Biomechanical pulping of kenaf

Harmohinder S. Sabharwal, Masood Aktar, Robert A. Blanchette, and Raymond A. Young

ABSTRACT: Cut kenaf bast strands, untreated and treated with a CZ-3 strain of the white-rot fungus Ceriporiopsis subvermispora *(for two weeks), were refined in a laboratory single-disc refiner under atmospheric conditions. First-stage refining was carried to 530 mL CSF. Second-stage refining was carried out at various clearance levels to several degrees of freeness. Yields of 96% and 93% from kenaf bast by RMP and bio-RMP, respectively were higher than TMP and CTMP from whole kenaf as reported in the literature. The energy consumption in refining was substantially lower, and the strength properties were higher for the fungal-treated kenaf. The burst, tensile, and tear strengths increased by 65%, 58.3%, and 56.6%, respectively at about 200 mL CSF for tbe fungal-treated material The opacity and drainage properties were also superior for biomechanical kenaf pulp; however, the brightness level was lower. Scanning electron microscopy of fungal-treated kenaf bast strands after refining showed that fibers appeared to separate more readily from adjacent fibers than with noninoculated treatments.*

KEYWORDS: *Bast fibers, biotechnology, energy consumption, kenaf, mechanical properties, mechanical pulping, nonwood plants, pulp properties, refiner mechanical pulping, scanning electron microscopy, white rot fungi.*

The preservation of forests and increasing environmental awareness have focused research on exploration of new renewable fibrous resources and less toxic pulp and bleaching processes. The 12.9 million hectares (ha) of land needed to produce the 1990 global fiber requirements will almost double to 23 million ha in 2010 *(1)*. The use of nonwood plants for pulp and paper in the United States is almost negligible; although nearly 330 million tons are available. However, nonwood plants already account for 9.1% of the total world papermaking capacity (as of 1990) *(2)*. The average annual increase in nonwood plant fiber pulp capacity is more than double the average annual increase in wood pulp capacity, i.e., 4.7% vs. 2.0% for wood pulp.

There is a wide variety of nonwood plant fibers that can be used for papermaking. Kenaf *(Hibiscus cannabinus) is* a herbaceous plant of the family Malvacae, which is grown in many parts of the tropics and in some subtropical and warm temperate areas. The plant grows to a height of 3.7–5.5 m with a diameter of 25–51 mm. Kenaf yields in the southern United States are about 6 tons/acre/year, which is double the yield of southern pine. Also, the delivered cost of kenaf per ton of pulp is less than that of southern pine (see **Table I**) (3) The outer bark, or bast (the portion mainly used for cordage fiber), is about 40% of the stem by weight, and the inner woody core is about 60%. Fibers from the bast portion of the stem are about 2.5 mm long, similar to the size of softwood fibers, while those from the core are shorter, about 0.6 mm long, and resemble hardwood fibers.

A search for new fiber crops by the U.S. Department of Agriculture in the 1960s and 1970s identified

Sabharwal is a senior researcher and Young is a professor at the University of Wisconsin, Department of Forestry, 120 Russell Lab, Madison, WI 53706. Akhtar is a research scientist at the University of Wisconsin Biotechnology Center and Institute for Microbial and Biochemical Technology, USDA Forest Products Laboratory, 120 Russell Lab, Madison, WI 53705. Blanchette is a professor at the University of Minnesota, Department of Plant Pathology, St. Paul, MN 55106.

kenaf as a promising alternative fibrous raw material for papermaking *(4)*. Numerous studies since then have appeared on various pulping approaches, mainly for use of the whole plant and to some extent on the bast and core portions separately (5–7). Conventional soda and kraft pulping of whole kenaf yields pulps with strength properties somewhere between those of softwood and hardwood pulps. The chemical pulps from the bast compare favorably with those of softwood pulp, whereas chemical pulps from the core have relatively low tear strength but high tensile and burst strength when compared to hardwood pulps. Another unique characteristic of the production of kenaf bast chemical pulp is that only a fraction of the refining energy required for a softwood pulp is necessary to develop strength properties *(4)*.

