Pulping and bleaching of Malaysian oil palm empty fruit bunches

ROBERT W. HURTER AND MEDWICK V. BYRD

ABSTRACT: Oil palm empty fruit bunch (EFB) was evaluated as a raw material for papermaking pulp production. The EFB was chopped, screened, and washed before cooking. Preliminary bench-scale trials were carried out using soda and soda-anthraquinone cooking followed by bleaching using elemental chlorine free and totally chlorine free sequences. Pilot-scale soda cooking was carried out in a 2300 L spherical digester using the soda process followed by a three-stage elemental chlorine free bleaching sequence. Unbleached and bleached EFB pulps were tested for physical and optical properties. Comparisons were made between the properties of the EFB pulps and bleached kraft eucalyptus pulp. The EFB unbleached and bleached pulps were acceptable for papermaking.

Application: For mills located near oil palm plantations, EFB could be a low-cost fiber resource for pulping.

Oil palm (*Elaeis guineensis*) is cultivated on a large scale as a source of edible oil in Central and West Africa, where it originated, as well as in Indonesia, Malaysia, and Thailand. Malaysia has about 4.7 million hectares of oil palm plantations that annually produce about 19 million metric tons of palm oil and 2 million metric tons of palm kernel oil. A typical plantation yields about 20 metric tons of fruit/ha/year but some new clones yield up to 28 metric tons/ha/year.

Oil palm plantations generate a significant amount of biomass in the form of fronds from harvesting and pruning, trunks and canopy from replanting, and empty fruit bunches (EFB). Fronds have no significant commercial uses and are typically returned to the soil as mulch. Trunks and canopy are typically pulverized and returned to the soil; some trunks are converted to plywood in combination wood veneers. Empty fruit bunches have been commercially used to produce low-value products such as construction materials, fiberboard, and molded fiber products. However, most EFB is returned to the plantations as mulch. Malaysian EFB production varies but is conservatively estimated at about 20 million metric tons/year, or about 4.3 metric ton/ha/year [1].

This study was carried out to establish pulping and bleaching conditions for EFB to produce paper grade pulps and to evaluate the pulp properties.

EXPERIMENTAL

All work was carried out at the North Carolina State University Department of Forest Biomaterials laboratory and pilot plant (Raleigh, NC, USA) under the direction of HurterConsult. All tests were conducted in accordance with TAPPI methods.

Materials

Malaysian EFB fiber strands were used for all experiments. The fiber strand raw material had been extracted from the EFB, thoroughly washed and cleaned, and then dried by forced air. The EFB fiber strands were tan in color and approximately 0.5–15 cm in length, with most fiber strands in the 5–12 cm range. The longer fiber strands were extensively intertwined in a manner similar to a bird nest. The EFB appeared to be free of stones and dirt, but dust and seed hulls were present.

Composite samples were taken from random boxes and tested for moisture content and hot water solubility. For the hot water solubility test, the samples were immersed in hot water (54°C) for 24 h. The hot water solubility was tested in this manner instead of using a standard test method (TAPPI T 207 “Water solubility of wood and pulp”) because the delivered EFB fiber had been dried by forced air, which made it difficult to absorb cooking chemicals. We found that soaking EFB fiber in this manner allowed for better cooking and thus needed to measure the solubility losses.

EFB fiber preparation

Through trial and error, we found that the as-received EFB needed to be chopped, screened, and soaked overnight before cooking. The EFB fiber raw material was chopped to 2–3 cm lengths by running it twice through an Appleton pilot-scale wood chipper (Appleton Manufacturing Division; Neenah, WI, USA). The wood chipper featured a 24-in. flywheel equipped with two knives and driven by a 20-hp motor at 300 rpm. The EFB raw material was fed normal to the disk rotation and the resulting kinetic energy, along with the high volume of air flow produced by the flywheel, propelled the chopped material out of the discharge chute. The chopped material was dry screened using a vibrating screen and stored in drums for later use.

Before introduction to the digester, the chopped and dry screened EFB fiber was soaked in warm water (30°C) overnight and then drained.

Variable	Range	Optimum
Cooking apparatus	(a) Two 3-L stainless bombs placed on rotating rack in heated-air oven (b) 30-L batch digester, direct steamed	30-L batch digester, direct steamed
Sample size	200–1000 o.d. g total batch size	1000 o.d. g total batch size
Cutting/Dry screening	No cutting or cutting and dry screening	Cut empty fruit bunches (EFB) to 2–3 cm lengths, wash/screen EFB to remove nut hulls and fines
Soaking	No soaking or overnight soaking	Soaked in warm water overnight, drained
Sodium hydroxide on o.d. fiber	18%–23%	21%
Anthraquinone on o.d. fiber	0%–0.1%	0%
Liquor-to-fiber ratio	4:1–10:1	10:1 start
Maximum temperature	160°C–170°C	165°C–170°C
Time to maximum temperature	45–90 min	45 min
Time at maximum temperature	90–187 min	135 min
H-factor target	1490–1750	1750
Post-cooking treatment	Mixed, washed, and screened	Mixed, washed, and screened

I. Bench-scale cooking apparatus, procedures, and conditions.

Cooking

For the bench-scale trials, both the soda and soda-anthraquinone processes were tested using a range of test conditions (**Table I**) to determine optimum cooking conditions. A total of 11 cooks was carried out (five using 3-L bombs and six using a 30-L batch digester). Only the results for the optimum test conditions are reported in this paper.

