

Non-Wood Fibers: Relationships of Fiber Properties with Pulp Properties

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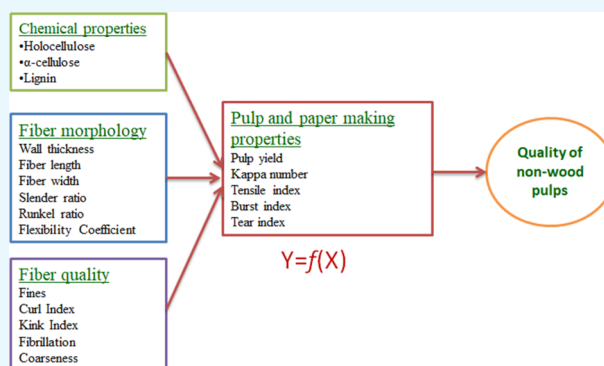
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ABSTRACT: In this investigation, the relationship between fiber properties and papermaking properties of 22 non-wood materials at the unrefined and refined states was assessed. The fiber length had positive and the cell wall thickness had negative correlation on the strength properties for the refined pulp. The relationship between papermaking properties with pulp quality, such as fines, curl index, kink index, external fibrillation, and coarseness, was also determined. The correlations of multiple regression equations of fiber quality parameters were 70.4% for the tensile index and 84.9% for the tear index for the refined pulp. The correlations of multiple regression equations of chemical characteristics of the samples were 81.9% for the pulp yield and 42.7% for the kappa number. Holocellulose and α -cellulose had a positive and lignin had a negative effect on the pulp yield.



1. INTRODUCTION

Depletion of forest resources calls for alternative resources for the traditional uses. An important part of this challenge is to develop technologies for the efficient conversion of biomass into fuels, chemicals, and paper products. A successful biomass-based fuel can be a replacement of fossil resources, burning of which play a major role in global warming. In this regard, the chemical composition of biomass and its fractionation technique can play a major role in predicting the feasibility of the bioproducts.¹

A major portion of the forest reserve of the world is used in conversion to pulp for use as paper and other products. Thus, selecting the appropriate alternate source of biomass is a big concern. In selecting a pulping raw material, the pulp yield is one of the most important factors. The pulp yield has also been related to the lignin and polysaccharide contents.² The rate of enzymatic hydrolysis of cellulose to sugars is inversely proportional to the amount of lignin present in biomass, and a difference of a few percentage points in the lignin content has a large effect on the efficiency of cellulose digestion.³ The predicted sugar yield of a raw material with a lignin content of 22% was only half that of a raw material with 17% content, while a raw material with 26% lignin content would yield almost no sugar.

Many studies have been carried out to correlate the cellulose content of wood with pulp yields. Dillner et al. found that kraft pulp yields of *Eucalyptus globulus* wood were well correlated

with cellulose contents.⁴ Wallis et al. showed that wood samples with a high cellulose content gave a higher pulp yield from eucalypt woods.² Cohen and Mackney established significant correlations between wood chemical properties and the properties of pulps derived from the woods under fixed conditions.⁵ Holocellulose gives a weak positive correlation with the pulp yield.⁶ Stewart et al. showed that the kraft pulp yields of *Eucalyptus regnans* samples were dependent on their lignin and pentosan contents.⁷ Batchelor et al. observed that kraft pulp yields of mixed eucalypt wood were well correlated with a combination of lignin, pentosan, and extractives.⁸

The paper sheet formation and its physical properties depend on original fiber characteristics and also on the fiber response to processing variables. The network and bond formed by the pulp fibers contribute to the basic strength of the paper. Morphology studies show that fibers are long narrow cells with tapering ends. They contain central canals, which are known as lumen.⁹ The fibers differ significantly depending upon geographical location and native species. The physical properties of paper differ from one species to another