The share of mechanical pulp in the United States is 10% compared to 21.4% for the rest of the world **(Figs. 1 and 2).** According to the National Council of the Paper Industry for Air & Stream Improvement (NCASI), environmental expenditures accounted for 11% of the total capital expenditure by U.S. pulp and paper mills in 1988 and 1989; this figure is expected to increase by 20% *(8)*. h increased share of mechanical pulp would, to some extent, mitigate the problem of environmental cleanup. The most frequently cited reasons for low mechanical pulp production are high energy cost and inferior pulp quality; these restrict pulp use to a limited number of paper grades.

Studies on mechanical pulping of kenaf on a laboratory scale were undertaken in the late 1970s in the United States *(9)*. It has recently been demonstrated that blends of 82-95% kenaf chemi-thermomechanical pulp (CTMP) with 5–18% kraft pulp can produce commercial grade newsprint *(10)*. A blend of 25% kenaf CTMP with 75% commercial deinked recycled pulp also produces acceptable newsprint *(11);* however, the production cost of CTMP is high. Studies on the atmospheric refiner mechanical pulping (RMP) and biorefiner mechanical pulping (BRMP) of kenaf bast were initiated to evaluate alternative envionmentally benign pulping approaches.

i. Comparison of wood and kenaf *(3)*

	Southern pine	*Kenaf*
Growing cycle, years	15–20	0.4–0.5
Average yield of dry fibrous material, tons/acre/year	3	6
Bleached yield, %	43	46
Delivered cost of fibrous raw material, US$/ton pulp	120–180	100–120

* Average of core and bark

The effect of fungi, especially white-rot fungi, on wood was systemically studied by Campbell in the 1930s *(1.2)*. However, the advantage of using fungal treatment prior to mechanical refining of wood with beneficial results first appeared in 1982 *(13)*. This was followed by more convincing evidence by Akamatsu *(14)*, who found that ten different white-rot fungi decreased the mechanical pulping energy and three of the ten fungi increased paper strength properties. Considerable energy savings and enhancement of strength properties were realized by using a strain of white-rot fungi known as *Ceriporiopsis subvermispora (15)*. More recently, an unidentified white-rot fungus treatment (IZU- 154) of coarse hardwood mechanical pulp for seven days reduced the refiring energy requirement by one-half to two-thirds and improved pulp strength properties by a factor of two *(16)*.

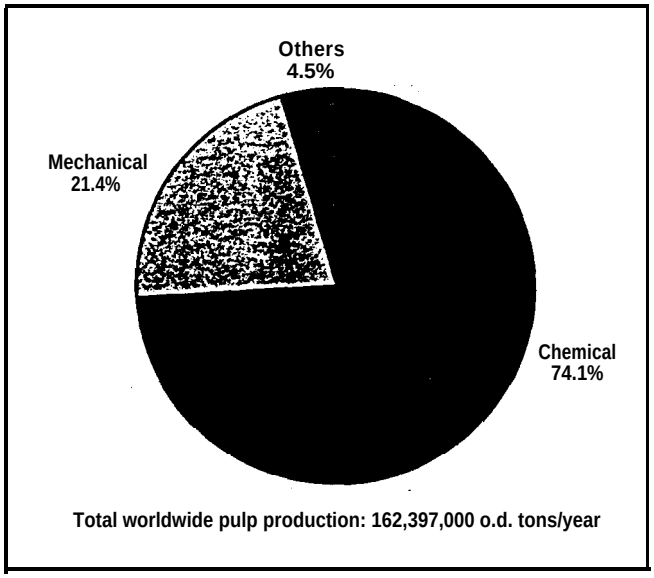
Little is known about the use of fungi for mechanical pulping of nonwood plants. Enzymatic pulping of mitsumata bast fibers by microbial polysaccharides has been shown to produce pulps with reasonable strength properties *(17)*. Efficient delignification of wheat straw by *Panus conchatus*, a white-rot fungus, has also been demonstrated. Up to 24.7% water-soluble modified lignin was released from the wheat straw by this fungus after three days of inoculation *(18)*. *Panus conchatus* has also shown great promise for biopulping of rice straw, where it selectively attacks the middle lamella, facilitating fiber separation. No cell wall thinning or cellulose degradation was reported *(19)*. Selective delignification of wheat straw by *Pleurotus eryngii* has also recently been reported *(20)*.