Pilot-scale cooking was done in a 2300-L spherical digester, rotated at 10 rpm, using the soda process with the test conditions in **Table II**. Prepared EFB material was loaded into the digester, followed by caustic and adequate water to achieve the desired liquor-to-fiber ratio. The digester was then closed and heated with direct steam injection during rotation. When the target temperature and pressure were achieved, the digester was allowed to rotate, with periodic injections of steam, until the target H-factor was achieved. Rotation was then terminated, followed by depressurization (no blowing) and dumping. A sample of black liquor was obtained and saved for testing.

Pulp washing, screening, and cleaning

The bench-scale cooked material was drained of black liquor and then fiberized in cold tap water for 20 min using an immersion mixer. The slurry was screened using a 0.25-mm slotted screen.

The pilot-scale cooked material was collected in a catch box covered with fine mesh wire. Black liquor passed through the wire and was separated from the pulp. The pulp was then washed in the box to remove the bulk of the black liquor. The resulting brownstock was then pumped into a 9500-L tank and diluted to approximately 1% consistency. This slurry was passed through an Ahlstrom pressure screen (Ahlstrom; Helsinki, Finland) equipped with 0.25-mm slots. Material passing through the screen was collected in a separate tank. Rejects were directed back into the feed tank, to minimize good fiber loss. This process was continued until no more good fiber was observed in the accept stream. The screen accepts were cleaned using a Beloit Posi-Flow cleaner (Metso; Helsinki, Finland) with a feed pressure of 25 psig and an accept pressure of 10 psig. The cleaner accepts were dewatered in the wire-bottom catch box described previously.

Black liquor passing through the wire was collected and tested for residual alkali, to provide an estimate of alkali consumption during cooking. Screen accepts were tested for kappa number (TAPPI Standard Test Method T 236 "Kappa number of pulp"), total yield, fiber length distribution (optical instrument), 0.5% CED viscosity (TAPPI Method T 230 "Viscosity of pulp [capillary viscometer method]"), brightness (TAPPI Method T 525 "Diffuse brightness of paper, paperboard and pulp [d/0] – ultraviolet level C"), and Canadian Standard Freeness (TAPPI Method T 227 "Freeness of pulp [Canadian standard method]").

Bleaching

Bench-scale bleaching trials tested two sequences, DEDED and OZPP, both with a target brightness of 90% ISO. Medium-consistency bleaching with chlorine dioxide, caustic, and hy-

Variable	For Unbleached Pulp	For Bleached Pulp
Cooking apparatus	2300-L batch digester, direct steamed	2300-L batch digester, direct steamed
Number of cooks	3	5
Cook size	45–68 o.d. kg	68 o.d. kg
Cutting/dry screening	Cut empty fruit batch (EFB) to 2–3 cm lengths, wash/screen EFB to remove nut hulls and fines	
Soaking	Soaked in warm water (30°C) overnight, drained	
Sodium hydroxide on o.d. fiber	21%	22%
Anthraquinone on o.d. fiber	0%	0%
Liquor-to-fiber ratio	10:1 start	10:1 start
Maximum temperature	165°C–170°C	165°C–170°C
Time to maximum temperature	20–60 min	40–45 min
Time at maximum temperature	115–147 min	135–146 min
H-factor target	1800	1750
Post-cooking treatment	Mixed, washed, and screened	Mixed, washed, and screened

II. Pilot-scale cooking apparatus, procedures, and conditions.

Sequence	Stage	Time, min	Temperature, °C	Pressure, psi	Pulp Consistency, %
Bench Scale					
DEDED	D_0	60	70	--	10
	E_1	60	70	--	10
	D_1	180	70	--	10
	E_2	60	70	--	10
	D_2	180	70	--	10
OZPP	O	30	105	100	10
	Z	9	20 (room temperature)	--	3
	Pp	90	105	--	10
	P	240	90	--	10
Pilot Scale					
DEpD	D_0	60	70	--	10
	Ep	60	70	--	10
	D_1	180	70	--	10

