

Timber bamboo pulp

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ABSTRACT: Fast-growing biomass, such as bamboo, has the potential to serve an important future role in the pulp and paper industry with potential to both lower resource costs and improve a product's sustainability. Moso bamboo is particularly interesting due to its fast growth and size, which allows it to be handled and chipped similarly to wood resources. In this study, we will share results of the chip preparation, kraft cooking, and ECF bleaching of this bamboo species and compare its pulpability, bleachability, and physical properties to a fast growing hybrid poplar tree. Results indicate that the bamboo chips cooked and bleached similarly to the poplar hardwood, allowing for co-cooking. The resulting pulps had superior tensile properties at low refining, but did have higher fines that lowered drainability as measured by Canadian Standard Freeness. The bamboo fiber morphology was also measured, indicating the fiber to have length weighted average fiber lengths and coarseness values to be greater than the poplar wood studied, which should allow this material to be used in many paper grades.

Application: The results of this study would be best used by industry professionals interested in the potential of Moso bamboo as a papermaking fiber. Cooking and bleaching conditions are provided along with handsheet properties and fiber morphologies.

With increasing burdens on land to produce food and biomass for energy and materials, in combination with rising costs of biomass resources, the pulp and paper industry will need fast growing materials to remain competitive. The plants in the Bamboo subfamily (*Bambusoideae*) are considered to be one of the world's fastest growing, and hence should be of interest [1]. These evergreen, monocotyledonous grasses produce primary shoots that can grow as high as 40 m and 30 cm in diameter in a growing season, where they mature over the next several years and nourish the plant rhizome system from which they grew [2]. Mature culms may be harvested for material between 3 and 5 years of maturity, when they have maximized their fiber content and structural rigidity [3]. The growth rate of bamboo has been reported to be about 15 to 30 dry metric tons/hectare/year, which is significantly higher than most trees [2,3].

Due to their high growth rate, bamboo plants are already used extensively in Asia for both timber and pulp. In China, where there is a fiber shortage in the pulp and paper industry, they currently produce about 1 million tons of bamboo pulp, primarily of mixed species [3]. Although bamboo appears to be a promising biomass source, few plantations exist due to the high inherent cost of establishment [2]. Bamboo plants flower infrequently, reproducing primarily through rhizomal propagation, which creates a shortage of seeds or creates high-cost root stock [2]. Recent advances in micropropagation could potentially mitigate the technical and economic constraints of large scale propagation, opening the way for single species bamboo plantations.

Moso bamboo (*Phyllostachys edulis*, which is also called *Phyllostachys pubescens*) is an ideal species to be considered

for the pulp and paper industry. This species originates in China, where it is still a major species harvested for its mature culms to use in construction material and pulp feedstock and for its young shoots to use for food. [2,4] This species requires a climate with annual precipitation of 120 to 180 cm, a mean annual temperature of 13°C to 20°C, and a mean monthly temperature >0°C, which would allow it to be grown in the Southeastern US [5,6]. This giant species has culms with similar dimensions as pulpwood, allowing the biomass to be handled in a similar manner for harvesting and chipping, which is essential if it is to be utilized by the current pulp industry infrastructure [5]. This paper investigates the pulping, bleaching, and physical properties of this species and compares it to hybrid poplar, *Populus maximowiczii* x *nigra*, another fast growing woody species currently used by the US pulp industry.

MATERIAL AND METHODS

Mature Moso bamboo stalks were provided by Booshoort Gardens LLC (Mount Vernon, WA, USA) from plants grown on a research plot located at Clemson University Experimental Forest in Anderson County, SC, USA. The green culms were harvested and chipped by a disc chipper. The chips were screened with accepts set at 2 mm and 8 mm holes and were cold stored (4°C) at an approximately 40% moisture content prior to use. Chipping resulted in material very similar to traditional chipped wood material, as Fig. 1 shows. NM-6 hybrid poplar, *Populus maximowiczii* x *nigra*, trees were harvested from Northern Wisconsin after 10 years of age and seasoned for 3 months before use. The tree boles were hand-debarked with a draw knife, chipped in a disc chipper, and screened with accepts set at 2 mm and 8 mm holes. The chips



1. Picture of Moso chips produced in a disc chipper.

were allowed to air-dry to approximately 25% moisture and cold stored until used. Chemicals utilized for the pulping and bleaching reactions were purchased from VWR International (Radnor, PA, USA) and used as received.

