KENAF AND OTHER NONWOOD SPECIES FOR PAPERMAKING

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Sociologic, technologic, and economic progress of the world during the past 19 centuries has been so closely associated with the production of paper that we must continually search for new sources of fibers with which to meet the increasing needs for that commodity. Historically, agricultural fibers were the first source of material for papermaking. Currently, wood is the major basic raw material for the production of pulp and paper. Nonwood pulps account for about 3% of the total tonnage of paper produced in the United States and about 5% of the world production[1].

Already many areas of the world are deficient in the forest resources required to provide pulpwood for a rapidly expanding economy. Fortunately, cellulosic fibers represent a major structural component of most plants; consequently, nonwood species represent a huge reservoir of undeveloped raw materials. Limited availability or complete absence of indigenous pulpwoods justifies resorting to these nonwood species as sources of fibers for papermaking. Many countries already rely on renewable sources of cellulosic fibers; e.g., sugarcane bagasse, straws, bamboos, esparto grass, and others that might be produced within a given region. However, even the quantity of a single species of a nonwood may not be adequate to meet all needs. Such a situation exists in India where stands of bamboo are insufficient to meet the increasing demands for pulp and paper products. India's need for other sources of nonwood fibrous materials has been discussed repeatedly in issues of *Indian Pulp and Paper*[2-7]. Statistical data about pulp production and consumption throughout the world, as reported in the review issue of *Pulp and Paper International*[8] reveal the direction and extent of pulp flow in world commerce. The disparity between pulp production and population indicates imbalances that could be well corrected by use of supplementary fibers, especially from nonwood plants.

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SUMMARY

Papermaking fibers from timber sources can be successfully supplemented by fibers from nonwood species. At present, available supplies of such fibrous materials as cereal grain straws, sugarcane bagasse, and bamboo are inadequate to meet the increasing demand for more fibers. Fiber screening and developmental reserch offer prospects of finding annually replenishable plant species that have potential use by the pulping industry. The Malvaceae, Gramineae, and Leguminosae provide the greatest promise as sources of useful fibrous species. Results of research on evaluation of green and field-dried stalks of kenaf, Hibiscus cannabinus, on development of storage and processing techniques, and on conversion of pulps to papers, indicate that this species has good opportunity for industrial acceptance in the United States. This species should also have good potential for India.

Even with its vast forest lands, the United States must take heed of its fiber resources for pulping. Greeley[9], of the U.S. Forest Service, has stated that the anticipated increase in pulpwood consumption in the United States will probably result in timber demands exceeding supply around 1980. This situation would be reached 10 years sooner than predicted in the 1965 Forest Resource Report 17. 'Timber Trends in the United States"[10]. For his forecast Greeley has assumed that the harvest of nonpulp timber products and the level of forest management will remain as indicated in the earlier study. However, it seems unlikely that these factors will remain static. The continuing growth in all segments of the pulp and paper market will aggravate the increasing demands placed on the industry. Many studies on pulpwood availability have been made but while statistics point to a generally adequate overall supply, the data fail to describe the situation for definite areas serving specific mills. For example, in some areas of southern United States reforestation is neither sufficiently effective in replenishing desirable hardwoods nor rapid enough to meet anticipated demand with any other acceptable species. Spier[11] pointed out in 1966 that many southern localities had reached the limit of their ability to sustain continued growth in pulp production.

Ability to use an annually replenishable plant to supplement available timber stock should permit continued mill expansions, as well as opportunity to devote greater attention to preservation and propagation of existing timber stands. When we consider the time usually needed for reforestation, the waiting period before harvesting can begin is quite significant. The concept for use of annual plants assumes, of course, that the selected species will have characteristics necessary for pulp and papermaking. Furthermore, the crop must be economically competitive with other fibrous materials, as well as with foods and feedstuffs.

STRAW

Rags from cotton and linen formed the backbone of the early paper industry. While these materials provide good papermaking fibers, their supply was not inexhaustible. Today it is difficult to find rags that do not contain an appreciable amount of some synthetic fiber and resins that render them unsuitable for papermaking. Since the mid-18th Century, much experimentation (originally in Europe) has been conducted to find replacement and supplemental materials to augment the supply of rags. In the United States, Magaw's successful experiments on pulping straw with leachings of wood ashes in 1827 led to commercial chemical pulping[12]. Although wood was introduced as a pulping raw material in the mid-19th Century, the straw-based industry continued to expand Straw container board was a quality product. Grain straw is also one of the recognized raw materials regularly used in India.

At present straw pulp has essentially disappeared in the United States for the following reasons :

(i) Introduction of the combine harvester for cereal grains meant a separate harvest for the straw. Sometimes this separate harvest was not possible because of adverse weather.

(ii) Genetic improvement produced wheat varieties with short stems and reduced the availability of straw.

(iii) Increased return of chopped straw to the soil when effective means for applying nitrogen to it were introduced.

(iv) High labor and transportation charges per unit straw solids.

(v) Storage and preservation problems. These are closely associated with labor charges.

(vi) Failure to achieve and maintain peak production efficiency at minimum cost by mill modernization.

Despite a similar trend that appears to be developing in a few other countries, continued new and expanded use of cereal grain straws is generally evident through out the world[12]. A modern mill for semi-chemical pulping of straw is operating in Denmark. Several new straw pulp mills have been constructed in Eastern Europe. Rumania's new straw pulp mill reportedly has a 160 tons per day capacity. The Hungarian operation at Dunavjvaros has a pulp capacity of 20,000 metric tons per year. The Szolnok mill uses both wheat and rice straw to produce about 9,000 metric tons per year of bleached pulp. Batchwise, soda pulping of rice straw at Tabia, near Alexandria, Egypt, produces about 60 metric tons per day of bleached pulp. Rice straw is also the principal raw material for several mills in Indonesia. Investigators at Dehra Dun, India have studied the use of rice straw soda pulp from pressure cooking in the preparation of white printing papers[13]. At the Northern Regional Laboratory, both pressure and Mechano-Chemical techniques were used to prepare pulps from rice straw. The latter process was instrumental in reducing the ash content to less than 5.0%; whereas, the kraft pressure technique resulted in ash values of greater than 12.0%. Lower lignin content and better bleachability were realized with the pressure technique. The hydrapulper used for cooking also removed debris and trash from the original straw before pulping[14].