III. Bleaching conditions.

Sequence	Stage	ClO_2	NaOH	H_2O_2	O_2	O_3	DTPA	DTMPA	$MgSO_4$	$NaSiO_3$	H_2SO_4
Bench Scale											
DEDED	D_0	18	--	--	--	--	--	--	--	--	--
	E_1	--	24	--	--	--	--	--	--	--	--
	D_1	14	7	--	--	--	--	--	--	--	--
	E_2	--	5	--	--	--	--	--	--	--	--
	D_2	5	--	--	--	--	--	--	--	--	--
OZPP	O	--	25	--	n/a	--	--	--	5	5	--
	Z	--	--	--	--	21	5	--	--	--	9.8
	Pp	--	40	40	--	--	--	2	5	5	--
	P		40	40	--	--	--	2	5	5	--
Pilot Scale											
DEpD	D_0	35	--	--	--	--	--	--	--	--	12
	Ep	--	30	10	--	--	--	5	5	--	14
	D_1	40	--	--	--	--	--	--	--	--	--

ClO_2 = chlorine dioxide; NaOH = sodium hydroxide; H_2O_2 = Hydrogen peroxide; O_2 = oxygen; O_3 = ozone; DTPA = diethylenetriaminepentaacetic acid; DTMPA = diethylene triamine penta (methylene phosphonic) acid; $MgSO_4$ = magnesium sulfate; $NaSiO_3$ = sodium silicate; H_2SO_4 = sulfuric acid.

IV. Bleaching chemical charges (kg/o.d. metric ton).

Moisture Content, %		Hot Water Solubility Losses, %	
Sample 1	6.6	Sample 1	13
Sample 2	6.1	Sample 2	7.2
Sample 3	6.7	--	--
Average	6.5	Average	11.1

V. Empty fruit bunches (EFB) raw material.

Material	% of Air-dried Mass by Weight		
	Trial 1	Trial 2	Average
Longer/coarser	64.0	73.2	68.6
Shorter/slender	22.4	10.9	16.6
Fines/dust	12.8	15.7	14.3
Hulls	0.8	0.2	0.5

VI. EFB chopped raw material dry screening analysis.

drogen peroxide was carried out in sealed plastic bags immersed in a heated water bath. Chemicals were mixed into the pulp using an industrial kitchen mixer fitted with a kneading blade. The pulp was then sealed into the bags. The bags were kneaded periodically during the reaction. Low-consistency bleaching using ozone (Z) was carried out by sparging ozone gas into a mixing vortex of pulp slurry. Bleaching with oxygen was carried out in 3-L pressure vessels placed on a rotating rack in a hot-air oven.

All pilot-scale bleaching was done at 10% consistency in a 950-L stirred tank. Bleaching was done using a three-stage elemental chlorine free sequence. After each stage, the slurry was tested for chemical consumption and then dumped into the wire-bottom catch box to separate most of the residual liquor.

After each bleaching stage, a liquor sample was collected and tested for residual chemical, to provide an estimate of chemical consumption. Washed pulp from each stage was tested for yield, brightness (TAPPI Method T 525), Canadian Standard Freeness (TAPPI Method T 227), and 0.5% CED viscosity (TAPPI Method T 230). **Tables III** and **IV** provide the bleaching conditions and bleaching chemical charges, respectively.

RESULTS AND DISCUSSION

EFB raw material

Table V shows the EFB raw materials. The moisture content of three random samples ranged from 6.1% to 6.7% with an average of 6.5%. The results show good uniformity between the samples; however, the moisture content was lower than one would expect from nonwood plant fiber raw materials. Over time, many lignocellulosic materials will achieve equilibrium of about 10% moisture content. The lower than expected moisture content was likely a result of the forced drying of the EFB fiber raw material.

The solubles losses in the two hot water solubility tests were 7.2% and 13.0% with an average of 11.1%. There was no evidence of oily residue in the filtrate, which was light tan in color, with a small amount of fine crill that settled out. It appeared there might be considerable variability in the hot water solubles content of EFB raw material; however, the samples were small, so it is likely that pulping larger samples will result in lower variability. That there was no evidence of oily residue in the filtrate indicates well-

Variable	Bench Scale	Pilot Scale							
		For Unbleached Paper			For Bleached Paper				
Cook no.	Optimum	13	14	15	16	17	18	19	20
Kappa number	18.4	20.3	21.4	24.8	28.0	26.7	28.5	29.8	26.8
ISO brightness	37.5%	36.1%	--	--	33.9%	34.4%	32.0%	30.9%	31.5%
Total yield	44.2%	42.6%			43.6%		50.9%		
Screened yield	43.6%	40.9%			41.2%		50.3%		
Screened rejects	1.53%	4.0%			5.5%		1.1%		
Black liquor terminal pH	11.8	12.5	--	--	10.9	10.8	10.8	10.9	10.9
Freeness, mL CSF	--	622	428	320	430	529	445	510	530
CED Viscosity, cp	--	20.3	--	--	16.5	15.8	--	--	--

VII. Cooking results.

washed material. The fine crill likely was residual dust from the fiber strand extraction process and would be mostly washed out in a good fiber preparation system in a commercial operation.