The pulping experiments were performed at three scales, including 2 L reactors placed into a rotating steam jacketed reactor, a 20 L circulating digester with an indirect heat exchanger, and a pilot scale 400 L rotating reactor with steam jacket heating. Bleaching was performed on a lab scale using a Quantum Mixer-Reactor Model V (Quantum Technologies; Akron, OH, USA). Bleaching was performed on a pilot scale utilizing the rotating reactor for oxygen delignification and a continuous recirculating 800 L tower for chlorine dioxide and hydrogen peroxide-reinforced alkaline extraction stages.

Samples were well-washed between bleach sequences with the lab samples employing a centrifuge with a cloth filter for dewatering, and the pilot scale samples employed a rotating screen washer with vacuum dewatering. Elemental chlorine-free chlorine dioxide (ClO_2) was prepared through acidifying sodium chlorite with 4 N sulfuric acid and collecting the ClO_2 gas into chilled water after passing through a sodium chlorate solution trap. Physical properties were measured on handsheets after they were refined in a PFI mill prepared following TAPPI Standards T-205 "Forming handsheets for physical tests of pulp" and T-248 "Laboratory beating of pulp (PFI mill method)." Freeness, basis weight, tensile, caliper and tear were measured using TAPPI Standards T220 "Physical testing of pulp handsheets," T411 "Thickness (caliper) of paper, paperboard, and combined board," and T414 "Internal tearing resistance of paper (Elmendorf-type method)."

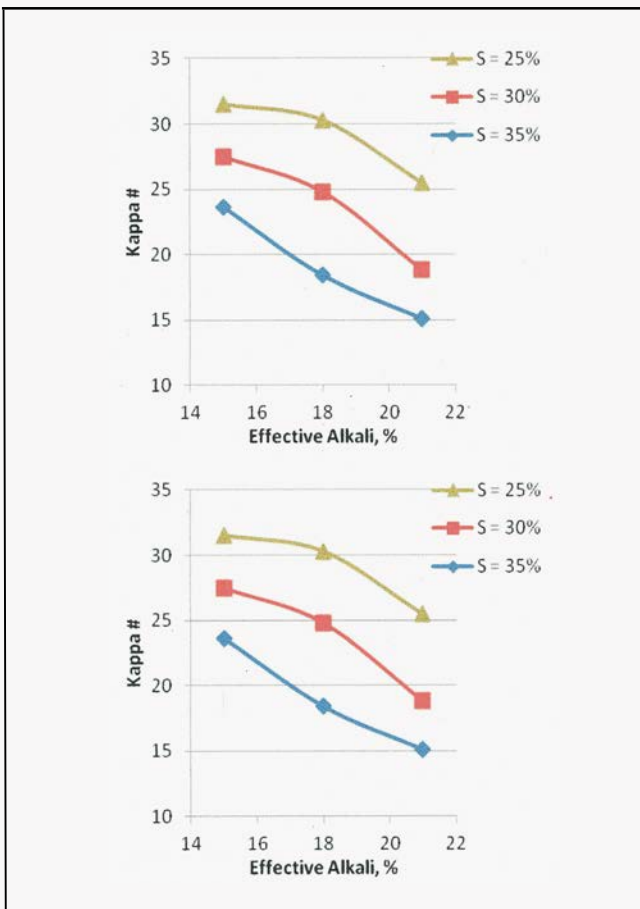
Hitachi S-570 LaB6 Scanning Electron Microscopy (Hitachi High Technologies America; Schaumburg, IL, USA) operated at 10.0 kV was used to image the bamboo fiber. Samples were coated with gold:palladium using a SeeVac (Pittsburgh, PA, USA) Auto Conductance IV vacuum sputter-coater to improve the conductivity of the samples.

