brightness by 11 to 12 points of pulps from fungal treated jute was also observed Table 5. The effect of fungi on decreasing brightness has been reported earlier (Blanchette *et al.* 1992).

The 5% and 10% sodium hydroxide treatment of cut jute bast prior to refining yielded pulps with higher strength properties but there was considerable loss in yield as is evident from Table 6. Although there is no direct comparison available in the literature, some data (Table 6) on cold soda refiner mechanical pulping of hardwoods (Leask 1983b) reflects similar superior qualities of pulps as obtained from jute bast in our investigation. Jute bast treated with 5% and 10% sodium hydroxide could be a serious contender

Table 6. Properties of refined pulps from cut jute bast treated with alkali

Sodium hydroxide %	Yield %	Freeness ml. CSF	Burst index K. Pa m^2/g	Tensile index N. m/g	Tear index m. Nm^2/g
Control*	95.0+	150	2.54	59.5	7.8
Bio-RMP	90.0+	330	3.54	72.6	10.4
5	81.0	170	4.25	86.0	5.7
10	73.5	170	4.42	102.2	7.2
6.5**	–	142	2.19	–	4.53

* RMP; ** Reference: Leask 1983b.

with bio-mechanical pulps. Since many chemi-mechanical processes cause pollution and are not cost effective, biomechanical pulping is an attractive alternative.

Conclusions

Jute is a viable fibrous source for papermaking by mechanical pulping processes in developing countries. Refiner mechanical pulping of jute is less energy intensive as compared to other conventional wood and non-wood fibrous materials for the production of mechanical pulp. Considerable energy savings and enhancement in strength properties can be realized by bio-treatment of jute bast with CZ-3 strain of *Ceriporiopsis subvermispora, a* white rot fungus. prior to refining. Bio-mechanical pulping of jute bast would result in energy saving of 115,000KWh per 100 tons of oven dry pulp if wood is replaced by jute bast with an added advantage of obtaining stronger pulps.

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References

Akamatsu, I., K. Yoshihara, H. Kamishiva, and I. Fujl. 1984. Influence of white-rot fungi on poplar chips and thermo-mechanical pulping of fungi-treated chips. Mokuzai Gakkaishi *30*, 697–702.

Atchison, J.E. 1983. Data on Non-Wood Plant Fibers. *In:* Pulp and Paper Manufacture. Ed. M.J. Kocurek. Joint Textbook Committee of the Paper Industry. (3) pp 4–16. Atlanta, GA.

Akhtar, M., M.C. Attridge, R.A. Blanchette, G.C. Myers, M.B. Wall, M.S. Sykes, J.W. Koning Jr., R.R. Burgess, T.H. Wegner, and T.K. Kirk, 1992. The White-rot Fungus *Ceriporiopsis subvermispora* Saves Electrical Energy and Improves Strength Properties during Biomechanical Pulping of Wood. *In:* Biotechnology in Pulp and Paper Industry. Eds. M. Kuwahara and M. Shimada. pp 3–8. UNI Publishers. Tokyo, Japan.

Akhtar, M., M.C. Attridge, G.C. Myers, and R.A. Blanchette. 1993. Biomechanical pulping of loblolly pine chips with selected white-rot fungi. Holzforschung *47:* 36–40.

Akhtar, M. 1994. Biomechanical pulping of aspen wood chips with three strains of *Ceriporiopsis subvermispora.* Holzforschung *48:* 199–202.

Bar-Lev, S.S., T.K. Kirk, and H-m, Chang. 1982. Fungal treatment can reduce energy requirement for secondary refining of TMP. Tappi J. *65* (10), 111–113.

Blanchette, R.A., T.A. Burnes, M.E. Eerdmans, and M. Akhtar. 1992. Evaluating isolates of *Phanerochaete chrysosporium* and *Ceriporiopsis subvermispora* for use in biological pulping processes. Holzforschung *46:* 109–115.

Clark, J. d'A. 1978. Structure of Wood and Other Fiber. *In:* Pulp Technology and Treatment For Paper. Ed. J. d'A, Clark. Miller Freeman Publications Inc. San Francisco. pp 125–144.

Hodgson, P.W., W.H. Lawford, J. Perrault, and C.A. Thompson. 1980. ANPA International Paper Sales Kenaf Newsprint Project. *In:* Nonwood Plant Fiber Pulping. Progress Report No. 11. Tappi Press, Atlanta, GA. pp 25–31.

