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Selection of plant population of kenaf (*Hibiscus cannabinus* L.) as a papermaking raw material on arid hillside land in China

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Abstract Agronomic properties (whole stalk yield, fiber length distribution, chemical composition) and whole stalk kraft pulp characteristics (total pulp yield, pulp fiber length distribution, pulp sheet strengths) were examined for kenaf (variety Zhehong 8310) at four plant populations, ranging from 135 000 to 405 000 plants/ha on arid hillside land at Anji, Zhejiang, China. For agronomic properties, the final whole stalk yield was higher as the plant population increased and as the altitude of the location on the slope decreased. Average fiber lengths of bast and core showed maxima at 225 000 plants/ha. Cellulose content increased as the plant population increased. For the kraft pulp characteristics of kenaf whole stalk, the total pulp yield was lower as the plant population increased, with the maximum difference about 1.3%. Sheet strengths and average fiber length attained maxima at around 225 000–315 000 plants/ha. The largest pulp strengths (breaking length, burst index, and folding endurance) were seen at a plant population of 225 000 plants/ha, and the largest tear index was seen at a plant population of 315 000 plants/ha. When the agronomic properties and whole stalk kraft pulp characteristics were combined, a plant population between 225 000 and 315 000 plants/ha, which is a little higher than that of kenaf bast production for textiles, was selected as the optimum cultivated kenaf plant population for whole stalk kraft pulp and papermaking on arid hillside land in China.

Key words Arid hillside land · Kenaf · Plant population · Agronomic properties · Chemical composition · Kraft pulp

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Introduction

In a previous paper[1] we reported that V241 (extremely late maturity) or V003 (late maturity) could be selected as a papermaking kenaf variety on the arid hillside land in China. The plant population was 300 000 plants/ha. An optimum period to obtain the materials with high whole stalk yield and pulp quality was proposed. In this study we present the results of a trial to determine the optimum plant population. The experiments were undertaken for the same experimental period and site as those in the previous paper.[1]

Several agronomic studies on kenaf plant population were undertaken to achieve a high quality for papermaking, but they were conducted on fertile farmland, and the final product (pulp) qualities were not examined.[2,3] Clark and Wolff[4] reported the influence of plant population on the physical characteristics of kenaf; but only the chemical compositions at 142 000 plants/ha were presented, and no data were shown on pulp quality.

Generally, for kenaf bast production for textiles, a plant population of 200 000–250 000 plants/ha has been recommended.[2,5] The objective of this study was to determine the effect of plant populations from 135 000 to 405 000 plants/ha on the agronomic properties and kraft pulp qualities.

Materials and methods

Experimental site and cultivation

As shown in our previous study,[1] the trials were conducted in the northern part of Anji County in Zhejiang Province of China. The area consisted of acidic soil with pH 5.5–5.7, low fertility, and poor physical properties; the soil had been mostly left uncultivated, except for plants such as soybean and sweet potato with low yields. The climate of this area is generally hot and dry with little rainfall, and the area is likely to suffer from drought from July to September.

During our experimental period, no rain fell from June 24 to August 8.

In our trial, plant populations were fixed at 135000, 225000, 315000, and 405000 plants/ha by the seeding rates of 1.5, 2.5, 3.5, and 4.5 g/m², respectively. An outline of the experiment is shown in Fig. 1. Kenaf was planted on hillside land 30 m in length, 20 m in width, and a slope of 30°. Four experimental districts were set up at different heights (4–5, 5–6, 6–7, and 7–8 m) on the slope. A buffer zone of 270000 plants/ha was set around the experimental area. The Zhehong 8310 variety,[6] late maturity, which is equivalent to the V003 used in the previous study,[1] was selected. Each trial area was 10 m² (5 × 2 m). Kenaf seeds were sown in five rows on each ridge of 2 m width, including a furrow, after herbicide treatment and ploughing. A base fertilizer and a supplementary fertilizer was applied as shown previously.[1] Seeding was on May 20, 1994; the final thinning of the plant populations was on June 9, 1994; and the final harvesting was on January 7, 1995.