SUGARCANE BAGASSE

Sugarcane, *Saccharum officinarum*, is a grass grown in most tropical and subtropical regions of the world. Bagasse from the cane received its first attention in 1844 when it was shipped from the Isle of Martinique to France as a raw material from which to prepare newsprint[12]. However, it was almost 100 years before the technology of processing bagasse to pulp could be considered commercially successful and mills were established in Peru, Formosa, and the Philippines Ready availability at central locations; i.e , the cane mill where the sucrose is extracted, has made sugarcane quite inviting as a fiber source for papermaking. In recent years, it has received more consideration for use in pulp and paper than any other nonwoody plant. Atchison has reviewed bagasse usage extensively[15].

Production and milling of sugarcane for sucrose do not, however, provide immediate assurance of bagasse availability for papermaking. First, it has been so often the normal fuel for cane mill boilers that heat requirements of the mill govern the extent to which it may be released for pulping. Frequently, just improving efficiency in boiler-firing releases a substantial portion of the bagasse. Availability and favourable cost of alternate boiler fuels; e.g., gas, oil, or coal, may release the entire bagasse production for use by a pulp mill. Secondly, the seasonal nature of cane grinding greatly influences the periods of bagasse availability. Interruptions in harvesting and processing sugarcane necessitate bagasse storage to sustain pulp mill operation throughout the year.

Two basic procedures are followed to maintain bagasse supplies over extended periods : (i) baling and storing in ricks as described by Chapman[16] and (ii) wet storage in bulk on concrete slabs. This latter technique is increasingly favoured over baling and, sometimes, includes adding an acid-forming microbial inoculum that aids in preserving the bagasse by inhibit ing deterioration due to other biological agents[17]. As in any situation where alternative procedures are possible, consideration must be given to labor and equipment required, cost of operations, effectiveness of preservation, and quality of the products.

Problems associated with baling and storage of bagasse are : (i) the high moisture content as it comes from the sugar mill, (ii) the requirement for rapid handling to avoid spoilage, (iii) heavy-duty equipment necessary to minimize down time, and (iv) need for large volumes of temporary labor during baling and storage. Baled wet bagasse has sufficient sugar to nurture an effective fermentation. Heat generated tends to dry the bale, but inefficient heat dissipation may cause spontaneous fires. The costs of labour, of efficient baling stations, and of shelter from rain make this procedure less desirable. Preservation of bales might be improved by treating with boric acid or borascu as has been done with straw. These chemicals retard fermentation and deterioration.

In bulk storage with continuous wetting, the bagasse is maintained in a saturated condition on a concrete slab. This procedure results in a nearly anaerobic treatment. The normal microbial flora in the bagasse may promote a favourable fermentation. Alternatively, in the Ritter process[17], the desired microbial action is achieved by addition of a "biological fluid." In each procedure, sugars are removed by fermentation, and then as needed the bagasse is sluiced to the processing area. This storage procedure generally yields a bright high-freeness pulp with improved burst strength and folding endurance. Wet storage prevents development of conditions that lead to bagassosis, a pulmonary infection sometimes suffered by workers handling dry, dusty bagasse.

As a typical member of the grass family, sugarcane has a physical structure consisting of three principal components : (i) the rind including the epidermis, cortex, and pericycle; (ii) the vascular fibre bundles comprising thin-walled conducting cells accompanied by crelatively thick-walled fiber with narrow lumen: and (iii) ground tissue (parenchyma) or pith in which the fiber bundles are embedded randomly. The relative proportions of these constituents vary with variety of cane, type of soil, climatic conditions, length of growing season, and other agronomic factors. The rind and vascular bundles have woody characteristics and exhibit an absorptive capacity for water equivalent to about five times their own weight, whereas the pith portion has an absorbency of about 30 times[18]. Lengths of bagasse fibers, averaging about 1.7mm, are similar to those of hardwoods but are shorter than those of coniferous woods. Dimensional data for fibers, parenchyma, and vessel segments of bagasse are given, together with some data for woods of the temperate zones, in **Table 1.**

Ranges in chemical composition of whole bagasse, separated fiber, and pith for sugarcanes from five widely scattered geographic locations are given in **Table 2**. The compositional data for the component fibers and pith fractions are remarkably similar to those for the whole material from the five locations. Separated fibers, of course, have higher cellulosic contents than whole bagasse or pith. The fibers are also slightly lower in ash. In addition, the quantities of hot-water and alcohol-benzene extractives from whole bagasse are greater than for isolated pith because these solubles are removed during wet separation. Effects of differences in length of growing seasons are reflected in the range of data. In regions where the growing season is long, the contents of lignin pentosans, Cross and Bevan cellulose, and cellulose produced are greater than those found in samples from areas with shorter growing seasons.

Initially, successful use of bagasse was hindered because of disregard for its pith content. After passing cane through sugar mill rolls, the ruptured pith cells pick up and retain dirt and other extraneous matter. These contaminants create an excessive demand for chemicals during cooking and bleaching. Pulps high in pith are slow-draining, deficient in strength properties, and lacking in brightness and generally good appearance associated with high-grade printing and writing papers. Advantages of pith removal are shown by data for pulps and pulp strength in table III. Several procedures for effective depithing have been developed, and some are now part of commercial operations. Basically, there are three methods: (i) dry depithing at 15 tó 20%

TABLE 1 DIMENSIONAL CHARACTERISTICS OF BAGASSE AND WOODS

Cellulosic material	Length, mm			Diameter, μ			Ratio average to length diameter
	Min.	Av.	Max.	Min.	Av.	Max.	
Sugarcane fibers	0.80	1.70	2.80	10.2	20.0	34.1	85.1
Parenchyma	—	—	0.84	—	—	140.0	—
Vessel segments	—	—	1.35	—	—	150.0	—
Temperate coniferous woods	1.2	—	7.3	22	—	50	75.1
Temperate deciduous woods	0.3	—	2.7	10	—	46	50:1

(Source : "Pulp and Paper Prospects in Latin America." pp. 256, 295, United Nations, New York, 1955.)