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Table 1. Chemical Characteristics and Pulp Yield and Kappa Values of Soda-AQ Pulping Process for 22 Non-Woods

raw materials	klason lignin (%)	acid soluble lignin (%)	holocellulose (%)	α -cellulose (%)	pulp yield (%)	kappa number
bagasse	20.4	2.28	62.2	39.3	42.3	19.8
bamboo	26.9	2.88	65.5	46.9	46.29	26.8
banana pseudo stem	24.1	2.74	66.2	40.2	30.55	19.1
banana leaf	20.7	2.36	64.9	41.4	43.7	17.7
banana peduncle	20.4	2.56	73.7	45.2	56.44	18.3
cassava stalks	20.6	3.64	50.2	36.4	18.46	36.6
chia stalks	23.2	2.73	60.5	30.5	28.9	39
corn stalks	19.7	2.09	59.5	35.1	33.32	10
cotton stalks	23.3	3.64	66	35.7	41.74	17.5
dhaincha stalks	24.1	3.98	71.2	39.7	48.86	17.5
eggplant stalks	28.4	2.04	63.2	35	42.11	22.9
jute fiber	14.6	2.89	77.9	54.3	63.97	11.8
jute stick	27.1	2.46	69.2	37.7	34.43	30.1
kash stalks	19.8	3.17	66.2	43.3	41.98	18.2
kaun straw	19.3	3.03	56.6	35.9	26.67	15.1
mulberry stalks	26.3	2.58	70.2	38.8	32.01	40
mustard stalks	18.1	2.17	62.9	33.7	27.59	18.5
okra stalks	18.7	3.62	56.8	29.6	37.55	47.4
pineapple leaves	17.9	5.03	51.6	27.6	30.49	12.7
red Lentil stalks	23.8	3.52	59.2	36.5	31.12	35.5
rice straw	22.9	4.08	61.7	38.7	36.8	18.5
wheat straw	25.1	2.59	65.6	37	41.7	13.2

due to a great variety of wood types. The effect of morphological characteristics of wood pulp fibers of hardwood species on pulp sheet strength was studied by Horn.¹⁰ Oluwadare and Ashimiyu also showed that the fiber length, diameter, cell wall thickness, lumen size, and their derived morphological factors such as runkel ratio, flexibility coefficient, slenderness ratio, and so forth are important criteria to predict the paper properties.¹¹ Oluwadare and Ashimiyu found that for physical properties of raw pulp without beating, the cell-wall thickness and fiber length had the maximum impact.¹¹ Dinwoodie summarized that the principal fiber factors, such as fiber density, fiber length, and fiber strength, controlled the strength properties of paper.¹² Wangaard and Woodson observed a positive influence on both breaking length and burst at a given level of sheet density fiber strength and fiber length.¹³

In addition to the morphological properties of the raw material, produced pulp quality parameters such as fines, fiber coarseness, and curl and kink indexes also affect papermaking properties. Horn observed a negative relation of stretch with fiber coarseness. The author also observed a detrimental effect to bursting and tensile strength with fines (parenchyma cells).¹⁰ Other scientists showed that the kraft pulp fines were effective in papermaking properties.¹⁴ It was observed that different non-wood pulps had a higher drainage resistance at the unrefined state, consequently showing better papermaking properties in the beaten state.^{15–18} The fiber deformations (kinks and curl) had a significant effect on the strength properties of kraft pulp.¹⁹ The fiber deformations decreased fiber segment activation in the fiber network, consequently decreasing tensile and tensile stiffness indices and increasing tear and fracture toughness indices of pulp sheets.¹⁹

Almost of all these studies were carried out either on hardwood or on softwood species, while similar correlations on non-wood fibers are scarce.

Therefore, the present study focuses on preserving the natural reserve of forests and use of the alternate source to produce pulp, which is one of the major uses of plant matter. The present paper seeks to understand the correlation of chemical composition and morphological properties of 22 non-wood samples with pulp yields and papermaking properties. The correlation of papermaking properties with fiber quality of chemical pulps was also established.

The successful prediction of the pulp yield and papermaking properties provides an opportunity for selecting the raw material. Also, the requirement to undertake time-consuming and expensive pulping and biomass conversion trials of many samples may be significantly reduced.