LAB-SCALE PULPING AND BLEACHING EXPERIMENTS

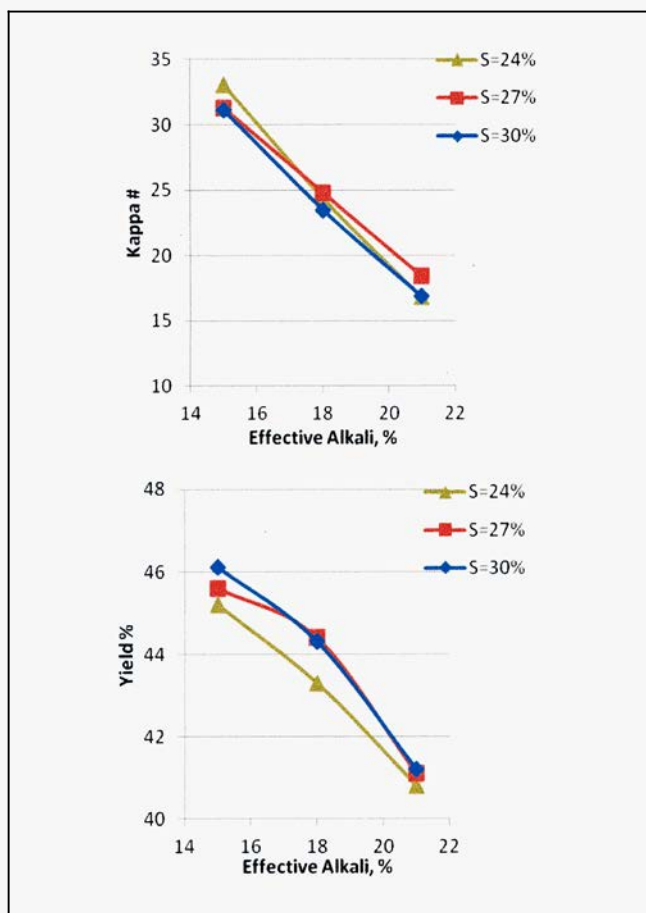
Pulping experiments

Cooking conditions for the Moso chips were pre-screened at a small scale by pulping approximately 100 g of bamboo chips in rotating batch reactors. Effective alkali was varied between 15% and 21%, and sulfidity between 25% and 35%, keeping the rest of the pulping parameters constant at a liquor-to-wood ratio of 5:1, H-Factor at 1100, and a maximum cooking temperature of 165°C. Results of fiber yield and kappa testing are shown below in **Fig. 2**. Based on this data, the conditions of 17% effective alkali and 35% sulfidity were selected to maximize pulping yield while achieving delignification to approximately a 20 kappa number. These conditions are in the same range as other bamboo species studies that utilized kraft pulping [7,8].

Cooking conditions for the poplar were also pre-screened by pulping approximately 100 g of the wood chips in rotating batch reactors. Effective alkali was again varied between 15% and 21%, with lower sulfidities between 24% and 30%, which is more typical for wood species. As in the bamboo experiments, the rest of the pulping parameters were held constant using a liquor-to-wood ratio of 5:1, an H-Factor of 1100, and a maximum cooking temperature of 165°C. Results of fiber



2. Moso pulping liquor experiments impact on yield and kappa number.



3. Poplar pulping liquor experiments impact on yield and kappa number.

yield and kappa testing are shown in Fig. 3. The data suggest a lower sensitivity to sulfidity than the bamboo chips, with 27% and 30% giving similar results. Sulfidity, which typically affects delignification, but not carbohydrate degradation, was not expected to impact yield. However, as a greater amount of shives were removed from the bamboo pulp with low sulfidity conditions, a yield impact could be rationalized. This kappa data also suggests that the bamboo chips were more difficult to delignify than the poplar, possibly due to chip size being less uniform, or inherent chemical differences in lignin composition.

Based on the preliminary data, the conditions of 19% effective alkali and 27% sulfidity were selected to maximize pulping yields, while achieving delignification to approximately a 20 kappa number, which is consistent with typical hardwood kraft cooking conditions.