TABLE II RANGE OF PROXIMATE CHEMICAL COMPOSITION OF WHOLE BAGASSE, BAGASSE FIBER, AND BAGASSE PITH FROM SUGARCANE REPRESENTING FIVE GEOGRAPHIC SOURCES, %

Material	Cellulose		Pentosans	Lignin	Ash	Extractives		
	Cross & Bevan	Alpha				Hot water	Alcohol-benzene	1% NaOH
Whole bagasse								
Min.	50.2	30.1	27.7	18.1	2.2	2.8	3.2	27.3
Max.	56.8	34.9	31.8	22.3	5.4	11.2	10.8	39.9
Depithed fibers								
Min.	56.0	36.7	30.7	19.1	1.2	1.4	2.0	26.8
Max.	62.9	41.2	32.5	21.8	2.2	4.5	3.6	31.2
Bagasse pith								
Min.	52.5	30.6	30.7	18.0	2.6	1.5	2.1	30.3
Max.	55.4	34.9	33.2	22.5	6.3	4.6	2.9	36.2

(Adapted from U.S. Dep. Agr. Mimeo Cir. ARS-71-4, March 1965.)

TABLE III CHEMICAL ANALYSIS AND PULP CHARACTERISTICS[a] OF BAGASSE AND SEPARATED BAGASSE FIBER

Source and form of bagasse	Screened pulp				Bleaching[b]		Strength characteristic at 500 ml S.R.				
	Yield %	Ash %	Lignin %	Pentosan %	Chlorine consumed %	Yield %	Initial, S.R. freeness, ml	Burst factor g/cm²/gm²	Breaking length m	Tear factor g/gm²	Folding endurance Schopper
Formosa											
Whole	49.1	1.2	4.4	33.8	15.5	43.6	800	43.9	8,190	38	280
Fiber	56.3	0.9	2.8	33.8	9.2	52.1	840	46.9	8,800	40	520
Florida											
Whole	42.3	1.6	5.5	31.5	26.8	33.8	750	54.4	9,470	43	580
Fiber	55.8	1.3	3.2	31.7	8.7	51.0	810	57.4	8,800	45	680
Hawaii											
Whole	47.6	3.0	4.6	26.5	18.8[c]	37.5	810	40.4	5,870	44	80
Fiber	52.2	1.5	2.7	32.0	2.7[c]	49.0	850	48.4	7,950	51	580
Louisiana											
Whole	52.5	1.5	4.3	32.1	8.6	48.9	800	43.9	7,900	35	330
Fiber	59.9	1.5	3.4	33.0	5.1	56.8	820	51.9	8,990	37	620

[a]Cooking conditions : 10.2% active alkali, 33.9% sulfidity, 1 hr, 170°C,
[b]Brightness 70, Hunter.
[c]Three stages.
Adapted from Ernst, A. J., Nelson, G. H., and Knapp, S. B., Tappi *40* : 873, 1957.

moisture content, performed with stored baled bagasse; (ii) humid or moist depithing, performed with bagasse at about 50% moisture content, as it comes from the cane mill, and (iii) wet depithing, usually conducted with bagasse coming directly from the cane mill. Wet depithing may also be performed with stored bagasse.

Generally, some combination of these procedures is used commercially.

Dry depithing is achieved by breaking up the bagasse in a disintegrator, passing the broken material over a series of classifying screens, and then through air separators to remove the pith from the fiber. About one-half to two-thirds of the pith is removed by this technique, but an appreciable amount of fiber is also lost.

Humid or moist depithing is done in modified hammer mills or disintegrators with special screen cages to loosen pith from fiber before screening. Applicable equipment includes verticalshafted Rietz disintegrators, Buffalo depithers, and Horkel machines. This treatment removes two-thirds or more of the pith. The pith from both this and the dry process is suitable for direct return to the cane mill boilers.

Equipment and techniques for wet depithing vary. Usually a 10% consistency is suitable for wet separation. The techniques developed at the Northern Regional Laboratory[19] were designed to accommodate either fresh bagasse from the cane mill or dried baled material. When fresh bagasse is to be depithed, the moisture content is increased to about 75% before the bagasse is passed between waveline plates in a disk mill. Dried bagasse is crumbled and then wetted by steaming before milling. Disk milling causes vigorous rubbing between particles to loosen pith from fiber bundles. The milled bagasse is then dewatered to about 50%. The expelled liquid contains about two-thirds of the sugar that remained in the bagasse as it left the cane mill. This solution can be sent back to the cane mill for recovery of sucrose. The compacted fibrous mass may be screened at 50% moisture content or dried to about 15% moisture in a rotary dryer before screening to remove the pith. At 50% moisture the pith may be returned directly to the cane mill boilers. Dry pith may be used as an absorbent carrier for feed molasses added to cattle rations.

Baled bagasse, when stored, dries to an equilibrium moisture content within 6 months of baling because of the heat generated by fermentation of residual sucrose. Dried bagasse resists wetting and is difficult to disintegrate. This bagasse can be prepared for depithing by passage through a bale breaker to loosen and fluff the particles. Loosened pith is removed by dry screening, and the fibrous portion is slurried to about 8% consistency in a vortex pulper, such as a Hydrapulper with a solid bottom. When consistency, size of charge, rotor speed, and vane size (medium high, $2\frac{1}{4}$ cm in a 91 cm diameter unit) are coordinated, a vortex is formed and bagasse rolls down this vortex that develops a rubbing action between the pieces. After a period of circulation, perhaps 20 min, the slurry is dumped into a chest, diluted to 1% consistency, and pumped to Jonsson screens with perforated plates having openings of 0.156 and 0.095 in. diameter. Fines passing the larger openings move to the plate with the smaller perforations. The fibers retained on both screens are combined, drained to about 20% consistency, and conveyed to the pulp mill. The pith would require dewatering at least to 50% consistency before it can serve as fuel.

Continuous depithing has been performed in Horkel machines to complete the operation after the Hydrapulper treatment. Continuous operations can also be achieved with two Horkel machines in series; dry depithing is performed in the first, followed by wet depithing of the fibrous material in the second.

In a process described by Villavicencio[20], initial depithing is done at the cane mill, and then the fiber-rich material is packed into bales of 250 lb for field curing. Forty days are sufficient for the cure. The low sucrose content of the fiber-rich material limits fermentation and consequently reduces fiber damage. Cured material is fluffed in a bale breaker before going to the pulp mill for further depithing. A hammermill-type unit is used. Swinging blades on the mill rotor develop a high level of turbulence in the screen chamber through which the fibrous mass moves parallel to the rotor axis. Loose pith is removed pneumatically through the screen.