Samples and measurements

Final kenaf plant number, plant moisture content, and whole stalk yield were determined when plants were harvested on January 7, 1995. Twenty kenaf plants of each trial area were sampled to examine plant height, stem diameter, and the air-dried bast/core ratio. Only samples from the experimental district at 6–7 m height on the slope (A_2–D_2, Fig. 1) were used as representative samples to examine the fiber length distributions, chemical compositions, and kraft pulp characteristics as shown in our previous studies.[1,7,8]

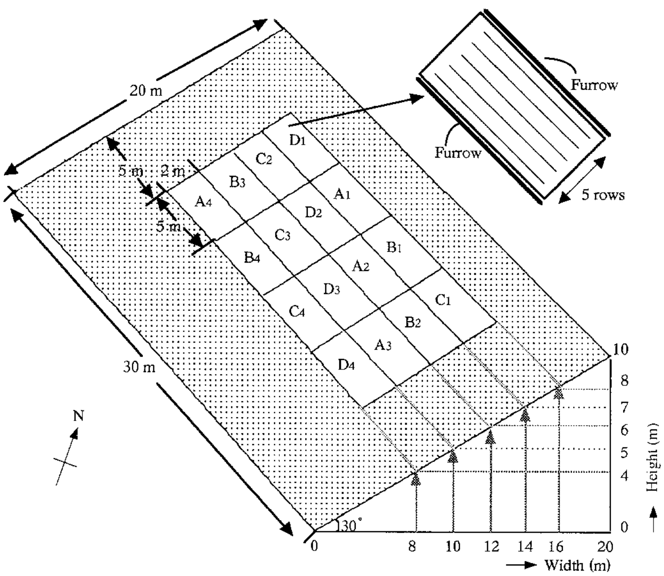

Fig. 1. Practical disposition of experimental areas of kenaf palnt populations on arid hillside land. A, B, C, D, plant populations of 135000, 225000, 315000, and 405000 plants/ha after final thinning, respectively. *Shaded area* indicates the buffer zone of about 270000 plants/ha

Results and discussion

Agronomic properties

Kenaf whole stalk yield

Statistically significant differences in kenaf whole stalk yield were detected among plant populations (Table 1). The kenaf whole stalk yield had a tendency to be higher as the plant population increased. The final whole stalk yields for plant populations of 225000, 315000, and 405000 plants/ha increased by 9.6%, 22.4%, and 24.3%, respectively, over that of the lowest plant population (135000 plants/ha). In addition, yields at the various heights on the slope were significantly different: The yield at the lower location on the slope was larger. Based on the data from the final yield from arid hillside land, we concluded that to increase the yield of whole stalk kenaf, a larger population is effective.

On flat, fertile farmland, the kenaf yield of whole stalk for textile is at least 12 tons/ha,[2,3,9] and the yields shown in Table 1 are about 70% of that. This result may indicate that kenaf growth was hindered by the special conditions of arid hillside land. Hence large population planting is important for biomass production in this area. The arid hillside land is not suitable for crop production and is mostly left uncultivated. In this sense, kenaf production for papermaking may be possible for hillside land development.

Harvested plant number

Statistically significant differences in the number and percentage of harvested small and effective plants were detected among plant populations, but they were relatively small for the heights on the slope (Table 2). This finding indicates that the plant population is a more important factor for the harvested plant number than the height on the hillside. The final harvested plant numbers showed that the higher the plant population, the greater are the plant death rate and the number of small plants. "Small" plants are the harvested plants smaller than one-third the average plant height or diameter. They may be restrained by growth competition, and they are clearly distinguishable from the "effective" plants, which are harvested plants excluding small plants. Long-stalked kenaf may regulate their growth by themselves in a plant colony by severe competition of individual plants, that is, by the suppression of weak plants. This situation seems different from the growth of a short-stalked crop (e.g., a rice colony). The gap between superior and inferior growth plants might be increased in a larger population as the competition becomes severe and the number of effective plants increases, which results in an increase in whole stalk yield (Table 1).