Three larger batch cooks of 250 grams (o.d.) of bamboo or poplar chips were digested to produce pulp for the subsequent lab bleaching sequence, using a 20 L circulating digester with indirect heat exchanger following the conditions shown in Table I. The pulp resulted in slightly higher kappa numbers and improved yield as compared to the initial lab cooks, presumably due to better liquor/chip mixing and heat transfer in the larger circulation reactor. The other observa-

Stage	Moso	Poplar
Effective alkali	17%	19%
Sulfidity	35%	27%
H-factor	1100	1100
Maximum temperature	165°C	165°C
Liquor-to-biomass ratio	5 to 1	5 to 1
Kappa no. (std dev)	23.4 (0.7)	18.5 (1.4)
Screened yield	43.3% (1.0%)	48.8% (1.2%)

Stage	Conditions
O	Pressurized with O ₂ to 80 psig, 10% csc, 2.5% NaOH, 60 min, varying temperatures
D	0.20 Kappa factor, 3.5% csc, 50°C, 45 min, initial pH adjusted to between 4 and 5 with 10% H ₂ SO ₄
EP	0.5% H ₂ O ₂ , 10% csc, 70°C, 60 min, 2.5% NaOH, terminal pH ~ 11.0
D	Varying % ClO ₂ , 10% csc, 75°C, 120 min, pH adjusted with 10% H ₂ SO ₄ to achieve final pH between 4.5 and 5.5

II. Bleaching conditions.

tion from Table I was that poplar chips had higher screened yield than the Moso bamboo. Presumably, this is due to the higher cellulose content of woods than grasses, such as bamboo. Ramifications of the lower yield from bamboo will negatively impact the economics of producing pulp, offsetting some of the gains of the higher land productivity.

Bleaching experiments

The resulting pulps from the larger cooks were then combined and bleached using a Quantum Reactor following an OD (EP) D sequence utilizing the conditions shown in Table II, which represents a typical sequence used for hardwood pulp [9]. Yield losses during bleaching were not able to be measured, as excessive fiber loss occurred due to fiber loss during reactor transfer and washing steps.

With an incoming kappa number of 18 and 23 for poplar and Moso bamboo, respectively, the pulps still contained approximately 3% lignin content. The oxygen stage was employed as a low cost method to further delignify, but at conditions mild enough to not further degrade cellulose or lower the yield. Consistency, caustic charge, temperature, and oxygen in this stage were held constant, with conditions and pressure set to have excess oxygen. Temperature was varied until the kappa number was reduced by 40% to minimize cellulose degradation and yield loss, with the results shown in Table III. The results suggest a similar response between the two pulps, with an optimal oxygen delignification between 100°C and 110°C.

NONWOOD PULPING

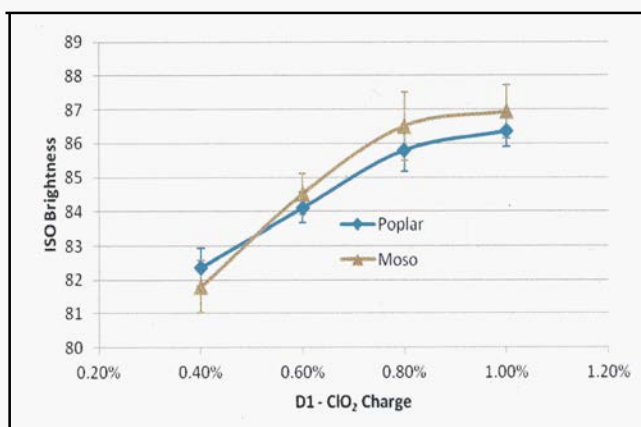
Temperature (°C)	Moso			Poplar		
	Initial Kappa	Final Kappa	% delig	Initial Kappa	Final Kappa	% delig
110	23.4	11.2	52%	18.5	9.9	46%
100	23.4	15.4	34%	18.5	10.4	44%
90	23.4	16.1	31%	18.5	12.4	33%

III. Oxygen delignification results.

The 100°C oxygen delignification step was repeated and utilized for the next two bleaching stages, D and E(P), which were designed to finish the delignification and remove the majority of the chromophores. Conditions, shown in Table 11, were not varied for these stages, which were modeled after bleaching hardwood pulp. The final chlorine dioxide stage was done with varying charges to optimize brightness and chlorine dioxide utilization. The initial pH was adjusted to maintain the final pH between 4.5 and 5.5 for optimal brightness. The pulp was used to create two brightness pads, which were measured twice to determine the average brightness with 95% confidence interval bars shown in Fig. 4. Based on the data, both pulps exhibited a similar bleaching response and should be able to reach high brightness required for market pulps, although an additional brightening stage may be required. Some shives (presumably from the nodes) were observed in the Moso pulp but should be easy to screen out in a larger operation.