2. MATERIALS AND METHODS

Twenty-two non-wood samples, mostly from agriculture waste, were collected from different parts of the country. The samples were (1) bagasse (*Saccharum*), (2) bamboo (*Bambusoideae*), (3) banana (*Musa Cavendish*) pseudo stem, (4) banana (*Musa Cavendish*) leaf, (5) Banana (*Musa Cavendish*) peduncle, (6) Cassava (*M. esculenta*) stalks, (7) Chia (*Salvia hispanica*) stalks, (8) Corn (*Zea mays*) stalks, (9) Cotton (*Gossypium*) stalks, (10). Dhaincha (*Sesbaniaaculeata*) stalks, (11). Eggplant (*Solanummelongena*) stalks (12). Jute (*Corchorus*) fiber, (13) jute (*Corchorus*) stick, (14) kash (*Saccharums pontaneum*) stalks, (15) kaun (*Seetaria-Italika*) straw, (16) mulberry (*Morus*) stalks, (17) mustard (*Brassica juncea*) stalks, (18) okra (*A. esculentus*) stalks, (19) pineapple (*A. comosus*) leaves, (20) red lentil (*L. culinaris*) stalks, (21) rice (*Oryza sativa*) straw, and (22) wheat (*T. aestivum*) straw.

2.1. Chemical Analysis. The Klason lignin (T222 om83), acid-soluble lignin (TAPPI UM 250 1991) of these 22 non-woods, were determined in accordance with TAPPI Standard Test Methods. Holocellulose was determined by treating the extractive free wood meal with NaClO₂ solution.²⁰ The pH of the solution was maintained at 4 by adding CH₃COOH–

Table 2. Correlation between the Pulp Yield and Kappa Number with Chemical Characteristics

	KL (%)	ASL (%)	holocellulose (%)	α -cellulose (%)	KN	PY
klason Lignin (%)	1	−0.206	0.153	0.038	0.167	−0.106
acid soluble lignin (%)	−0.206	1	−0.376	−0.420	0.178	−0.133
holocellulose (%)	0.153	−0.376	1	0.505 ^a	−0.378	0.775 ^b
α -cellulose (%)	0.038	−0.420	0.505 ^a	1	−0.267	0.359
KN	0.167	0.178	−0.378	−0.267	1	−0.404
PY	−0.106	−0.133	0.775 ^b	0.359	−0.404	1

^aCorrelation is significant at the 0.05 level (2-tailed). ^bCorrelation is significant at the 0.01 level (2-tailed) PY—pulp yield, KN—kappa number, ASL—acid soluble lignin.

CH₃COONa buffer, and α -cellulose was determined by treating holocellulose with 17.5% NaOH.

2.2. Morphological Properties. For the determination of fiber morphological properties, first, these samples were macerated in a solution containing 1:1 HNO₃ and KClO₃. A drop of the macerated sample was taken on a slide, and the fiber length and diameter were measured using an image analyzer Euromex-Oxion using Image Focus Alpha software. For measuring the fiber length, 200 fibers were measured from the slides and the average reading was taken.

The scanning electron microscopy (SEM) image of the cross section was recorded using a scanning electron microscope (model EV018, Carl Zeiss AG, Germany). Fiber width, wall thickness, and lumen diameter were measured from the SEM image.

2.3. Pulping. Pulping was carried out using the soda-anthraquinone (AQ) process. The conditions were described in detail elsewhere.^{16–18} The pulp yield and kappa number of these 22 non-woods samples are presented in Table 1.

2.4. Papermaking Properties. The papermaking properties of paper sheets mainly include tensile, tear, and burst index as parameters. Pulp samples from each sample were beaten in a valley beater to different freeness (°SR), and hand sheets of about 60 g/m² were made in a Rapid Kothén Sheet Making Machine. The sheets were tested for tensile (T 494 om-96), burst (T 403 om-97), and tear strength (T 414 om-98) according to TAPPI Standard Test Methods. The papermaking properties in the unrefined state and refined state at the maximum tensile-tear were taken for the regression analysis.

Fiber quality of the pulp samples was determined by the Fiber Quality Analyzer—360, OpTest, Canada.

2.5. Modeling. Pearson Correlation coefficients among Klason lignin (%), acid-soluble lignin (%), holocellulose (%), and α -cellulose (%), the kappa number and pulp yield were computed first to assess the association between these parameters. The significance of correlation coefficients was tested with 2-tailed *t*-test at 1 and 5% levels of significance.

Next, linear regression models have been developed taking pulp yield, kappa number, and papermaking properties as dependent variables and Klason lignin (%), acid soluble lignin (%), holocellulose (%), α -cellulose (%) morphological properties, and fiber quality parameter as independent variables. Coefficients of multiple determination (*R*²) have been calculated for each model, which articulate how much the independent variables can express the total variation in the dependent variable in the model. *R*² varied from 0 to 100%.