Fiber preparation

Table VI shows the fiber preparation. The wood chipper separated the EFB material and reduced the length of long strands well. It did not appear to excessively cut or damage fiber. There was, however, a large amount of dust produced. The average length of chopped EFB fiber was 2–3 cm.

Dry screening analysis shows that the chopped EFB contained a significant amount of fines and dust. The longer/coarser and shorter/slender fractions appeared suitable for pulping and papermaking. However, the fines/dust fraction was of concern, especially because it made up more of the material weight than anticipated. About half of this fraction was finely powdered material and dust and the other half was fine filaments and hairlike fibers. This combined fraction could be responsible for the high alkali consumption and lower yields obtained from bench-scale cooks 2 and 3. Bench-scale cooks 4 and 5 were carried out with dry screened EFB raw material and bench-scale cooks 6–11 were carried out using dry screened and washed EFB raw material.

Because the bench-scale cooking trials showed that the fines/dust fraction had a negative effect on alkali consumption, yield, and pulp quality, this fraction along with the hulls was not used in the pilot-scale cooks.

Cooking

Table VII shows cooking results. The optimum bench-scale cooking conditions resulted in a total and screened yield on o.d. raw material of 44.2% and 43.6%, respectively. The pulp had a kappa number of 18.4% and 37.5% ISO brightness. Alkali consumption was 99.1%.

An initial pilot-scale cook was carried out at the optimum bench-scale cooking conditions. The resultant pulp was not acceptable so the pilot-scale cooking conditions were adjusted accordingly.

A total of eight pilot cooks were carried out: three to produce pulp for unbleached papermaking and five to produce pulp for bleached papermaking. Pulp washing, screening, and cleaning were done in three batches:

- Group 1—for pulp for unbleached papermaking, cooks 13, 14 and 15
- Group 2—for pulp for bleached papermaking, cooks 16 and 17
- Group 3—for pulp for bleached papermaking, cooks 18, 19, and 20

The results from group 1 and 2 pilot cooks are reasonably comparable with the optimum bench-scale cook results in terms of yield, despite the lower kappa number of the optimum bench-scale cook, particularly with respect to group 2 cooks.

For group 1 and 2 pulps, the total yield was 42.6% and 43.6%, respectively, and the screened yield was 40.9% and 41.2%, respectively, even though the average kappa number was 22.2 for group 1 cooks and 27.4 for group 2 cooks. However, group 3 pulps had significantly higher total and screened yield, 50.9% and 50.3%, respectively. The average kappa number for the group 3 cooks was 28.3, similar to group 2. We have no explanation for the significant yield gain seen for group 3, other than the possibility that the EFB samples used might have been more heavily weighted toward the longer/coarser fraction than group 2 cooks.

Bench-scale bleaching

Table VIII shows bleaching results. For the DEDED sequence, the final brightness was 90.7% ISO, which met the target of 90% ISO. This was achieved using a total of 37 kg of

Stage	pH	Consumption			Residuals, kg/ o.d. metric ton	Yield, %	Freeness, mL CSF	Brightness, % ISO	Kappa Number	Viscosity, CP
		—	%	kg/ o.d. metric ton						
DEDED Sequence – Bench Scale										
D_0	2.4		100	18.0	0	n/a	n/a	44.4	n/a	n/a
E_1	12.5		n/a	n/a	n/a	92.3	577	56.9	3.8	16.6
D_1	4.5		89.2	12.5	1.5	95.6	555	84.0	1.1	13.6
E_2	11.6		n/a	n/a	n/a	n/a	n/a	84.2	n/a	n/a
D_2	4.5		85.4	4.3	0.7	96.7	540	90.7	0.5	12.0
					Overall Yield	85.3				
OZPP Sequence – Bench Scale										
O	10.9	NaOH	73.5	18.4	6.6	95.8	660	48.2	11.3	16.1
Z	1.5		2.1	21.0	nil	97.2	540	57.5	8.2	14.5
P_1	11.3	NaOH	86.9	34.8	5.2	93.1	510	80.1	4.1	8.7
		H_2O_2	94.8	37.9	2.1					
P_2	11.7	NaOH	80.3	32.1	7.9	94.4	430	85.5	3.3	8.3
		H_2O_2	59.5	23.8	16.2					
					Overall Yield	81.2				
DEpD Sequence – Pilot Scale										
D_0	3.3		97.1	34.0	1.0	92.6	250	62.0	2.7	12.9
Ep	10.8		98.0	29.4	0.6	94.1	210	68.5	2.0	12.8
D_1	3.6		78.5	31.4	8.6	98.4	201	85.1	1.4	10.4
					Overall Yield	85.7				

VIII. Bleaching results.

chlorine dioxide per o.d. metric ton of unbleached pulp. Because 100% of the chlorine dioxide was consumed in the D_0 stage, increasing the chlorine dioxide charge in this stage likely would allow for achieving an 86% ISO brightness after the D_1 stage. The viscosity decreased from 20.3 cp for the unbleached pulp to 12.0 cp for the fully bleached pulp. Although this is a significant drop in viscosity, the final pulp viscosity is still reasonably good. The final kappa number of 0.5 is in the range expected for fully bleached wood pulps. Overall, pulp freeness after bleaching is high, which indicates good drainability of the pulps. The overall total bleaching yield was 85.3%.