The Cusi-San Cristobal process[21] starts with a screening to remove fines. The actual depithing is performed by closely controlled, high-speed mechanical scraping to preserve the quality of both pith and fibers. Pith is removed by screening. Its developer claims that this system provides a means of classifying bagasse fibers into an infinite number of fractions; however, for practical purposes fractions are generally limited to two. Thus, the most appropriate pulping procedure can be used with the various fiber fractions.

Recent trends in pulping bagasse have led to continuous pulping with soda or kraft liquors in tubular or tower-type digesters. Operation of a Pandia Chemipulper for continuous production of 100% bagasse pulp at Mandya National Paper has been described elsewhere [22]. These same techniques are being applied in increasing extent to other nonwood fibers Development of a techinque for mechanical processing of bagasse has been claimed to produce a groundwood-type pulp for newsprint service [23]. A few years back several reports indicated that this technique was being seriously considered in India[24-26].

BAMBOO

Bamboo is already being used extensively in India where, under present forestry practices, the productive limits of existing stands have been sorely strained. These stands can become more productive when harvesting of culms is done by swath cutting; i. e., harvesting alternate strips of perhaps 4 to 5 meters width so that the rhizomes and new culms in succeeding years can be nourished by the uncut plants. Harvesting cycles of 3 to 5 years would provide culms in nearly optimal condition for pulping. Although botanically members of the grass family, bamboos are quite unique in their physical characteristics. Once root systems are established, the culms grow rapidly and attain their full growth within the season. The hardening of the culm occurs over a 3 to 5 year period so that harvests should be within this time. Long-term agreements; e. g., 30-40 years, regarding the manner in which the stands will be maintained and harvested by mill operators are essential if bamboos are to continue as a primary source of fibrous material for papermaking. Better productivity in the field and easier handling of raw material would be two of the benefits that would be quickly realized.

In the past throughout Southeast Asia, bamboo has been used quite extensively as a pulping raw material but most frequently by methods that depend upon an abundance of inexpensive hand labor. In the past few years, handling and processing of this plant material have been changed so that bamboo is treated by modern techniques and even in continuous pulping equipment. This progress is well exemplified by several of the pulp and paper producers in India. Sometimes, batch cooking is still practiced[27-29]; in others, continuous cooking is performed in towers[30] or horizontal tube digesters [31]. Sometimes the digester charge is a mixture of chips from bamboo and hardwoods [30,32] and in at least one mill, the same cooking units are used for bamboo and for sugarcane bagasse [31]. Chemical recovery is essential for favorable economics, as well as reduction of pollution by mill effluents.

In India emphasis for commercial utilization is placed on *Bambusa arundinaria* and *Dendrocalamus strictus*. Because many of the other species are cold-tolerant and can withstand some of the wintertime temperatures in parts of the United States, some of these species are potential commercial crops. *Phyllostachys bambusoides*, the giant timber bamboo, has received considerable attention. *Arundinaria alpina* and *Guadua amplexifolia*, although found in tropical locations, are quite cold-resistant and also offer promise in the United States. In fig. 1 are shown strength indices[33] with respect to extent of refining for the *A. alpina* in comparison with those of other plant species. In this comparison the bamboo has been cooked under limited conditions so that its potential could not be fully evaluated. Results of investigations [34-37] conducted by the U.S. Department of Agriculture or sponsored under contract have already been published. Twelve species were investigated as part of a fiber screening program[38-40].

Culms of some species approach 15 cm in diameter and some grow as high as 30 meters. Bulkiness of culms for storage, because of hollowness, is partially compensated by a relatively high density of the culm walls (0.64 g/cc). More effective use of space is possible when culms are split or chipped before storing. Bulk density of bamboo chips range from 200 to 240 kg/m^3 compared to 150 to 200 kg/m^3 for southern pine[41]. Dimensions of ultimate fiber range from 3.0 to 4.0 mm long and about 14μ in diameter in contrast to 2.7 to 4.6 mm for softwood with thickness of about 40μ.

Figure—1 Photo Micrograph of Bagasse Chemi-Mechanical Pulp

FIBER SCREENING

Aside from the bamboos, we have so far discussed materials that accumulate as residues from the collection and processing of agricultural crops for their primary components. As research on residues was deemphasized, a concept of cultivating annual plants specifically for papermaking was introduced by the U.S. Department of Agriculture in 1956. Success in finding species with the necessary characteristics could promote stability in an agricultural economy in one or more of the following ways: (i) by providing farmers with a valuable and profitable crop, (ii) by permitting diversification of acreage as desired, (iii) by satisfying present and potential needs of industry, (iv) by providing a supply of strategic and critical raw materials, and (v) by replacing nonrenewable resources in the industrial market. The plant kingdom with a reservoir of about 250,000 species should provide ample opportunity for discovering those with industrial potential. Only about 0.1% has found any significant commercial outlet.

Analytical screening to discover and evaluate species as sources of papermaking fibers requires close collaboration between trained individuals representing many disciplines. Initially, botanists collected and evaluated plant species, most often from the wilds, for their potential agronomic capabilities. Those species having acceptable agronomic characteristics were then submitted to chemists and paper technologists for further evaluations. The various factors were assigned ratings according to their magnitude and totaled as shown in table IV[38]. Data for 387 species (44 families) have

TABLE IV SELECTION FACTORS AND RATING RANGES

Factors	Rating ranges
Agronomic potential	1-5
Chemical composition	1-3
Fiber length	1-3
Maceration yield	1-3
Individual assessment[a]	1-3

(Promising : sum = 5-8)[b]

[a]Appraisal of prpmising, questionable, or not promising by a panel of experienced personnel.
[b]Maximum potential, total 5 ; minimum, 17.
Adapted from Nieschlag *et ql.*[38].

been reported[38-40]. Species demonstrating greatest promise are mainly members of the Malvaceae (mallow), Gramineae (grass), and Leguminosae (legume) families. Occasionally an isolated promising species would show up in families such as Linaceae, Moraceae, and Typhaceae. Based on these initial appraisals, a number of species were examined further by laboratory-scale sulfate pulping with constant cooking conditions[33,42]. Indices representing pulp strengths for selected promising species are given in table V. Of the species investigated, members of the grass family (mostly bamboos) occupied the better positions in the listing. Dicotyledons with their bast fibers displayed better bursting strength and folding endurance than the Gramineae. The *Cannabis sativa*, common hemp, has promising field productivity, and its pulp has a good strength index. This particular value may not be directly comparable to the other indices in table V because of differences in preparation and refinding. In spite of the favorable technical factors, this species has little commercial potential as a pulp source in the United States because of restrictions against production of hemp.