For calculating the correlation coefficient and developing linear regression models, statistical software, SPSS of its version 22.0, has been used.

3. RESULTS AND DISCUSSION

The chemical properties of 22 non-wood samples, pulp yield, and kappa number under the optimum conditions are shown in Table 1.

The relationship of the pulp yield and kappa number with chemical properties

$$\begin{aligned} \text{PY} = & -39.462 - 0.614 \cdot \text{KL} (\%) + 1.985 \cdot \text{ASL} (\%) \\ & + 1.340 \cdot \text{holocellulose} (\%) - 0.008 \cdot \alpha\text{-cellulose} (\%) \\ (R^2 = & 0.819, \text{ adjusted } R^2 = 0.671) \end{aligned} \quad (1)$$

$$\begin{aligned} \text{KN} = & 44.129 + 0.54 \cdot \text{KL} (\%) + 1.895 \cdot \text{ASL} (\%) - 0.591 \\ & \cdot \text{holocellulose} (\%) - 0.032 \cdot \alpha\text{-cellulose} (\%) \\ (R^2 = & 0.427, \text{ adjusted } R^2 = 0.183) \end{aligned} \quad (2)$$

PY—pulp yield, KN—Kappa number, ASL—acid soluble lignin.

The kraft pulp yield can be determined from the cellulose content in wood and can therefore be used as an indirect measure of it.^{2,21} The chemical characteristics of 22 non-woods were determined, and these data were used to determine the correlation with the pulp yield and kappa number by multiple regression analysis. The detailed correlations are shown in Table 2. Equation 1 shows the relationship between the unbleached pulp yield and chemical characteristics. Holocellulose had a positive correlation with the pulp yield, but Klason lignin was negatively correlated with the pulp yield (eq 1). Similarly, Wallis et al. showed that the total carbohydrates of *E. globulus* wood samples were positively correlated with the pulp yield and lignin was negatively correlated.² Figures 1 and 2 show individual correlation of the pulp yield with holocellulose and α -cellulose, respectively. The *R*² value was 74.5% for holocellulose and 56.7% only for α -cellulose, which slightly improved to 76.4% and 60.5% in polynomial relation,

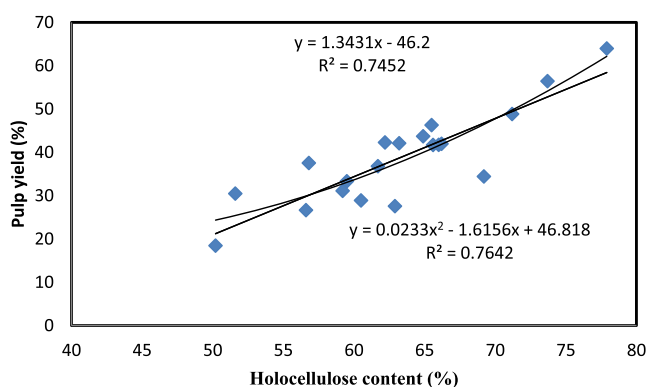


Figure 1. Relationship between holocellulose and pulp yield.

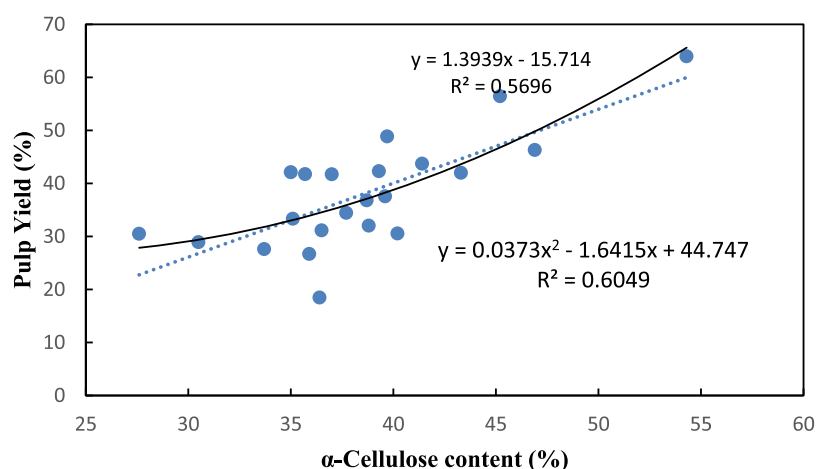


Figure 2. Relationship between α -cellulose and pulp yield (not needed).