Physical dimensions of stalks

Generally, to increase the bast fiber for textile use, a kenaf variety with both higher yield and superior individual physi-

Table 1. Whole stalk yield of kenaf in four plant populations and at four heights on the slope

Plant population (plants/ha)	Whole stalk yield (oven- dried weight, kg/m^2), by height on slop					Mathematically estimated yield (tons/ha)
	4–5 m	5–6 m	6–7 m	7–8 m	Average[a,b]	
A_{1-4} (135 000)	7.2	6.9	7.4	5.4	6.7b	6.7
B_{1-4} (225 000)	7.9	7.5	8.1	5.9	7.4ab	7.4
C_{1-4} (315 000)	9.5	9.1	8.2	6.1	8.2a	8.2
D_{1-4} (405 000)	8.4	9.4	8.4	7.2	8.4a	8.4
Average (on slope)[a,c]	8.2a	8.2a	8.0a	6.2b		

[a] Averages followed by a different letter (a, b) were found to be statistically different at the 0.05 level of significance.
[b] Average whole stalk yield of same plant population.
[c] Average whole stalk yield of same height of slope.

Table 2. Harvested plant number of kenaf in four plant populations and at four heights on the slope

Parameter	Final thinned seedling stand[a] (plants/10 m^2)	Plant death rate[b] (%)	No. of harvested plant[c] (plants/10 m^2)		Harvested plant[c] (%)	
			Small plant[d]	Effective plant[e]	Small plant[f]	Effective plant[g]
Plant population (plants/ha)						
A_{1-4} (135 000)	135	5.2	22d	106b	17.4c	82.6a
B_{1-4} (225 000)	225	11.6	64c	135b	32.4b	67.6b
C_{1-4} (315 000)	315	14.0	95b	176a	34.5b	65.5b
D_{1-4} (405 000)	405	14.3	165a	182a	47.3a	52.7c
Height on slope (m)						
4–5	270[h]	15.5	67	150	28.5	71.5
5–6	270	14.3	79	147	31.4	68.6
6–7	270	8.4	96	154	35.9	64.1
7–8	270	6.8	104	148	35.8	64.2

[a] Seedling stand was thinned finally for the designed plant population on June 9.
[b] Averaged value from $(a - d - e)/a \times 100\%$.
[c] Averages within columns followed by a different letter (a, b) were found to be statistically different at the 0.05 level of significance.
[d] Harvested plants smaller than one-third of average plant height or diameter.
[e] Harvested plants excluding small plants.
[f] Averaged value from $d/(d + e) \times 100\%$.
[g] Averaged value from $e/(d + e) \times 100\%$.
[h] Averaged seedling stand of four designed plant populations (A_n, B_n, C_n, D_n; $n = 1 - 4$).

cal dimensions should be selected. The kenaf variety Zhehong 832 has been shown to have a higher yield with less dimension decrease and a larger number of effective plants.[10] The Zhehong 832 variety for textile is recommended for large population planting on flat land. Mei[6] recommended Zhehong 8310 as an optimum variety on hillsides for papermaking. We used the Zhehong 8310 in this investigation.