Crotalaria juncea (Sunn hemp) exhibits good strength properties, but it suffers from variability in productivity and from a tendency to lodge. Resistance to lodging is essential for efficient mechanical harvesting. Seeds of some varieties contain a toxic factor so that widespread production might be hazardous to livestock. The culture of Sunn hemp in India and its utilization have been described by Kundu[43]. Crotalaria fibers are used in producing pulp for cigarette paper in at least one paper mill near Calcutta. Other crotalaria species common to India have been examined by chemical and pulping studies at the Regional Research Laboratory at Jammu-Tawi[44].

Sorghum almum has excellent drought resistance and is adaptable to cultivation on a wide variety of soil types. It is highly productive—annual yields of 25 metric tons per hectare can be harvested in some areas. Because this species is a forage crop, a substantial amount of the solids produced is foliage and this foliage does not contribute to good pulp properties. As a possible dual-purpose crop the foliage could be used for livestock feeding and the fibrous stalks for pulping.

That the genus *Hibiscus* is a good source of potential plant materials for papermaking is confirmed by the close grouping of indices for four species in **Table V.**

KENAF

Based on the preceding observations and cultural aspects, kenaf, *Hibiscus cannabinus*, was selected for detailed developmental studies. Although this species is grownwidely in India, often the term kenaf also implies *H. sabdariffa* or roselle which is grown much more extensively in India. However, of the two *H. cannabinus* is more productive, and the term kenaf will refer exclusively to this species in this review.

Kenaf is an herbaceous annual with straight slender stems often reaching heights of 5-6 meters or more. Basal diameters of the stems may reach 5 cm. Under a variety of local names[45,46], kenaf has long been cultivated in many parts of the world as a source of bast fibers. These fibers are similar to those of jute and constitute about 20% of the stalks dry weight. When considered for pulping, the interior woody portion of the stalk also needs to be used as a source of fiber for economic reasons.

TABLE V STRENGTH INDICES[a] FOR SULFATE PULPS[b] FROM SELECTED PLANT SPECIES

Species	Family	Strength indices
Stipa tenacissima	Gramineae	2,826
Cannabis sativa[c]	Moraceae	2,642
Guadua amplexifolia	Gramineae	2,609
Gynerium sagittatum	Gramineae	2,135
Phyllostachys bambusoides	Gramineae	2,091
Sinarundinaria murielae	Gramineae	2,038
Crotalaria juncea	Leguminosae	1,001
Hibiscus sabdariffa	Malvaceae	1,977
Hibiscus esculentus	Malvaceae	1,904
Hibiscus cannabinus	Malvaceae	1,895
Hibiscus eetveldeanus	Malvaceae	1,836
Triticum aestivum	Gramineae	1,808
Sorghum almum	Gramineae	1,722

[a]Strength index = 100 (burst factor X tear factor X log folding endurance)$^{1/3}$.
[b]Pulp preparation : 17.7% active alkali, 33.9 sulfidity, 2 hr, 170°C, and refined in Morden Stockmaker.
[c]Active alkali, 16.4%; sulfidity, 33.9%, Pulp was beater refined. Value at 600 ml S.R.
Source : Cunningham *et al.*[33].

TABLE VI CHEMICAL AND FIBER CHARACTERISTICS OF MATURE KENAF (GROWN IN ILLINOIS), SPRUCE, AND MAPLE

Characteristics	Kenaf	Spruce	Maple
Alpha-cellulose, corr., %	36.0	39.4	39.1
Crude cellulose, %	53.3	60.0	60.2
Lignin, %	17.8	27.6	23.3
Pentosans, %	21.5	10.6	22.6
Ash, %	2.2	0.5	0.5
Alcohol-benzene solubles, %	3.9	2.4	2.4
Solubles in 1% NaOH%	31.4	13.9	15.7
Solubles in hot water, %	7.7	3.6	2.3
Maceration yield			
Bast%	21.2	52.0	58.0
Woody%	36.8	—	—
Fiber length			
Bast, mm	2.50	—	—
Woody, mm	0.58	3.16	0.76
Combined, mm	1.28		
Fiber width			
Bast, %	23.3	—	—
Woody, %	39.4	—	—
Combined, %	33.5	43.8	20.2

Source : Clark *et al.* [48].

Fibers in the bast portion of kenaf are more narrow than most wood fiber, and in ultimate fibers, length ranges from about 1 mm to almost 10 mm[47]. The average length is greater than for fibers of most hardwoods and is comparable to that of some softwoods. Comparative chemical and fiber characteristics of mature kenaf, spruce, and maple are listed in table VI. Experiments with population density showed that planting density had little if any effect on the relative amounts of best woody fiber or on dimensional characteristics[49]. Planting densities have been governed largely by the characteristics of available planters and cultivators. However, densities that restrict branching would be favored. Under normal climatic conditions, little variation in relative bast content or fibre demensions could be attributed to differences in maturity in excess of 120 days from seeding[49,50].

Although normally well-drained, sandy soils are preferable for kenaf, it is adaptable to a wide range of soil types and also to varied climatic conditions. Rainfall spread over a period of 4 to 5 months during the growing season should be at least 50 to 65 cm per year. Sowing of seed should be done when soil temperature is 14 to 16°C. Kenaf is photoperiodically sensitive, so that flowering and seed maturation depend upon day length. For effective production of stem solids for papermaking, plantings and harvests should be so scheduled that setting of seed is avoided.