respectively. Kien et al. studied the effectiveness of cellulose content as a selection trait in breeding programs for the kraft pulp yield in *Eucalyptus urophylla*.²² The regression of the pulp yield of disk samples on cellulose content was strong. A lower correlation can be explained by heterogeneous non-woods with a lot of variation in anatomical properties.^{15–17}

Equation 2 shows that multiple regression of the kappa number was 42.7%. Klason lignin and acid-soluble lignin had a positive influence on the kappa number. Linear regression of the kappa number involving Klason lignin was accounted for 31% only (Figure 3).

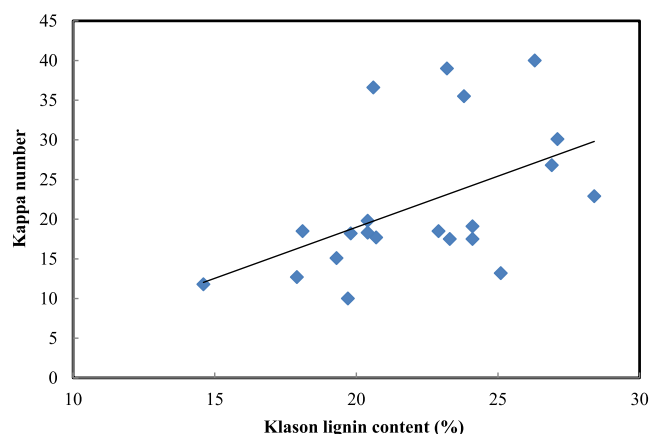


Figure 3. Relationship between Klason lignin and kappa number.

3.1. Correlation of Papermaking Properties with Fiber Morphology. The original pulp fiber characteristics and its processing determine the papermaking properties of final products. The slenderness of the fiber is obtained by the length to width ratio. The solid mass of the fiber depends on the fiber cell wall. The central cavity in the fiber is known as fiber lumen, which is void. Pulp refining depends on the fiber wall thickness and lumen. Fibers with the thin cell wall collapse readily. Therefore, importance of the fiber wall on properties of paper had been acknowledged. The pulps from thin-walled and wide lumen fibers give dense and well-bonded sheets and those from the thick wall give bulky sheets with high tearing resistance.⁹ The morphological and papermaking properties of 22 non-woods pulps are shown in Table 3.

Tensile and bursting strengths of pulps are the two properties that are highly dependent on fiber-to-fiber bonding.²³ In this study, the tensile index of the unrefined pulp had no correlation with the fiber length, while the tensile index of the refined pulp showed a positive correlation (Figure 4). The fiber length was the dominant factor for burst and tensile strength in the unbeaten state.¹⁰ Wangaard and Woodson obtained a positive influence on both breaking length and burst pulp from slash pine at a given level of sheet density with fiber strength and fiber length.¹³ Regressions for breaking length and burst factor of that study accounted for 88 and 90%, respectively. Wangaard et al. also showed that the slash pine had a positive correlation between latewood fiber length and zero-span breaking length within this species.²⁴

As shown in eqs 3 and 4, the multiple regression analysis of the tensile index involving these variables accounted for 57 and 66% for unrefined and refined pulps, respectively. The slender ratio, runkel ratio, and flexibility coefficient had a positive influence on the tensile index of both refined and unrefined pulps.

The tear index of both refined and unrefined pulps was directly related to the fiber length. The correlation was 76.5% (Figure 5) and 66% (Figure 6) for unrefined and refined pulps, respectively. Horn showed correlation between the tearing strength of unbeaten ($r = 0.817$) or beaten ($r = 0.832$) hardwood pulp with the fiber length.¹⁴ Wimmer et al. showed that the fiber length had a strong effect on the tear index of *E. globulus*.²⁵ Labosky and Ifju also found for Loblolly Pine wood that the tear strength was highly correlated with the fiber length.²⁶ The lower correlation in the present experiment can be explained by different non-wood species with heterogeneous anatomical properties. Therefore, multiple factors affect strength properties.