Handsheet properties

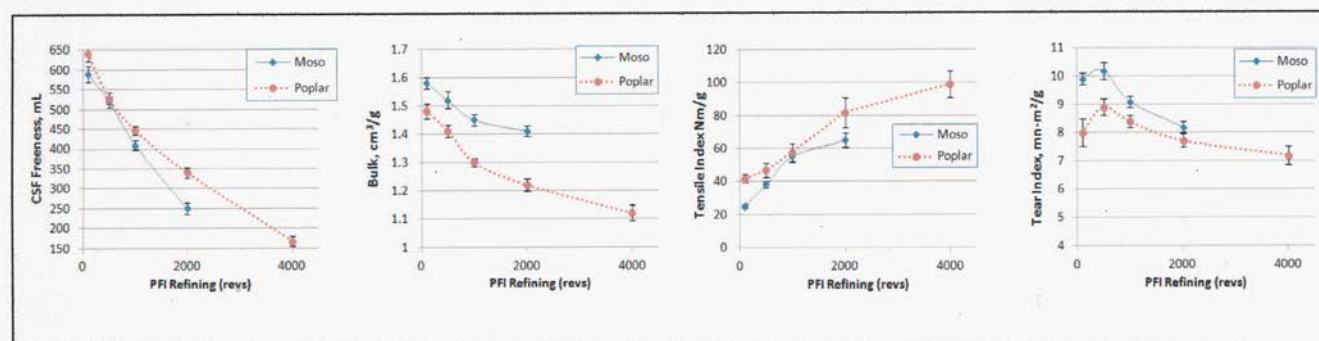
The 1% ClO₂ pulps produced were utilized to make TAPPI standard handsheets to measure the physical properties. The



4. Bleaching response of the laboratory cooks. Error bars represent a 95% confidence interval of 4 tests.

results, shown in Fig. 5, demonstrate that the Moso bamboo and poplar kraft pulps have quite similar properties, with poplar responding better to refining with higher freeness and tensile index values.

The Moso fiber showed higher bulk and tear than the poplar, which suggests a thicker cell wall fiber with higher intrinsic strength. This was confirmed through fiber morphology measurements, as shown in Table IV. The Moso fiber was shown to have slightly higher coarseness and length. Additionally, it had significantly higher fines content, as measured by the FQA, than the hardwood poplar, which may explain the lower freeness values. Other studies have shown similar results of high fines in bamboo pulps and have suggested this may cause higher chemical consumption in some grades [3,10]. Scanning electron micrographs were taken to visualize the fines. Two micrographs are shown in Fig. 6 with the fi-



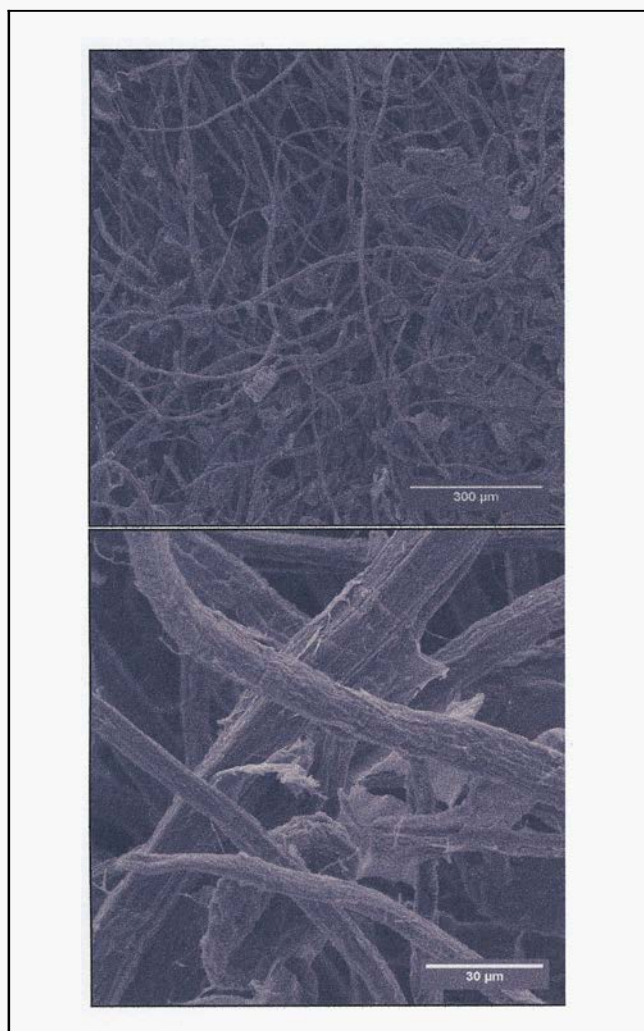
5. Physical properties of handsheets from the laboratory cooks. Error bars represent a 95% confidence interval of 4 tests.