The yield potential for kenaf throughout southern and southeastern United States is excellent. This coastal plains region lies between 25° and 36° north latitude. Temperatures in the northern portion of this region range from 4.5° in winter to 27°C in summer. Yields of dry stem solids in Georgia have been as high as 27 metric tons per hectare; in Texas, 34 metric tons per hectare; and in Florida, 45 metric tons per hectare[51,52]. According to economists of the U.S. Department of Agriculture[53], annual plant species meeting certain specified agronomic requirements should be able to compete economically with corn and soybeans in many farming areas of the Southern States. Kenaf is one species having favorable qualifications. In fact, this species should also compete monetarily with hardwoods when both materials are delivered to digesters ready for cooking.[53] The climatic conditions that prevail before plant maturation and up to the time of processing have a significant influence on harvesting, storage, and preservation. We have shown that materials from green plants or from frost-killed, field-dried plants could be cooked and processed to sulfate pulps of good quality[50]. Where weather conditions permit, mature stalks may be allowed to stand in the field uncut until needed by a pulp mill. Land usage, such as rotation with other crops, may necessitate earlier harvesting, in which event some type of storage and preservation may become necessary. However, to avoid handling undesirable moisture and for better preservation of stalks, the moisture content should be as low as practical at time of harvest. Physiological changes that accompany maturation and subsequent loss of moisture may be beneficial in pulping and bleaching by reducing chemical requirements below those of the wet green plant.

Harvesting of kenaf with some conventional farm equipment has been demonstrated[54]. Sickle-bar mowers have been used without trouble, but a more effective and efficient operation is one that combines cutting and chopping. The chopped product can then be delivered either to the storage and processing area or to the pulp digesters.

When green plant material is to be harvested, the leafy top portion of the stalk must be removed as part of the harvesting sequence. Inclusion of the foliage as part of a digester charge causes processing problems and undesirable characteristics in pulps[52]. Because of the high nitrogen content in the top foliage, salvage of tops by returning them directly to the soil as nutrient or by diverting them to animal feeds has been advocated[49]. A report of a feeding trial at the University of Florida[54] indicates that no adverse effects were observed when kenaf was part of a silage ration for dairy cattle. Extent of required top removal can be controlled, in part, by the population density of the kenaf planting. Where the density is sufficiently great; e.g., 150,000 plants per hectare, the amount of sunlight reaching lower portions of the stalks is reduced by the top foliage so that lower foliage sloughs off. In stalks 5 to 6 meters high, the top foliage may be concentrated in a 1 to $1\frac{1}{3}$ meter section. The extent of this section may also be influenced by maturity; the older the plant, the less extensive the foliage section.

Equipment to perform simultaneous top removal, stalk cutting, and chopping of green kenaf is not yet available, but the basic design principles have already been applied in some sugarcane harvesting units[55]. These have not been tried on kenaf, and it appears quite likely that some features will have to be modified to make their use with kenaf practical. Units with ribboning features as used in the mechanical recovery of textile fibers from the green plant should also be considered. In the event that stalks are allowed to field-dry before harvesting, foliage is no longer a problem. A preprocessing stage would be desirable to clean and remove extraneous materials.

An initial report of the behaviour of chopped green kenaf stored under anaerobic conditions in trails at the Northern Regional Laboratory was made at the First Conference on Kenaf for Pulp[54]. Pulping effeciency of ensiled material at the end of 4 months was greater after a washing treatment than for original or unwashed ensilage. Wash ensilage from wet stalks harvested and ensiled 16 days after frost behaved in a manner similar to that of the washed ensilage from green stalks. In this latter situation the yield of screened pulp was 50%: the permanganate number. 16; and the bleach requirement, 7%, as chlorine, for a 75 brightness. Strength characteristics were superior to those of a commercial hardwood sulfate pulp.

A further report on this investigation was presented at the technical conference of TAPPI's Nonwood Plant Fibers Committee held in New Orleans, Louisiana, November 2-3, 1970. Three techniques were investigated. One procedure used the compacted silage approach, and the other procedures involved either continuous water immersion or intermittent immersion. A version of the latter procedure, periodic spraying, has been used successfully with sugarcane bagasse. The water treatments or variations thereof might offer other advantages such as easier cleaning, aiding pith removal, and leaching out water-soluble compounds. Possibilities for storage of kenaf under these three conditions include: (i) trench and bunker silos and (ii) wet bulk storage on concrete slabs. Rick storage or baled, field-dried stalks as a possible means for their preservation before pulping was performed at the Georgia Agricultural Experiment Station. Preliminary data[54] indicated that some compositional changes could be attributed to decomposition resulting from excessive moisture in stalks at the time of baling, and to losses of solubles leached from the stalks by rain water. Good preservation of cellulosic solids and of fiber quality occurred when bales were protected, such as in a barn or in a covered rick. When estimated costs for kenaf delivered to the pulp mill and for pulping chemicals were calculated, these combined costs were less for baled, field-dried kenaf from the covered rick than for wet-stored green kenaf. Processing, handling, and bleaching costs must also be considered before the economic relationships of these techniques are fully apparent.

Pulp mill requirements, type of material desired, and avilable facilities will have significant bearing on the use of stored kenaf as raw material. Field-dried stalks should demand less immediate attention than those harvested in a green condition. Problems that would be encountered with field-dried materials are: (i) excessive bulkiness when the kenaf is kept in stalk form, (ii) the tendency in the chopped form for bark to separate from core and to cause uneven distribution of bast fibers among the woody core, and (iii) the opportunity for excessive exposure to climatic factors that could be deleterious. We anticipate that protective covering will be required for the dried kenaf in much the same manner as it has been for baled straw and sugarcane bagasse.

Operation of a pulp mill in an area where kenaf could be grown throughout the year would simplify storage problems, if not eliminate them. To ensure the mill of a continuing supply of raw material, the timing of seeding should be consistent with scheduled demands of the mill. If harvests, for some uncontrollable reason, can not meet mill demands on schedule, some supplementary processing with temporary storage may be required to avoid a mill shutdown. Part of this processing might be removal of a portion of the plant juice with its fermentables.

Characteristics of kenaf juice were investigated at the Northern Regional Laboratory[56]. The juice contains sugars, mainly fructose and glucose, and nitrogenous matter (nonprotein). Nearly one-fourth of the juice solid is ash. The juice appears to be a promising nutrient for fermentation media. The feasibility of dejuicing the green plant before pulping would probably depend on the economic value of juice solids. Removal of the juice before green kenaf is introduced into screw conveyors is desirable to eliminate the slime and its highly lubricating action.