Some researchers reported that long-fibered wood species provided desirable paper strength properties.^{27–29} Also, some research results showed that the fiber length had little effect on the production of paper of acceptable strength.^{30–32}

Generally, tensile and burst strengths of handsheets made from hardwoods and softwoods respond to have the same fiber morphological effects. However, the non-wood pulp behaves differently. For example, straws, banana waste fibers, corn stalks, and so forth contain high amounts of fines; consequently, it increased the bonding potential in the unrefined state and exhibited higher tensile and burst

Table 3. Morphological Properties of Raw Materials and Papermaking Properties of the Corresponding Pulp

raw materials	fiber length (mm)	fiber width (μm)	wall thickness (μm)	slender ratio	runkel ratio	flexibility coefficient	tensile index (N·m/g)		burst index (kPa·m ² /g)		tear index (mN·m ² /g)	
							unrefined	refined	unrefined	refined	unrefined	refined
bagasse	1.36	16.2	1.9	79.2	0.317	73.45	58.96	85.41	3.41	4.9	6.6	5.98
bamboo	2.0	18.4	2.6	108.7	0.4	70.65	25.8	60.8	1.2	5.5	12.1	14.5
banana pseudo stem	1.22	14.81	1.51	82.37	0.27	78.3	44.64	76	3.59	5.16	10.1	6.85
banana leaf	1.92	13.75	2.52	139.63	0.57	63.3	48.74	83.7	3.69	5.93	10.58	7.6
banana peduncle	1.5	25.18	1.27	59.57	0.16	86.2	48.5	70.4	3.11	4.54	7.47	7
cassava stalks	0.65	25.5	2.09	25.49	0.204	78.9	38.1	52.9	1.2	2.43	4.6	5
chia stalks	0.67	15.55	1.91	43.1	0.34	71.43	43.3	72.3	1.7	3.8	5.9	4.4
corn stalks	0.9	15.7	1.78	57.3	0.33	66.9	52.39	78	2.82	4.15	6.85	5.36
cotton stalks	0.9	17.2	2.21	52.3	0.36	71.1	25.2	66	1	3.3	5.6	5
dhaincha stalks	0.73	19.5	2.12	37.4	0.28	78.7	55.6	93.7	2.2	5.6	8.1	8.1
eggplant stalks	0.58	13.2	2.49	43.84	0.678	55.61	34.1	58.2	1.9	3.5	6.65	6.85
jute fiber	2.02	10.8	3.5	187.03	1.71	37.96	28.9	85.7	2.2	6.8	18.7	20.8
jute stick	0.67	20.7	3.5	32.37	0.54	62.3	34.8	70.3	3.1	5.3	6.8	6.3
kash stalks	0.86	13.6	2	63.2	0.408	72.1	64.71	87	3.31	5.26	6.85	6.6
kaun straw	0.814	13.9	3.3	58.56	1.015	46.76	42.8	67.3	2.3	3.7	6.23	4.98
mulberry	0.65	16.3	2.21	39.88	0.391	69.38	33.59	67.56	2.24	3.79	7.47	6.9
mustard stalks	0.87	13.7	2.53	63.5	0.61	60.1	43	73.5	1.7	3.2	5.9	5.4
okra stalks	1.14	21	1.75	54.29	0.339	77.23	40.1	78.2	2.14	4.04	7.47	7.06
pineapple leaves	1.06	7.35	1.9	144.2	1.08	47.6	40.3	73.2	2.4	3.5	7.21	7.1
red lentil stalks	0.74	14.3	2.32	51.7	0.49	66	36.1	58.6	1	3.3	2	3
rice straw	0.78	11.6	1.83	83.87	0.56	60.21	60.5	80.4	2.9	5.1	5.7	6.4
wheat straw	0.97	9.3	1.99	83.62	0.65	61.63	36.1	53.5	2.14	3.11	5.6	4.98

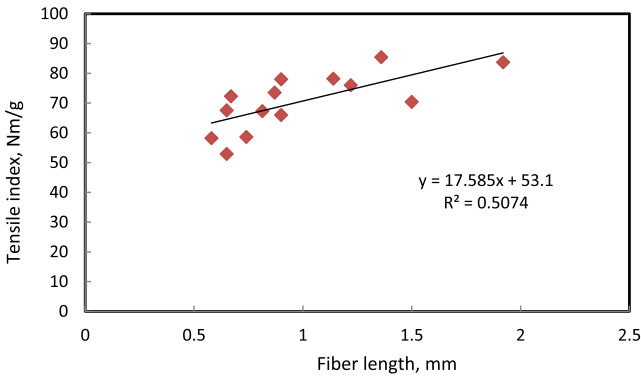


Figure 4. Relationship between the fiber length and tensile index of the refined pulp.