For the OZPP sequence, the final brightness was 85.5% ISO, well below the target of 90% ISO despite using 80 kg of hydrogen peroxide per o.d. metric ton of unbleached pulp. Peroxide consumption in the first pressurized P stage was 94.8% but only 59.5% in the second unpressurized P stage. It is possible that better brightness results might have been achieved with a second pressurized P stage rather than an unpressurized stage. The viscosity decreased from 20.3 cp for the unbleached pulp to 8.3 cp for the fully bleached pulp. It appears that most of the drop in viscosity occurred in the oxygen delignification and pressurized peroxide stages. It is possible that using a second pressurized peroxide stage would result in a further viscosity drop. Further process optimization might reduce the drop in viscosity. Although this is a significant drop in viscosity, the final pulp viscosity is still in an acceptable range. The final kappa number of 3.3 is much higher than expected for fully bleached pulp. Overall, pulp freeness after bleaching is high, which indicates good drainability of the pulps. The overall total bleaching yield was 81.2%.

The overall total bleaching yield was lower than expected for both bleaching sequences. Our previous R&D and commercial observations indicate that typically, for nonwood fibers starting with an unbleached kappa number of about 15, a total bleaching loss in the order of 6%–7% is anticipated. For an unbleached pulp with a kappa number of 20, one could expect a yield loss in the order of 9%–11%. However, the total bleaching yield for both sequences shows higher losses than

Sequence	Brightness, % ISO	Brightness After Aging, % ISO_{1h}	Brightness Reversion, % ISO_{1h}	Brightness After Aging, % ISO_{3h}	Brightness Reversion, % ISO_{3h}
Bench Scale					
DEDED	89.2	88.5	-0.7	88.1	-1.1
OZPP	85.5	84.5	-1.0	83.9	-1.6
Pilot Scale					
DEpD	85.1	84.5	-0.6	84.3	-0.8
Note: The final brightness for the DEDED sequence was 90.7% ISO immediately after the bleaching trial. Some natural reversion (-1.5% ISO) took place during the time between the completion of the bleaching trial and the brightness reversion test.					

IX. Brightness reversion after final bleaching stage.

Pulps	Rev	Average Fiber Length (w/w), mm	Average Fiber Width, µm	Fines Content by Number, %
Bench Scale				
Unbleached Pulp	0	0.684	18.9	24.79
DEDED	0	0.822	18.3	28.06
OZPP	0	0.918	18.4	34.20
Pilot Scale				
Unbleached Pulp	0	0.720	19.4	25.76
DEpD	0	0.862	18.4	32.55
DEpD	4000	0.744	18.6	39.02

X. Fiber length analysis.

typically anticipated. We have no explanation for the high bleaching losses.

Pilot-scale bleaching

On the basis of the bench-scale bleaching results, we decided to use a DEpD sequence for the pilot-scale bleaching. The final brightness was 85.1% ISO, which met the target of 85% ISO. This was achieved using a total of 65 kg of chlorine dioxide per o.d. metric ton of unbleached pulp. The viscosity decreased from 16.1 cp for the unbleached pulp to 10.4 cp for the fully bleached pulp. Although this is a significant drop in viscosity, the final pulp viscosity is still reasonably good. The final kappa number of 1.4 is in the range expected for 85.1% ISO bleached pulp, but is still on the high side.

The freeness of the bleached pulp dropped substantially versus the unbleached pulp. This is an indication that mechanical action on the pulp using pilot-scale equipment during bleaching had a significant negative effect on the pulp and likely was the source of fines generation. Minimizing mechanical action in the commercial mill will be important for good quality bleached EFB pulp.

Overall bleaching yield of 85.7% is low but is similar to that experienced with the bench-scale testing. Even though the average kappa number of the unbleached pulp from the five cooks was 28.0, the total yield is still lower than what we would have anticipated. We have no explanation for the high bleaching losses.

Brightness reversion

Table IX shows brightness reversion results. For the bench-scale bleaching sequences, the DEDED sequence had brightness reversion ranging from 0.9 to 2.6 units if the natural reversion is included. The OZPP sequence experienced higher brightness reversion. Brightness reversion for the pilot-scale DEpD bleached pulp was the lowest at 0.8 units

Fiber length analysis

Table X shows results of fiber length analysis. For the bench-scale pulps, the average unbleached pulp fiber length on a weight/weight basis is 20%–30% shorter than that of the bleached pulps with no refining.