Statistically significant differences in plant height and stem diameter were detected among plant populations (Table 3). In terms of the location on the slope, significant differences were detected only in plant height. Large plant height causes a larger yield at a lower location on the slope. The larger plant population results in inferior physical dimensions, short plant height, and thin stem diameter. A statistically significant difference is not detected in the bast/core ratio, although it tends to increase slightly with an increase in plant population. From the combined results in Tables 1 and 3, it can be coucluded that a larger population can increase the whole stalk yield of the colony at the cost of the individual physical dimensions. Therefore, the plant population should be selected after considering both the whole stalk yield and the dimensional requirement, which affects the whole stalk pulp qualities.[7]

Fiber length distributions

Representative samples from trial areas A_2 (135 000 plants/ha), B_2 (225 000 plants/ha), C_2 (315 000 plants/ha), and D_2 (405 000 plants/ha) were used to analyze the fiber length distribution; the Kajaani FS-200 fiber length analyzer was used. Fiber separation and impurity removal from the samples were conducted by methods we reported earlier.[8] A representative pattern of the fiber distribution is shown in Fig. 2. There is a significant difference between bast and core fiber distributions but small differences between the bast and core fiber distributions among the four plant populations. Both bast and core showed similar tendencies in terms of average fiber lengths and proportions of long fiber among the four plant populations (Table 4). The smaller plant populations of A_2 and B_2, well-grown plants with large

Table 3. Physical compositions of kenaf stalk in four plant populations and at four heights on the slope

Parameter	Height[a] (cm)	Diameter[a,b] (cm)	Bast/core ratio[c]
Plant population (plants/ha)			
A_{1-4} (135000)	274.0a	0.91a	0.513
B_{1-4} (225000)	265.7ab	0.84ab	0.539
C_{1-4} (315000)	253.4bc	0.79b	0.569
D_{1-4} (405000)	246.4c	0.78b	0.574
Height of slope (m)			
4–5	270.4a	0.87	0.587
5–6	269.1a	0.86	0.552
6–7	257.7a	0.81	0.525
7–8	242.3b	0.78	0.531

[a] Averages within columns followed by a different letter (a, b) were found to be statistically different at the 0.05 level of significance.
[b] Stem diameter at one-third of the plant height from the bottom.
[c] Ratio of oven-dried weight.

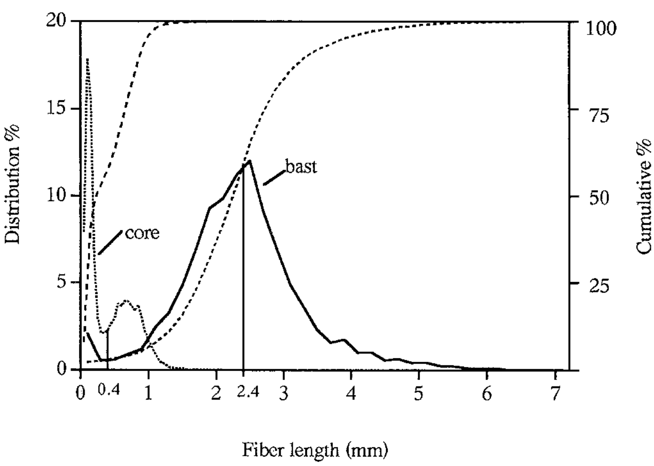

Fig. 2. Representative fiber distribution charts of bast and core samples from trial area B_2

stalk dimensions of height and diameter as shown in Table 3, had a longer average fiber length and higher proportion of long fiber compared to those from C_2 and D_2. The results in Table 4 show that the plant population of B_2 had a longer fiber length and a better fiber length distribution than that of A_2, which might be caused by elongation of kenaf fiber. The fiber, elongation have been affected by both the self-growth of fiber and the individual plant growth competition. In other words, the large plants from the A_2 population experienced less competition among plants, and the fiber elongation was not enough. The severe competition in the D_2 plant population caused the average fiber length of bast and core to be only 2.10mm and 0.46mm, respectively. For this reason, B_2 was considered the best of the four populations in Table 4.