Experimental

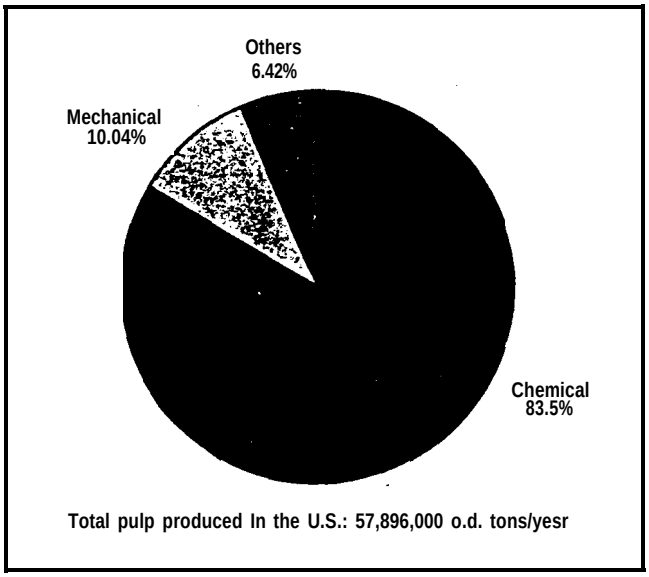
Refining

Atmospheric refiningwas carried out in a 12 -in. 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

1. Distribution of pulps produced by various processes in the world



2. Distribution of pulps produced by various processes in the United States



at 2600 rpm. Kenaf bast fibers (2–4 cm) were used in the experiments. Primary-stage refining was carried out at a feed rate of 250 g/min (366 kg/day) at 0.02 in. clearance with a resulting CSF of 530 mL. The discharge consistency was maintained at 1–2%. Sufficient pulp was obtained from the primary-stage refining for secondary-stage refining at various clearance levels to obtain pulp at several freeness levels. The secondary-stage refining was carried out at 10% consistency, and feed rate was maintained at 600 g/min (864 kg/day). The energy consumption was measured by a watt meter attached to the power supply of the driving electric motor.

Fungus

Ceriporiopsis subvermispora (Fil.) was selected for this study, because of its greater lignin selectivity *(21, 22)* and superior biopulping performance compared to other fungi *(23)*. Strain CZ-3 of this fungus was selected based on its superior biopulping performance compared to the other strains *(24)*. The strain was obtained from the University of Wisconsin, Center for Mycology Research, Forest Products Laboratory, Madison. WI.

Inoculum preparation

The fungal culture was maintained on potato dextrose agar (PDA) (Difco Laboratories, Detroit, MI) 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 330 mL of water containing potato dextrose broth [(7.2 g) Difco Laboratories, Detroit, MI] and yeast extract [(2.18 g) Amberex 1003, Universal Foods Corp., Milwaukee, WI]. This medium was poured into a 2.8-L flask. The Fernbatch flask containing the medium was covered with aluminum foil and autoclaved for 20 min at 121°C and 15 psi. After cooling to room temperature, the flask was inoculated with 30 plugs cut with a 9-mm-diam. borer 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 was washed with sterile distilled water and then blended aseptically in a Waring blender. Sterile water was then added to the blended mycelium to bring the total volume of the suspension to 100 mL. Twenty-five grams of this suspension (0.1% fungus on a dry weight basis) was added to the medium prior to inoculation.

Medium preparation

A glucose-containing medium as previously described *(25)* was used to increase the fungal biomass and suppress cellulose degradation. The medium was added in two bioreactors (one for control and the other with treatment) in sufficient quantity to bring the moisture content to about 80% on a wet weight basis. Each bioreactor contained about 350 g of kenaf (sterilized by autoclaving) on an oven-dry weight basis. The bioreactor used in this study was described in a previous publication *(26)*.

Pulp testing

TAPPI Test Methods were used to evaluate all of the pulps after removing the latency by the standard method.