For the pilot-scale pulps, the average unbleached pulp fiber length on a weight/weight basis is 16.5% shorter than that of the bleached pulp with no refining. Even with significant re-

Test	Units	DEDED Bleached Pulp					OZPP Bleached Pulp				
Beating	rev	0	500	1000	1500	2000	0	300	500	1000	1500
Freeness	CSF, ml	540	423	364	306	252	430	300	248	195	143
Basis weight	g/m²	67.5	66.9	65.9	66.6	65.9	66.6	66.5	65.3	65.2	65.5
Thickness	µm	123.2	102.6	95.4	91.2	84.6	107	94.6	91.4	82	76.8
Bulk	cm³/g	1.83	1.53	1.45	1.37	1.28	1.61	1.45	1.4	1.25	1.17
Density	g/cm³	0.546	0.654	0.690	0.730	0.781	0.621	0.690	0.714	0.800	0.855
Tear index	mN·m²/g	9.78	10.19	9.77	9.84	9.84	7.57	8.04	7.57	7.26	7.05
Burst index	kPa·m²/g	3.12	3.78	4.39	4.58	5.05	3.66	3.92	3.98	4.00	4.29
Tensile index	Nm/g	37.85	47.75	47.55	47.81	50.95	39.49	44.85	45.05	47.47	48.42
Fold		48	115	203	340	700	67	131	177	312	652
Stiffness	mN	7.3	6.6	6.1	5.8	5.8	5.42	5.16	5.03	4.35	4.83
TEA	J/m²	111.9	195.5	153.8	125.6	140.5	113.3	130.2	122.3	119.6	88.1
Stretch	%	5.61	7.83	6.25	5.02	5.31	5.26	5.43	5.48	4.77	3.49
Smoothness	Sheffield, s	357	273	258	250	240	287	274	269	246	238
Porosity	Gurley, s	2.26	6.87	15.68	27.72	79.04	11.4	44.46	76.14	226.44	639.38

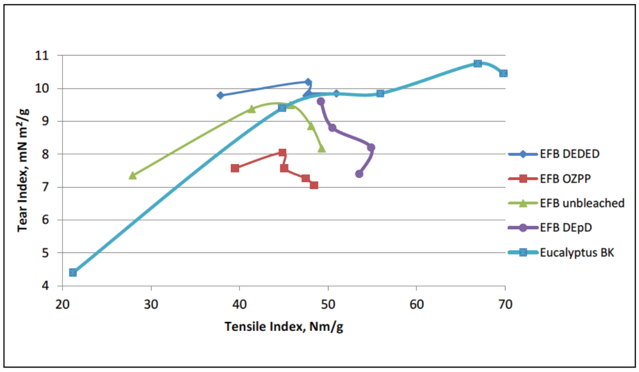
Notes: 1. Tear Index based on 4 ply. 2. Fold test based on M.I.T. Double Fold (2.5P). 3. Stiffness test based on Gurley 1 in. * 1-1/2 in. test.

XI. Bleached pulp properties (bench-scale pulps).

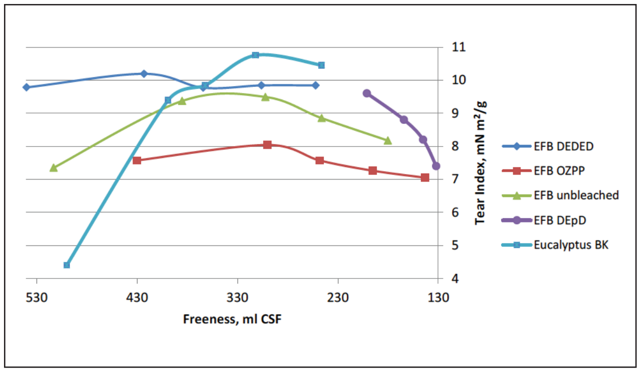
Test	Units	Unbleached Pulp					DEpD Bleached Pulp			
Beating	rev	0	750	1500	2250	3000	0	1000	2000	3000
Freeness	CSF, ml	513	385	302	246	180	201	164	145	132
Basis weight	g/m2	65.0	66.2	66.9	66.2	62.7	65.2	65.3	64.9	64.9
Thickness	µm	151.8	116.6	109.8	97.0	83.2	96.8	80.2	80.4	79.6
Bulk	cm³/g	2.34	1.76	1.64	1.47	1.33	1.50	1.20	1.20	1.20
Density	g/cm³	0.427	0.568	0.610	0.680	0.752	0.667	0.833	0.833	0.833
Tear index	mN·m²/g	7.35	9.37	9.49	8.85	8.17	9.6	8.8	8.2	7.4
Burst index	kPa·m²/g	1.75	3.54	4.21	4.25	4.72	4.1	4.4	4.5	4.6
Tensile index	Nm/g	27.95	41.38	45.76	48.11	49.29	49.19	50.48	54.86	53.52
Fold		13	51	122	368	570	310	946	1397	1238
Stiffness	mN	7.1	6.8	6.8	5.7	4.1	n/a	n/a	n/a	n/a
TEA	J/m²	51.3	138.2	166.2	138.1	115.0	156.0	108.5	120.0	85.3
Stretch	%	3.60	6.34	6.85	5.50	4.72	5.95	4.10	4.20	3.23
Smoothness	Sheffield, s	387	344	302	280	228	322	241	226	n/a
Porosity	Gurley, s	0.88	5.59	9.99	27.94	74.87	3.45	18.7	101.0	n/a

Notes:1. Tear Index based on 4 ply. 2. Fold test based on M.I.T. Double Fold (2.5P). 3. Stiffness test based on Gurley 1 in. * 1-1/2 in. test.