	Coarseness ^a (mg/100m)	AFL (mm)	LWAFL (mm)	Fiber/Gram (millions)	LW Fines (%)
Moso	11.8 (0.6) ^b	0.85 (0.03)	1.24 (0.03)	10.0 (0.3)	24 (2.1)
Poplar	8.1 (0.5)	0.53 (0.02)	0.80 (0.02)	24.7 (0.3)	9.9 (1.2)

^a Coarseness measurements were made on samples with their fines removed.

^b Number in parentheses is the standard deviation of 3 tests

IV. Laboratory cook fiber morphology.



6. Scanning electron micrographs of Moso pulp depicting fiber and fines morphology.

bers at two magnification levels, depicting the fines to be round fairly thick cells, possible due to the nodal regions of the bamboo fiber.

PILOT-SCALE PULPING AND BLEACHING EXPERIMENTS

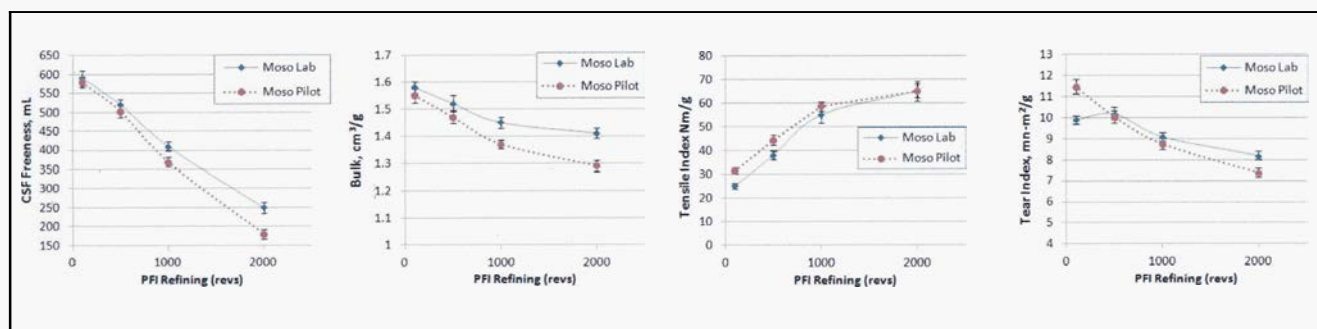
Based on the results from the laboratory cooks, a set of larger pilot scale cooks and bleaching runs were conducted on the

Moso bamboo chips to confirm the pulpability and bleachability at a larger scale. Never-dried chips were cooked in four successive batches of approximately 85 kg (o.d.) of material in a 400 L rotating digester equipped with indirect heating through a steam jacket. The cooks utilized an H-factor of 1100 and a maximum temp of 165°C. The white liquor consisted of an effective alkali of 17%, a 35% sulfidity, and liquor-to-wood ratio of 4:1. Composite samples for the four cooks were characterized, and indicated slightly better results than the lab cooks with a kappa number of 17.2 and an unscreened yield of 46.5%. The pilot cooks resulted in minimal shives, so the decision was made to not screen the material and allow the material to be further processed in the O₂ stage.