Scanning electron microscopy

Samples of inoculated and noninoculated kenaf bast strands were infiltrated with water and frozen in a microtome at –20°C. Transverse sections were made through the strands to provide a clear-cut surface, and

	Clearance, in.	CSF, mL	Energy consumption, kW·h/ton o.d. pulp	Energy saving, %	Cumulative energy saving, %
Untreated					
Primary stage	0.020	500	800	-	-
Secondary stage	0.005	325	885	-	-
Secondary stage	0.003	218	1080	-	-
Secondary stage	0.002	110	1170	-	-
Fungal-treated					
Primary stage	0.020	486	500	37.5	37.5
Secondary stage	0.005	355	565	23.5	36.2
Secondary stage	0.003	202	780	Nil	27.7
Secondary stage	0.002	142	830	10.8	29.0

III. Comparison of kenaf bast, whole kenaf, and southern pine mechanical pulp properties

	C.E. Bauer 36-in. refiner (32)			12-in. Sprout Waldron single-disc refiner	
Characteristic	Whole kenaf		Southern pine	Kenaf bast	Fungal-treated kenaf bast
Pulp type	TMP	CTMP	TMP	RMP	RMP
CSF, mL	117	60	85	218	202
Yield, %	91	86	95	96	93
Power, kW·h/a.d. ton pulp	1888	1611	2472	1080*	780*
Burst index, kPa·m²/g	0.9	1.7	1.5	2.0	3.3
Breaking length, km	2.8	3.9	3.4	3.4	5.4
Tear index, mN·m²/g	6.3	8.0	9.7	6.0	9.4
Opacity, %	98	93	92	99	98
Brightness, %	47	66	54	28	30

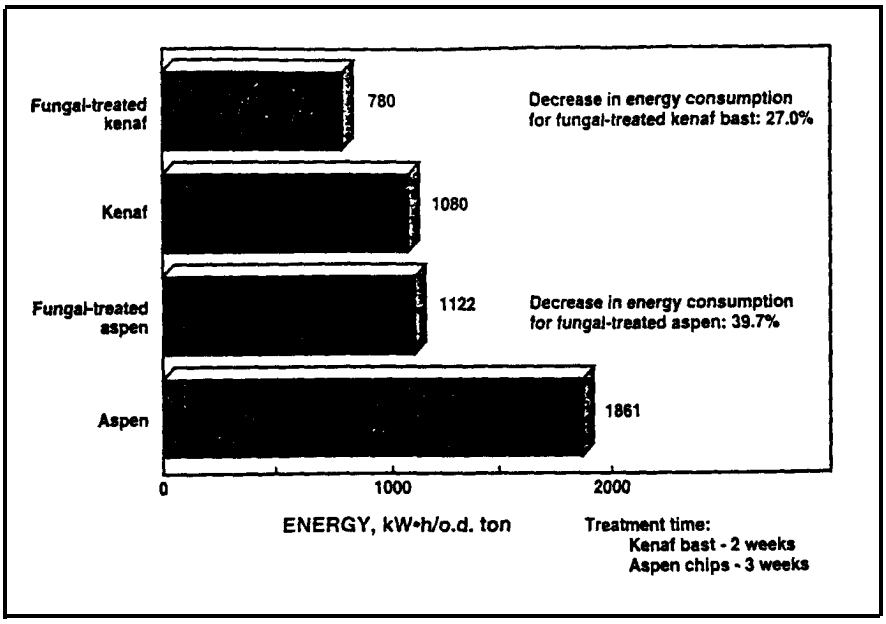
*kW·h/o.d. ton pulp

the material was allowed to air dry on the aluminum stubs used for scanning electron microscopy. Specimens were coated with 40% gold and 60% palladium and examined with a Hitachi 450 scanning electron microscope.