Kano, T., T. Iwamida, and Y. Sumi, 1982. Energy consumption in mechanical pulping. Pulp and Paper Canada. *83* (6): 80–84.

Kuhn, S., S. Camerero, M. Valmaseda, G. Almendros, M.J. Martinez, A.E. Gonzalez, and A.T. Martinez. 1992. Straw Biopulping: Selective Delignification with Pleurotus eryngii. *In:* Biotechnology in Pulp and Paper Industry. eds. M. Kuwahara, and M. Shimada, Publisher. Tokyo, Japan. pp. 15–20.

Kulkarni, A.G., R.M. Mathur, S. Naithani, G.C. Agarwal, and R. Pant. 1989. Whole Mesta Plant-A promising Raw material substitute For Newsprint manufacture, Silver Jubilee International Seminar & Workshop Appropriate Technology For Pulp and Paper Manufacture in Developing Countries. New Delhi, India. pp. 1–20.

Leask, R.A. 1983a. Introduction. *In:* Pulp and Paper Manufacture. Ed. M.J. Kocurek. Joint Textbook Committee of the Paper Industry, Tappi (2). Atlanta, GA. pp. 87–92.

Leask, R.A. 1983b. Refining Processes. *In:* Pulp and Paper Manufacture. Ed. M.J. Kocurek. Joint Textbook Committe of the Paper Industry, Tappi. (3), Atlanta, GA. pp. 98–128.

Leatham, G.F., G.C. Myers, and T.H. Wegner. 1990. Biomechanical pulping of Aspen Chips: Paper Strength and Optical Properties Resulting from Different fungal Treatments. Tappi J. *73* (3): 249–255.

Lee, S., and I. Kim. 1983. Structural properties of cellulose and cellulase reaction mechanism. Biotechnol. Bioeng. *25:* 33–51.

Mackie, D.M., and P. Joyce. 1987. CTMP/CTLF-A flexible mechanical pulping process. Pulp and Paper Science *13:* J77–J81.

McGovern, J.N. 1990, Fibers, Vegetables *In:* Polymers: Fibers and Textiles, A Compendium Ed. J.L. Kroschwitz, John Wiley & Sons, New York, pp. 412–430

McGovern, J.N., D.E. Coffelt, A.M. Hurter, N.K. Ahuja and A. Wiedermann. 1983. Other Fibers. *In:* Pulp and Paper Manufacture. Ed. M.J. Kocurek. Joint Textbook Committee of the Papier Industry, Tappi. Atlanta, GA, pp. 110–121.

Pommier, J-C, J.L. Fuentes and G. Goma. 1989. Using enzymes to improve the process and the product quality in the recycled paper industry. Tappi J. *72* (6): 187–191.

Preston, R.D. 1963. Observed fine structure in plant fibers. *In:* Fiber Structure. Eds. J.W.S. Hearle and R.H. Peters. Butterworth & Co., London, pp 235–268.

Sabharwal, H.S., M. Akhtar, R.A. Blanchette and R.A. Young. 1994. Biomechanical pulping of kenaf. Tappi J. *77* (12), 105–112.

Sachs, I.B., R.A. Blanchette, K.R. Cease, and G.F. Leatham. 1991. Effect of wood particle size on fungal growth in a model biomechanical pulping process. Wood and Fiber Science *23:* 363–37.

Yashinori, K., N. Tomoaki, T. Yoshimasa, F. Koki, K. Ryuichiro, and S. Kokki. 1993. Biomechanical pulping using white-rot fungus IZU-154 Tappi J. *76* (12): 167–171.

Yu, H.S. and K.E. Eriksson. 1985. Influence of oxygen on the degradation of wood and straw by white-rot fungi. Svensk Papperstidn. *88:* R57–R60.

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Dr. H.S. Sabharwal
Prof. Raymond A. Young
Dept. of Forestry
University of Wisconsin
1630 Linden Drive
Madison, WI 53706–1598
U.S.A.

Dr. Masood Akhtar
Institute for Microbial and Biochemical Technology
USDA Forest Products-Laboratory
One Gifford Pinchot Drive
Madison, WI 53705.
U.S.A.

Prof. Robert A. Blanchette
Dept. of Plant Pathology
University of Minnesota
495 Borlaug Hall
St. Paul, MN 55108
U.S.A.

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