The bimodal system of fibers; bast and woody, in kenaf plants provides opportunity to pulp them as unfractionated stalks or as separated bark and woody core. As unfractionated stalks, purping conditions,of necessary must able compromise whereby attempts are made to capitalize on the good features of the individual components. Consequently, our initial studies were directed toward avoiding decorticating operations which might be too slow and expensive for papermaking purposes. On the other hand, cost of the separation might be offset by advantages realized from tailoring the processing of the two fractions to produce pulps with optimal or superior characteristics. Some of our future studies will be designed to investigate this possibility.

Although sulfate pulping has been more thoroughly investigated, both soda and neutral sulfite techniques have also been studied at the Northern Regional Laboratory 33,48,57. Date for sulfate and soda pulping indicate that active alkali applied should be 16.0 to 16. 5% (as Na_2O) of dry solids charged into batch digesters for bleachable grades of pulp. Low sulfidity in sulfate cooking contribute to low permanganate values, low bleach consumption, and high bulk. Strength properties. except tear factor, favor high alkalinity and low sulfidity. Kenaf grown in central Illinois and northern Florida has been pulped and characterized at several green stages as well as after frost[50]. Cellulose and pentosan contents of the stalks, as well as pulp yields, were higher for the Florida-grown materials. This difference is consistent with the relative maturities attained in the two areas. Little change in yield of screened sulfate pulp (Florida, 53-55%; Illinois, 44-47%) or in pulp quality occurs in the processing of green kenaf stalks harvested 120 days after seeding. Yield of sulfate pulp from Illinois kenaf, harvested about 3 months after a terminating frost, increased to 50%. This increase may be attributed to leaching of water solubles while standing in the field.

Strength characteristics of kenaf pulps were superior at the same freeness levels to those of commercial hardwood pulps and, except for resistance to tear, comparable with softwood pulps[48].

Removal of juices and solubles from green stalks decreases chemical requirement during pulping and subsequent bleaching with no loss in strength properties.

Aside from a limited number of pulping trials conducted with other types of digesters[54,58], the reported experimental work[48,50,57] has been performed with tumbling digesters having indirect steam heating. In these batch cooking operations, which did not include a time study, an appreciable portion of time was required for warmup and blowdown. Discharge of cooks to a blowpit was not possible with the rotary digester used. Possibilities for short-period cooking (7-10 min) were indicated when sulfate pulps were prepared from both green and field-dried kenaf in a two-tube Pandia Chemipulper[58]. Applied chemicals, basis kenaf solids, amounted to 16.3% active alkali as Na_2O with sulfidity at 10%. The necessity for dejuicing green stalks before their introduction into the screwfeeder was also demonstrated. However, some moisture is necessary to aid in compaction and lubrication of the mass as it moves along the feed screw. These runs showed a need to: (i) improve mechanics of introducing chopped kenaf into a continuous cooker, (ii) achieve homogenous digestion, and (iii) improve drainage in the resulting pulps.

Because we wished to determine the influence of agronomic factors, geographic location, and storage techniques on pulp quality; our conditions for pulping, refining, and bleaching have been maintained essentially constant. Additional studies need to be made to optimize the protocol for developing kenaf pulps ready for ultimate use.

KENAF PAPERMAKING

Kenaf sulfate and neutral sulfite pulps have been combined with variety of commercial wood pulps to provide synergistic effects in handsheets[59]. This study was carried out with pulps at one level of freeness, and it should be extended to include other refining conditions. Recently a pilot-scale study was completed of continuous cooking of green and field-dried kenaf and conversion of the bleached sulfate pulps to bond papers[58]. The pulps were prepared with the Pandia Chemipulpur as mentioned. They were bleached in a four-stage sequence (CEHD) involving sodium chlorite in the chlorination stage. The bleached pulps were blended with commercial wood pulps (40 : 60), and the furnishes were run on a 32-in. fourdrinier machine. Except for resistance to tear (table VII), strengths of these experimental kenaf papers were superior to those of all-wood control sheets. Values for surface smoothness (wax pick test), elongation, and tensile energy absorbed were greater in the kenaf-wood bond than in the all-wood control This first known production of a

TABLE VII BOND PAPER CONTAINING CONTINUOUSLY PULPED KENAF ; FURNISH AND PAPER CHARACTERISTICS

Factors	Wood (control)	Green kenaf	Dried kenaf
Machine furnish[a]			
Softwood pulp	67	40	40
Hardwood pulp	33	20	20
Kenaf pulp	0	40	40
Headbox freeness, C.S., ml	400	330	400
Physical characteristics			
Burst factors (g/cm²) (g/m²)	22	27	27
Breaking length, M.D., m	5,530	6,190	6,280
Tear factor, C.D., g/(g/m²)	136	125	119
Folds, MIT, M.D., No.	200	400	300
Air resistance, sec	26	91	70
Wax pick test			
Wire	11	13	12
Felt	11	14	14
Elongation, M.D., %	1.3	2.1	1.9
TEA (kg-m/m²)/(100 g/m²)	4.8	8.6	7.7

[a]Plus additives : rosin, 0.8%; clay, 8.0%; TiO_2, 2.0%; and H_2SO_4 or alum to maintain pH 5.5.

Source : Clark *et al.*[58].

commercial-type bond paper containing kenaf pulp demonstrated the adaptability of the pulp to processing in commercial papermaking facilities.