Chemical compositions

Table 5 shows the chemical compositions of harvested kenaf whole stalk samples (A_2–D_2). The larger plant populations of C_2 and D_2 had higher holocellulose contents than those of A_2 and B_2. The lignin content of D_2 showed the highest value, and the alcohol-benzene extractives content showed only small differences among the four plant populations. The average sum of alcohol-benzene extractives, holocellulose, and lignin content was 91.7%, which is different from that of wood (generally a little more than 100%).[11] This might be due to a large amount of hot-water extractives (15.6% average) in these kenaf whole stalks. The hot-water extractives content of 5.0% (average) from 16 softwood species and 3.9% (average) from 21 hardwood species were reported by Fengel and Wegener.[11] The larger plant populations of C_2 and D_2 showed lower hot-water extractives contents than those of A_2 and B_2. Hot-water extractives and holocellulose contents had an adverse tendency: They showed a minimum and maximum in the plant population of B_2, respectively. Cellulose content increased as the plant population increased.

Table 4. Fiber lengths and their distributions of kenaf bast and core in four plant populations

Plant population (plants/ha)	Bast fiber length[a] (mm)	Proportion[b] of long fiber ≥ 2.4 mm (%)	Core fiber length[a] (mm)	Proportion[b] of long fiber ≥ 0.4 mm (%)
A_2 (135000)	2.59	37.54	0.60	40.83
B_2 (225000)	2.71	46.97	0.68	42.69
C_2 (315000)	2.34	24.81	0.53	37.52
D_2 (405000)	2.10	17.07	0.46	29.97

[a] Fiber length-weighted average length.
[b] Calculated from the distribution chart.

Pulp characteristics

Total pulp yield

Table 6 shows the whole stalk kraft pulp yields of kenaf grown in the four plant populations. The pulp yield decreased with an increase in plant population, with a maximum difference in pulp yield of 1.3%. Larger plant populations had a higher bast/core ratio (Table 3) and lower hot-water extractives and higher holocellulose and cellulose content (Table 5), which are usually considered to be favorable for obtaining a high pulp yield. The results in Table 6 show an opposite tendency. Cheng et al.[7] showed that small kenaf plants (inferior growth) that had a higher bast/core ratio, lower hot-water extractives content, and higher holocellulose content gave a lower pulp yield than superior growth plants. This result also argues against the general consensus regarding pulpwood. Some results have attributed the reported structural differences of kenaf lignin to the different varieties of kenaf and the different growing conditions used.[12,13] Thus kenaf fiber quality for pulping should be confirmed by an actual pulping condition. More detailed study is required on this matter.

Table 5. Chemical compositions of kenaf whole stalk in four plant populations

Plant population (plants/ha)	Alcoho–benzene extractives[a] (%)	Holo-cellulose[b] (%)	Lignin[b] (%)	Sum of Al-ben, holocellulose, and lignin (%)	Hot water extractives[a] (%)	Cellulose[a,c] (%)
A_2 (135000)	2.7	72.7	13.8	89.2	16.5	37.1
B_2 (225000)	2.8	72.1	14.4	89.3	17.8	38.0
C_2 (315000)	2.6	76.4	14.1	93.1	15.1	38.3
D_2 (405000)	2.7	76.2	16.1	95.0	12.9	39.1
Average	2.7	74.4	14.6	91.7	15.6	38.1

[a] Based on unextracted samples.
[b] Based on alcohol–benzene extractives free samples.
[a] Nitric acid–ethanol procedure.

Table 6. Yields and fiber properties of kenaf whole stalk kraft pulp[a] in four plant populations

Plant population (plants/ha)	Pulp yield[b] (%)	Length-weighted fiber length (mm)	Proportion[c] of fiber length ≤ 0.4 mm (%)	Fiber coarseness (mg/m)
A_2 (135000)	43.5	1.20	60.57	0.171
B_2 (225000)	43.4	1.27	61.68	0.171
C_2 (315000)	42.2	1.24	62.73	0.164
D_2 (405000)	42.2	1.21	60.16	0.159

[a] Pulping condition: 18% active alkali as Na_2O; 25.0% sulfidity; 60 min to 170°C and 90 min at 170°C; heated in a 110-ml microbomb.
[b] Based on the oven-dried weight of the whole stalk.
[c] Calculated from the distribution chart.