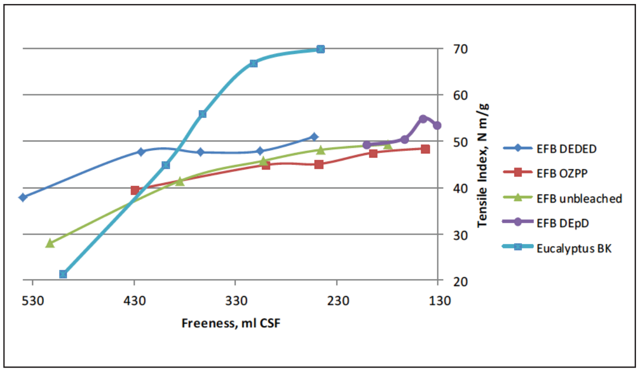
XII. Bleached pulp properties (pilot-scale pulps).



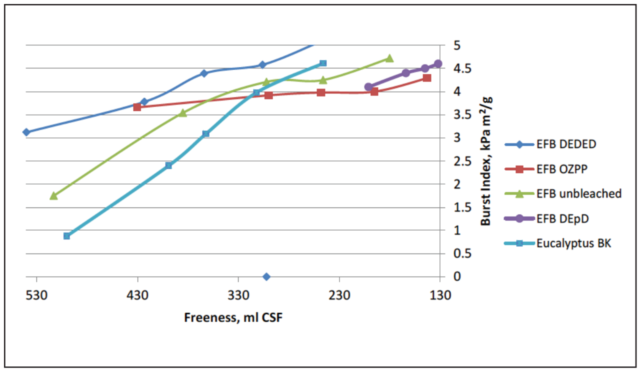
1. Tear index vs. tensile index.



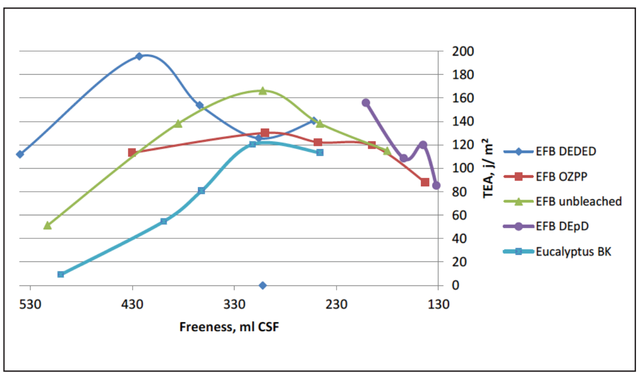
2. Tear index vs. freeness.



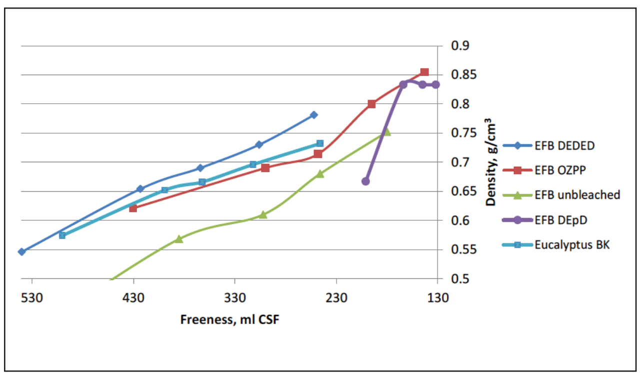
3. Tensile index vs. freeness.



4. Burst index vs. freeness.



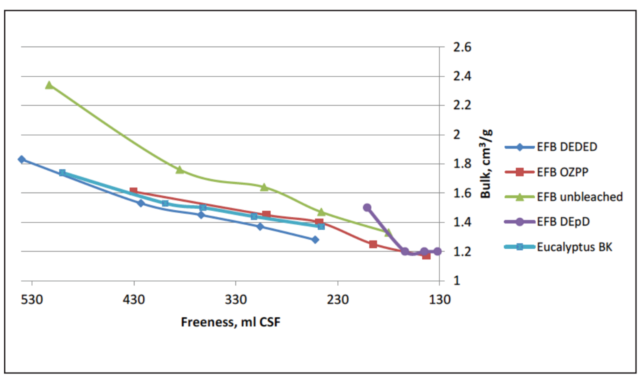
5. Tensile energy absorption (TEA) vs. freeness.