REFERENCES:

1. Atchison, J.E., Pap. Trade J. *151* (9) : 52, 1967.
2. Anon., Indian Pulp Pap. *17* (7) : 6, 1963.
3. Anon., Indian Pulp Pap. *19* (11) : 679, 1965.
4. Anon., Indian Pulp Pap. *21* (4) : 255, 1966.
5. Anon., Indian Pulp Pap. *18* (8) : 457, 1964.
6. Anon., Indian Pulp Pap. *20* (6) : 375, 1965.
7. Anon., Indian Pulp Pap. *21* (12) : 733, 1967.
8. Anon., Pulp Pap. Int *12* (9) : 7, 1970.
9. Greeley, A.W., Pulp Pap. *41* (14) : 79, 1967.
10. U.S. Department of Agriculture, Forest Service, "Timber Trends in the United States," Forest Resources Report No. 17, Washington, D C., U.S. Government Printing Office, 1965.
11. Spier, W.B , S. Pulp Paper Mfr. *29* (4) : 50, 1966.
12. Clark, T.F., "Annual Crop Fibers and the Bamboos," In Pulp and Paper Manufacture, 2nd ed., Vol. 2, pp 1-74 (R.G. Macdonald and John N. Franklin, Eds.), New York, McGraw Hill, 1969.
13. Guha, S. R. D., Mathur, G.M., and Sharma, Y.K.. Indian Pulp Pap. *19* (8) : 499, 1965.
14. Ernst, A J., Fouad, Y., and Clark, T.F., Tappi *43* : 49, 1960.
15. Atchison, J.E., Indian Pulp Pap. 23 (1) : 131, 1968.
16. Chapman, A.W , "Purchasing, Handling and Storing of Bagasse." In Pulp and Paper Prospects in Latin America. p.p. 335-337, New York, Food and Agriculture Organization of the United Nations, 1955.
17. Ritter, E.A., Brit. Pat. 497, 960 (Dec. 30, 1938).
18. Naffziger, T.R., and Mahon, H.I., J. Agr. Food Chem. *1* : 847, 1953.
19. Lathrop, E. C., Naffziger, T.R., and Mahon, H.I., "Methods for Separating Pith-Bearing Plants into Fiber and Pith," U.S. Dep. Agr., ARS-71-4, Mimeo Cir. 49 pp. plus 28 tables and 20 figures. Peoria,, Ill., March 1955.
20. Villavicencio, E.J. Pulp Pap. Int. *5* (3) : 52, 1963.
21. Cusi, D.S. Pulp Pap. *33* (6) : 76, 1959.
22. Misra, D.K., Indian Pulp Pap. *19* (10) : 611, 1965.
23. Henderson, J. T., and Knapp, S.B., U.S. Pat. 3,013,935 (Dec. 19, 1961).
24. Krishnaswamy, S.R. Indian Pulp Pap. *17* (5) : 309, 1962.
25. Anon., Chem. Week *88* (5) : 39, 1961.
26. Anon., Pulp Pap. *34* (13) : 94, 1960.
27. Anon., Pulp Pap. Int. *8* (8) : 38, 1966.
28. Chaudhari, A.D., Pulp Pap. Int. *10* (6) : 64, 1968.
29. Williamson, D.F., Pap. Trade J. *153* (6) : 52, 1969.
30. Aggarwala, J.C., Pulp Pap. Int. *9* (10) : 47, 1967.
31. Anon., Pap. Trade J. *147* (37) : 38, 1963.
32. Anon., Pulp Pap. Int. *11* (9) : 47, 1969.
33. Cunningham, R.L., Clark, T.F., Kwolek, W.F., Wolff, I.A., and Jones, Q., Tappi *53* : 1697, 1970.
34. Naffziger, T.R., Matuszewski, R.S., Clark, T.F , and Wolff, I.A., Tappi *43* , 591, 1960.
35. Naffziger, T.R., Clark T.F. and Wolff, I.A.. Tappi *44* : 108, 1961,
36. Naffziger T.R., Clark, T.F., and Wolff, I:A., Tappi *44* : 472, 1961.
37. Haun, J.R., Clark, T.F., and White, G.A. "Fiber and Papermaking Characteristics of Bamboo," U.S. Dep. Agr. Tech. Bull. 1361, 19 pp., Beltsville, Md., August 1966.
38. Nieschlag, H.J., Nelson, G.H., Wolff, I.A., and Perdue, R.E., Jr., Tappi *43* : 193, 1960.
39. Nieschlag, H.J., Earle, F.R., Nelson, G.H., and Perdue, R.E., Jr., Tappi *43* : 993, 1960.
40. Nelson, G.H., Clark, T.F., Wolff, I.A. and Jones, Q., Tappi *49* : 40, 1966.
41. McGovern, J.N. Pulp Pap. *41* (4): 5, 1967.
42. Nelson, G.H. Nieschlag, H.J., Daxenbichler, M.E., Wolff. I.A., and Perdue, R.E., Jr., Tappi *44*, 319, 1961.
43. Kundu, B.C., Soil Crop. Sci. Soc. Fla. Proc. *24* : 326, 1964,
44. Chawla, .iJ.S.. Sharma, A.N., and Abroz, B. K., Indian Pulp Pap. *22* (5) : 285, 1967.
45. Crane. J.C., Econ. Bot. *1* : 334, 1947.
46. Amanquah, S.Y., "A Review of Kenaf Research with Special References to Ghana," Crop Research Institute, Ghana Academy of Science, Bull. No. 1, 17 pp., Ghana University Press, Accra, 1968.
47. Nieschlag, H.J., Nelson. G.H., and Wolff, I.A., Tappi *44* : 515, 1961.
48. Clark, T.F., Nelson, G.H., Nieschlag, H.J., and Wolff, I.A., Tappi *45* : 780, 1962.
49. Clark, T.F., and Wolff, I.A., Tappi, *52* ; 2111, 1969.
50. Clark, T.F., Uhr, S.C., and Wolff, I.A., Tappi : *50*:52A, 1967.
51. White, G.A., Crops Soils Mag., *21* (2) : 13, 1968.
52. White, G.A., Tappi *52* : 656, 1969.
53. Trotter, W.K., and Corkern, R.S., "Economics of Kenaf for Pulp in the South," In Proceedings-First Conference on Kenaf for Pulp, pp. 13-31, U.S. Dep. Agr., Northern Utilization Research and Development Division, Peoria, Ill., April 1968.
54. Proceedings-First Conference on Kenaf for Pulp, 114 pp. U.S. Dep. Agr., Northern Utilization Research and Development Division, Peoria, Ill., April 1968.
55. Clayton, J.E., and Whittemore, H.D., Sugar Azucar, *64* (7) : 16, 1969.
56. Bagby, M.O.. Wolff, I.A., and Cadmus, M.C., Tappi *52* : 442, 1969.
57. Clark, T F., and Wolff, I A., Tappi *48* : 381, 1965.
58. Clark, T.F., Cunnigham, R.L., and Wolff, I.A., Tappi, accepted for publication, 1970.
59. Clark, T.F. and Wolff, I.A. Tappi *45* : 786, 1962.