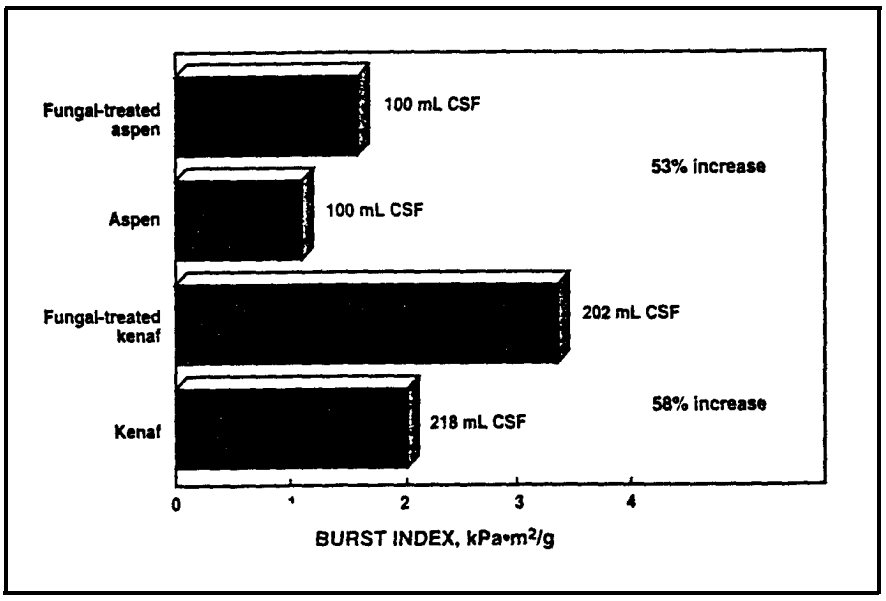
Results and discussion

Refining involves the repeated compression and relaxation of the plant material and fibers in water provided by the bars and grooves of refiner discs. This results in both energy consumption and mechanical disruption of the middle lamellae that bonds the secondary walls of woody cells *(27)*. The refining process can be augmented by pressure and temperature using processes known as pressurized refiner mechanical pulping and thermomechanical pulping. Low-density, long fibers and large lumen size enhance the compressibility of the material in mechanical refining. Kenaf bast material has these qualities and should respond better than wood to refiner mechanical pulping. Two factors that distinguish kenaf bast from woody materials are the orientation of the fibrils and the lignin content. The fibrils of bast fibers lie generally parallel to the fiber axis, unlike wood fibers whose fibrils are spirally

3. Comparative energy consumption for refining of aspen wood and kenaf bast



4. Comparative burst index of pulps from untreated and fungal-treated aspen and kenaf bast



wound. The kenaf bast fibers can therefore be split lengthwise by mechanical action to yield fine, relatively long fibrous threads *(28)*. The lignin content of kenaf is as low as 7.7% *(29)*. Both these factors should make less-drastic approaches possible for mechanical pulping of kenaf.

Another difference between kenaf and wood is the very high hot-water volubility (17%)*(30)* and 1% NaOH volubility (15-20%) of kenaf *(31)*. Therefore, any thermal or chemithermomechanical pulping process used with kenaf may result in considerable loss of yield. The present investigation was undertaken (a) to determine if these special characteristics would be advantageous in atmospheric refiner mechanical pulping of kenaf and (b) to see if the same features would render kenaf more susceptible to fungal treatment by known fungal strains. The main focus was to evaluate energy consumption at various stages of refining, before and after fungal treatment, and to determine the effect on the strength properties.

The refiner mechanical pulping and biorefiner mechanical pulping of kenaf bast in our investigation gave 96% and 93% yields, respectively, which are more than the yield obtained for TMP and CTMP from whole kenaf *(32)*.

Energy consumption

The energy consumption data in **Table II** show that nearly 68% of the total energy required to obtain a kenaf refiner mechanical pulp at 110 mL CSF was consumed in the primary stage. However, energy consumption varies widely with conditions, and data given in the literature are seldom comparable. The heat generated from atmospheric RMP of kenaf bast was sufficient to partially soften the lignin, although there was still considerable energy consumption at this stage. The low lignin content and large lumen size have a more beneficial effect during the second-stage refining. However, the overall energy consumption, as compared to TMP and CTMP from whole kenaf and TMP from southern pine, is far less **(Table III).**

The energy consumption of fungal-treated kenaf bast during the primary refining stage was 60% of the total energy required to obtain pulp at 142 mL CSF. Maximum energy savings of 37.6% and 23.5% were realized in the primary refining stage and the initial stage of secondary refining, respectively, when the pulp was still coarse. This suggests that the fungal attack was primarily in the region of middle lamella, where it modified the region, thereby making the separation of fibers easier. It has also been reported that white-rot fungus attacks the middle lamella in rice husk *(19)*. The cumulative energy savings at a level of 202 mL CSF, where optimum strength properties were obtained, was 27.7%. A comparison of