Fiber length distribution of whole stalk pulp

The length–weighted average fiber lengths of whole stalk kraft pulp and its distribution at the four plant populations are not significantly different (Table 6), but they are different from the order of the original bast and core. The plant population of B_2 still had the longest pulp fiber length, reflecting the fiber length of bast and core shown in Table 4. The plant population of C_2 showed the largest amount of pulp fiber length shorter than 0.4 mm. This does not reflect the original order of short fiber proportion (≤ 0.4 mm) which is mainly found in the core (Fig. 2). The order difference in fiber length between kenaf whole stalk kraft pulp and original bast and core has been reported,[1] and the order difference in Tables 4 and 6 might come from some anatomical development differences in the four plant populations. Table 6 also shows that the larger the plant population, the smaller is the fiber coarseness of whole stalk kraft pulp.

Strength properties of kraft pulp sheets

Table 7 shows the strength properties of whole stalk unbeaten kraft pulp sheets of kenaf from samples grown in the four plant populations. The plant populations B_2 and C_2 have the advantage in pulp sheet strength properties over A_2 and D_2. B_2 shows the highest values in breaking length, burst index, and folding endurance; and C_2 shows the largest tear index. The initial freeness of the pulps decreased slightly with increasing plant population. The smallest population (A_2) and the largest population (D_2) showed rather inferior pulp sheet strength properties. Such weakness might partly be due to their shorter fiber length and lower proportion of fibers shorter than 0.4 mm in the kraft pulp (Table 6).

In this connection, Fig. 3 shows that the length-weighted average fiber length of the pulp had a highly positive correlation with the breaking length (correlation coefficient r = 0.962), burst index (r = 0.989), and folding endurance (r = 0.977) but not with the tear index (r = 0.666). Figure 4 shows that the proportion of pulp fiber shorter than 0.4 mm had a high positive correlation with the tear index (r = 0.998) but less correlation with the other three strength properties. These results indicate that a little higher content of short kenaf pulp fiber can increase the tear index of unbeaten kenaf whole stalk pulp, and that the length-weighted average kenaf fiber length greatly affects the other pulp strength properties.

Overall evaluations

The overall evaluations of agronomic properties and whole stalk kraft pulp characteristics in four plant populations are shown in Table 8. The largest plant population (D) had the advantages of whole stalk yield and cellulose content, but its total pulp yield and pulp sheet strength were lower. The smallest plant population (A) had the advantages of stalk physical dimension and total pulp yield, but pulp sheet strength was lower. The plant population of B was superior in all properties except whole stalk yield and cellulose content. The plant population of C was also superior in all properties except total pulp yield and stalk physical dimension. Therefore, a kenaf population between 225000 and 315000 plants/ha, which is a little higher than that for kenaf bast fiber production for textiles, is an optimum plant population for kenaf whole stalk production for kraft pulping in this area.

Conclusions

Kenaf whole stalk yield of about 70% compared to that of normal flat farmland was obtained from arid hillside land in