6. Density vs. freeness.

fining, the bleached pulp still has a longer average fiber length. However, the average fiber width of the unbleached and bleached pulps for all pulps is not significantly different.

Given the high fines content of the unbleached pulp, one would have thought that bleaching might reduce the fines content, thus giving the higher average fiber length for the bleached pulps. However, the fines content of the bleached pulps exceeds that of the unbleached pulp in all cases. One possible reason for the fiber length discrepancy might be the EFB samples used for the respective pulping and bleaching trials. Data are insufficient to determine whether this is the reason and more work needs to be done for a definitive answer.



7. Bulk vs. freeness.

Foelkel [2] provides a selected list of some important eucalyptus fiber/pulp characteristics and their range of variation for eucalyptus pulps. In this list, the weighted average fiber length is provided as 0.6–0.85 mm for eucalyptus. This places the EFB pulp in the range of good quality eucalyptus pulp in terms of average fiber length.

Bleached pulp properties

The properties of bench-scale soda cooked EFB DEDED and OZPP bleached pulps are provided in **Table XI**, and the properties of pilot-scale soda cooked EFB unbleached and DEpD bleached pulps are provided in **Table XII**. Selected physical properties of the EFB pulps are compared with eucalyptus bleached kraft pulp in **Figs. 1–7**.

Bench-scale EFB DEDED and OZPP bleached pulps (Table XI) both exhibited similar tensile index and burst index. However, the EFB DEDED bleached pulp had significantly higher tear index, tensile energy absorption (TEA), and bulk than the OZPP pulp.

Compared with eucalyptus bleached kraft pulp:

- EFB DEDED and DEpD bleached pulps achieved a tear index close to the maximum for eucalyptus pulp but with significantly less energy input (i.e., in a PFI mill, reaching maximum tear index required 3000 revolutions for eucalyptus versus 500 revolutions for EFB DEDED and 0 revolutions for EFB DEpD pulps).
- Tensile index for all EFB pulps was significantly lower.
- Burst index and TEA for all EFB pulps was higher.
- Bulk for the EFB bleached pulps was lower (especially for the OZPP bleached pulp).
- Bulk for the unbleached EFB pulp was higher.

CONCLUSIONS

Malaysian oil palm EFB can produce acceptable quality unbleached or bleached papermaking pulps using the soda process and either elemental chlorine free or totally chlorine free bleaching. For a commercial facility, bleaching using a three-stage DEpD sequence would reduce both capital and operating costs. Given the vast EFB resource, further study of this interesting fiber raw material is warranted. **TJ**

LITERATURE CITED

1. Daud, W.R.W. and Law, K-N., *BioResources* 6(1): 901(2011).
2. Foelkel, C., "The eucalyptus fibers and the kraft pulp quality requirements for paper manufacturing," *Eucalyptus Online Book & Newsletter*, ABCTP, Sao Paolo, February/March 2007. Available [Online] at www.eucalyptus.com.br/capitulos/ENG03_fibers.pdf <27June2017>.

ABOUT THE AUTHORS

This research was part of a 3-year project carried out during 2004-2007 for a HurterConsult client that was looking for new sources of low cost fiber. HurterConsult retained the copyright of all of the work and the client did not proceed with a project using EFB. Therefore, we decided to publish the work so that others could possibly benefit from it.

This research was similar to other work we have carried out at North Carolina State University (NCSU) on other nonwood fiber raw materials such as sisal, wheat straw, oat straw, flax, and industrial hemp. Only the raw material differed.

At the outset of the project, we were given cooking conditions for EFB fiber developed in Malaysia. However, using these conditions, we could not duplicate the cooking results at NCSU on the EFB fiber sent from Malaysia. It took some time to discover that the fiber had been dried by forced air before shipping. This appeared to have hornified the material to some extent, making it react differently in the digester. We found that soaking EFB fiber in hot water overnight allowed it to cook properly. We do not believe that this would be required in a commercial mill using fresh EFB fiber.

Interestingly, we found that totally chlorine free bleaching was less effective than elemental chlorine free bleaching. Also, elemental chlorine free bleached EFB pulps were almost as good as bleached eucalyptus pulp.

Mills that could benefit from this work will be location specific; that is, they need to be located near the source of EFB fiber as it cannot be shipped long distances cost effectively. For these mills, EFB fiber could be a low cost fiber resource as it is a waste from the palm oil industry.

As the next step, at PEERS 2017, November 5-8 in Norfolk, VA., we plan to report on unbleached and bleached pilot papermaking trials using high EFB pulp furnishes, which were done as part of the project.


Hurter


Byrd

Hurter is president, HurterConsult Inc., Ottawa, ON, Canada. Byrd is associate teaching professor, North Carolina State University, Raleigh, NC, USA. Email Hurter at bob@hurterconsult.com.