IV. Strength and optical properties of pulps from untreated and fungal-treated kenaf bast fiber

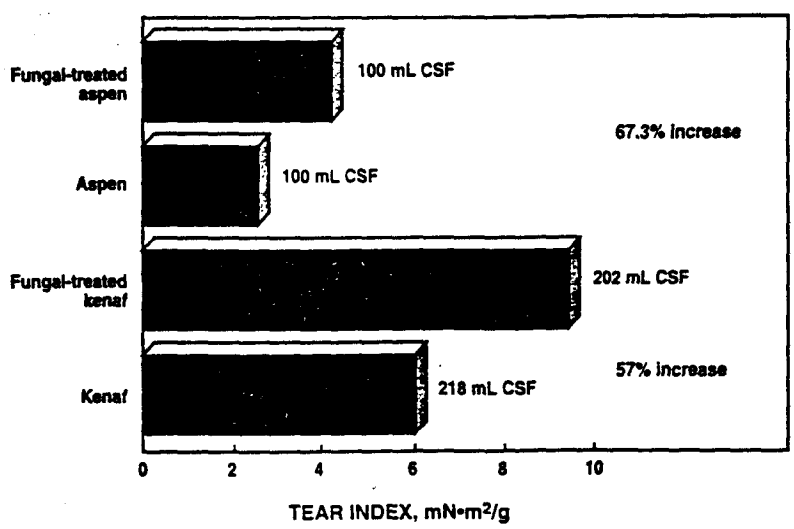
Sample	CSF, mL	Caliper, μm	Bulk App. density, cm³/g	Bulk App. density, g/cm³	Burst index, kPa-m²/g	Tensile index, N·m/g	Tear index, mN·m²/g	Brightness, %	Opacity, %	Light-scattering coefficient, m²/kg
Control										
	500	174	2.74	0.36	1.8	26.9	7.2	28	99.0	31
	218	154	2.42	0.41	2.0	33.6	6.0	29	99.3	35
Fungal-treated										
	486	154	2.49	0.40	2.6	33.6	11.8	34	96.1	32
	202	146	2.33	0.43	3.3	53.2	9.4	31	98.3	35
	142	143	2.30	0.43	3.0	46.0	8.2	33	98.4	38

Strength improvement, %	Burst	Tensile	Tear
At 500 mL (untreated) vs. 486 mL (fungal-treated)	44	24.9	63.8
At 218 mL (untreated) vs. 202 mL (fungal-treated)	65	58.3	56.6

the reduction in energy consumption by *Ceriporiopsis subvermispora* treatment of aspen chips *(15)* and kenaf bast material shows that, although a greater reduction in energy consumption (39.7%) was realized for aspen chips as compared to kenaf bast material (26%), the overall energy consumption is 30.5% less for fungal-treated kenaf bast material compared to treated aspen **(Fig. 3).**

Pulps obtained from untreated kenaf at 110-150 mL CSF were very slow draining, whereas pulps obtained from fungal-treated kenaf were not only easy to drain at low freeness levels, they also exhibited good strength properties. The effect of fungal treatment on the drainage characteristics of kenaf pulps is concordant with the earlier finding of Pommier *et al. (33),* who 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 *(34).* According to Pommier *et al.,* if the peeling effect is controlled, the enzyme will remove only a small amount of the components that have the greatest affinity for water, but do not contribute to the hydrogen bonding potential of the fibers. Thus, better pulp drainage is allowed without affecting the mechanical properties. The fungus strain CZ-3 of *C. subvermispora* used in our investigation possesses all these enzymes, i.e., cellulases, hemicellulases, and ligninase. The

5. Comparative tear index of pulps from untreated and fungal-treated aspen and kenaf bast



6. Scanning electron mlcrographs of untreated kenaf and kenaf pretreated with *Cerlporiopsis subvermispora* after refining to aoproximately 200 and 500 mL CSF

a and b: Untreated kenaf fibers refined to 218 mL CSF showing detached cells as well as groups of cells that remain unseparated (arrows).
c and d: Kenaf fibers that have been pretreated with *C. subvermispora* and refined to 202 mL CSF can be seen separated and detached from adjacent cells. Very few groups of cells remain attached after refining.
e: Untreated kenaf after refining to 500 mL CSF with groups of attached cells still evident (arrows).
f: Fungal-treated kenaf. refined to 486 mL CSF, showing well separated and detached fibers.
Bar=50 µm

cellulase enzyme activity, however, was suppressed in our investigation by adding sufficient glucose to the reaction mixture to avoid cellulose degradation. The other enzymes were free to act without inhibition.