The resulting pulps were bleached with the bleaching sequence conducted as follows:

- O₂-stage, using 2.5% NaOH at 10% pulp consistency, 1 h reaction time at 110°C. The pulp was washed and resulted in a kappa number of 8.2.
- D₀-stage, using a 0.2 kappa factor (0.64% charge of ClO₂), a 1 h reaction time, 10% solids, and 50°C in a recirculating tower reactor after the initial pH was adjusted to 4 by the addition of sulfuric acid. The pulp was thoroughly washed and dewatered to approximately 20% consistency.
- EO-stage, using 2.5% NaOH and 0.5% H₂O₂, temperature 55°C, 1 h reaction time, with the final pH measured at 12.6°C.
- D₁-stage, using 0.6% ClO₂ charge at 70°C for 2 h. No initial pH adjustment was utilized, which resulted in a final pH of 6.4.

Samples of pulp were beaten in a PFI refiner, and standard handsheets were evaluated for mechanical properties. The data were compared to the initial laboratory cooks, as shown in Fig. 7. Overall, the data indicate that the materials responded similarly, validating the laboratory results. The data suggest the pilot scale material to have slightly higher bonding than the lab scale pulp, with higher initial tensile strength and lower bulk. Additionally, the pilot material freeness was lower, and it displayed lower tear strength at high refining levels. These results suggest the fiber in the pilot scale may have been overly processed, and performs as if it were “pre-refined.” This could be due to either the higher delignification in the initial cook or excessive mechanical action in the larger



7. Physical properties of handsheets made from Moso pulps.

NONWOOD PULPING

	Unbleached Pulp	O ₂ -stage Pulp	D1-Stage Pulp
LWA ^a fines	29	28	30
LWA fiber length (mm)	0.99	1.01	0.90
LWA curl index	0.10	0.16	0.41
Kink index (1/mm)	1.25	1.81	3.27
^a Length weighted average (LWA).			

V. Pilot cook fiber morphology.

reactors during rotation or during the depressurization or “di-gester blowing step.”

To investigate the hypothesis that the pilot scale processing caused “pre-refining,” fiber quality analysis (fines, fiber length, kink, and curl) was performed on several samples throughout the pilot processing. Three samples were tested: (1) unbleached bamboo kraft pulp, (2) bamboo pulp after the O-stage, and (3) final pulp after the D₁-stage. The results, shown in **Table V**, indicate the curl and kink of the pulp were increased during the bleaching sequence. This confirms the hypothesis that this bamboo pulp may have undergone excessive mechanical damage during the pilot processing, which explains some of the differences noted from the laboratory cook. Additionally, the pulp fines were higher than in the laboratory cooks, which is speculated to be due to higher fines retention during bleaching/washing.

CONCLUSIONS

Kraft pulping of Moso bamboo chips can create an interesting non-wood pulp with properties similar to those of a poplar hardwood pulp. The giant timber bamboo can be processed similarly to wood, while maintaining the high productivity of a non-wood species. Tensile properties appear to be slightly lower than poplar, but the fibers exhibited higher bulk and tear properties, presumably due to higher coarseness values. The cooking and bleaching conditions were similar to poplar wood, which should allow for easy co-cooking, possibly representing a convenient means of incorporating these materials into pulp and paper grades. Negative aspects of the pulp included slightly lower yield than the hardwood pulp, which will offset some of the gains of lower cost feedstocks. Additionally, fines content of the pulps were quite high, which could negatively impact paper machine runnability, although freeness levels were not severely impacted in this study. Optimization of the cooking and bleaching parameters is essential for this pulp, and the data presented in this paper should serve as a guide for appropriate conditions. **TJ**

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ABOUT THE AUTHORS

We choose to work with Bamboo as it is one of the fastest growing plants, and thus has the potential to lower feedstock costs for pulp companies. We found working with bamboo to be surprisingly similar to wood pulping and bleaching as compared to other herbaceous plants considered for pulp production.

Getting access to mature bamboo biomass of interest in the United States was one of the most challenging aspects of this research. Luckily, co-author Jackie Heinricher had contacts at a facility in South Carolina that had a mature grove of timber bamboo, and was willing to part with several mature culms.

In working with bamboo, we learned quite a bit about this amazing plant, from how it grows and propagates to its unusual fines morphology. We hope US pulp companies and other researchers consider bamboo as a viable nonwood material that has higher land productivity than trees. There is still much re-



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search to do on the processing side, and we plan to continue our work with co-cooking experiments with hardwoods.

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