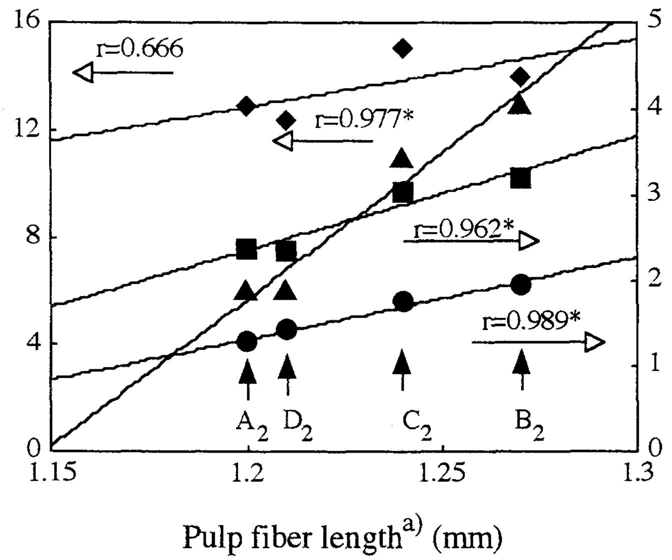

Fig. 3. Relations between sheet strength properties and fiber length of kenaf whole stalk kraft pulp (on unbeaten and unbleached kraft pulp). The pulp fiber length is the length-weighted average fiber length. *r*, correlation coefficient; *, significant at 0.05 level. A_2–D_2, as in Fig. 1. *Triangles*, bolding endurance (MIT, No.); *diamonds*, tear index ($mN{\cdot}m^2/g$); *squares*, breaking length (km); *circles*, burst index ($kPa\,m^2/g$)

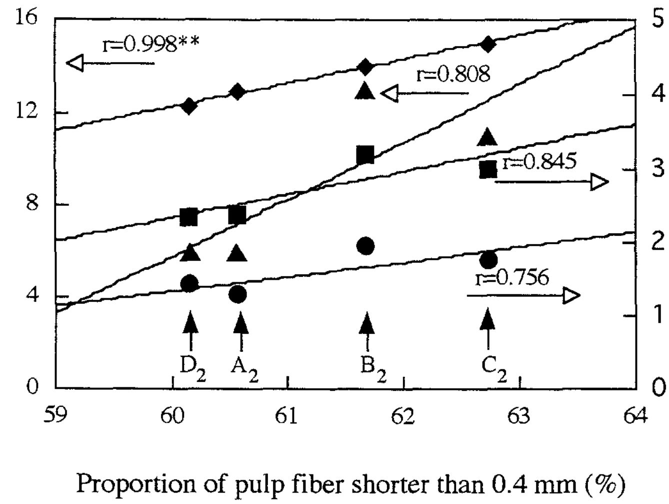

Fig. 4. Relations between sheet strength properties and short fiber distribution of kenaf whole stalk kraft pulp (unbeaten and unbleached kraft pulp) *r*, correlation coefficient; **, significant at 0.01 level; A_2–D_2, as in Fig. 1. See Fig. 3 for explanation of symbols

Table 7. Sheet strength properties of kenaf whole stalk kraft pulp[a] in four plant populations

Plant population (plants/ha)	Freeness (ml)	Breaking length (km)	Burst index ($kPa\,m^2/g$)	Folding endurance[b]	Tear index ($mN{\cdot}m^2/g$)
A_2 (135 000)	670	2.39	1.28	0.78	12.98
B_2 (225 000)	660	3.22	1.95	1.11	14.03
C_2 (315 000)	660	3.04	1.76	1.04	15.07
D_2 (405 000)	650	2.37	1.41	0.78	12.39

[a] On unbeaten and unbleached kraft pulp.
[b] Log10 MIT folding endurance.

Table 8. Overall evaluations of agronomic properties and whole stalk kraft pulp characteristics in four plant populations

Agronomic properties and whole stalk kraft pulp characteristics	Ratings for four plant population (plants/ha)			
	A (135 000)	B (225 000)	C (315 000)	D (405 000)
Whole stalk				
Yield	−	±	++	++
Dimension	+	+	±	−
Fiber length	+	++	+	−
Cellulose	−	−	+	+
Lignin	+	+	+	−
Kraft pulp				
Yield	+	+	−	−
Fiber length	−	+	+	−
Sheet strength	−	+	+	−
Total	4+	8+	8+	3+

−, inferior; ±, general; +, superior; ++, excellent.

China. A plant population of 225000–315000 plants/ha can be recommended because of a higher whole stalk yield and pulp qualities. Other factors, including confirmation of the selected plant population in this work, should be examined further to increase the yield and pulp qualities. Establishment of a pulp mill in China will facilitate such confirmation.

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