Strength and optical properties

The strength properties of refiner mechanical pulps from untreated kenaf bast at a freeness of 500 mL CSF were comparable with TMP from whole kenaf at 117 mL CSF, with the exception of burst strength, which was twice that of TMP from whole kenaf. The strength properties at 218 mL CSF were comparable with CTMP from whole kenaf at 60 mL CSF except in tear strength. Also, TMP from southern pine at 85 mL CSF had lower burst but higher tear strength compared to pulp from untreated kenaf bast at 218 mL CSF, as shown in Table III and **Table IV.**

A comparison of RMP pulps from untreated and treated kenaf bast indicates that fungal-treated kenaf yielded pulps with strength properties much greater than the pulps from untreated kenaf bast at all the freeness levels. The increase in burst, tensile, and tear strength was 44%, 24.9%, and 63.8%, respectively, in the range of 480–500 mL CSF; the increase was 65%, 58.3%, and 56.6% for tensile, burst, and tear strength, respectively, in the range of 200–220 mL CSF. The drainage rate of pulps from untreated kenaf at 100–140 mL CSF was too low, and the pulps were rejected at these levels. On the contrary, the drainage rate of pulps obtained from fungal-treated kenaf bast at this freeness level were not only easy to drain, but formed sheets having good strength properties.

The significant enhancement in strength properties realized from fungal treatment of plant material has also been reported in many previous investigations. Treatment of aspen chips with *Ceriporiopsis subvermispora (15)* for three weeks followed by pressurized refiner mechanical pulping resulted in enhancement of burst and tear strengths by 53% and 67.3%, respectively. In comparison, the kenaf bast treatment was applied for two weeks followed by standard atmospheric refining; it resulted in enhancement of burst and tear strengths by 58% and 57%, respectively, as shown in Figs. 4 and 5. The softening of the middle lamella and subsequently controlled fibrillation, which restricts the formation of fines, is believed to be responsible

for the enhancement of the strength properties.

The optical properties invariably suffer from fungal treatment. However, considerable variation has been reported in brightness depending upon the source of kenaf *(35)*. A slight increase in the brightness value of pulp obtained from fungal-treated kenaf may be a result of hyphae left in the pulp. However, the brightness is considerably lower compared to pulps from whole kenaf and southern pine pulp, as shown in Tables III and IV. The opacity values were comparable to values reported in the literature.

Scanning electron microscopy of untreated kenaf fibers refined to 218 mL CSF **(Figs. 6A and 6B)** shows detached cells and groups of cells that remain unseparated (denoted by arrows). Kenaf fibers that have been pretreated- with *C. subvermispora* and refined to 202 mL CSF are separated and detached from adjacent cells, with very few groups remaining attached after refining **(Figs. 6C and 6D).** After refining to 500 mL CSF, untreated kenaf **(Fig. 6E)** shows groups of cells attached (see arrows), whereas fungal-treated kenaf refined to 486 mL CSF shows well separated and detached fibers **(Fig. 6F).**

Conclusions

The following conclusions were drawn from our work

- Kenaf bast material does not require pressurized or thermomechanical pulping processes to produce acceptable pulps.
- The energy requirement for kenaf during the defiberization stage is 60% of the total refining energy required to achieve 150 mL CSF, compared to 33% for wood.
- A strain of *Ceriporiopsis subvermispora* CZ-3, appears to modify the cell wall and middle lamella of kenaf bast fibers, which results in considerable savings in energy consumption in refiner treatment and enhanced strength properties of the pulps.
- If kenaf bast were to completely replace wood for mechanical pulping processes in the United States, a net energy saving of 4.64 billion kW·h/year would be anticipated.
- The biomechanical approach for bast fibers provides a new class of pulps with properties between mechanical and chemical pulps. These new pulps may be substituted for chemimechanical pulps. TJ

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