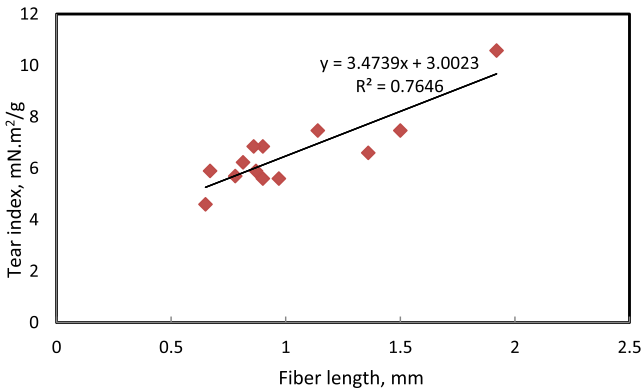


Figure 5. Relationship between the fiber length and tear index of the unrefined pulp.

index.^{16–18} Therefore, multiple factors affecting the fiber bond depended on paper properties in different non-wood pulps.

As shown in Table 4, the papermaking properties were negatively correlated with the cell wall thickness. The correlation coefficient of the tensile index of the refined pulp with the fiber wall thickness was 62.2% (Figure 7). The correlation coefficients for the tear index and burst index were very low (data are not shown). In an earlier study, parenchyma cells were removed from the white oak pulp, which increased strength properties slightly due to the thick cell wall of the oak fiber.¹⁰

$$\begin{aligned} \text{UTenI} = & -16.344 - 20.721 \cdot \text{FL} + 0.020 \cdot \text{FW} - 11.593 \\ & \cdot \text{WT} + 0.389 \cdot \text{SR} + 42.524 \cdot \text{RR} + 0.918 \cdot \text{FC} \\ & (R^2 = 0.570, \text{ adjusted } R^2 = 0.325) \end{aligned} \quad (3)$$

$$\begin{aligned} \text{TenI} = & -26.920 - 0.862 \cdot \text{FL} - 1.772 \cdot \text{FW} + 0.773 \cdot \text{WT} \\ & + 0.144 \cdot \text{SR} + 33.193 \cdot \text{RR} + 1.53 \cdot \text{FC} \\ & (R^2 = 0.659, \text{ adjusted } R^2 = 0.435) \end{aligned} \quad (4)$$

$$\begin{aligned} \text{UBI} = & -0.512 + 0.7162 \cdot \text{FL} - 0.056 \cdot \text{FW} - 1.117 \cdot \text{WT} \\ & + 0.010 \cdot \text{SR} + 3.271 \cdot \text{RR} + 0.049 \cdot \text{FC} \\ & (R^2 = 0.811, \text{ adjusted } R^2 = 0.658) \end{aligned} \quad (5)$$

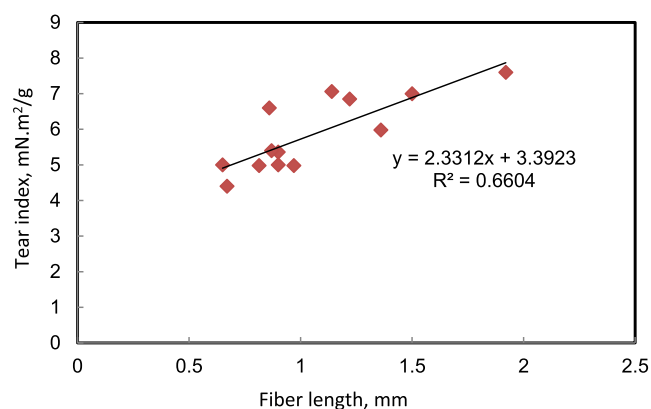


Figure 6. Relationship between the fiber length and tear index of the refined pulp.

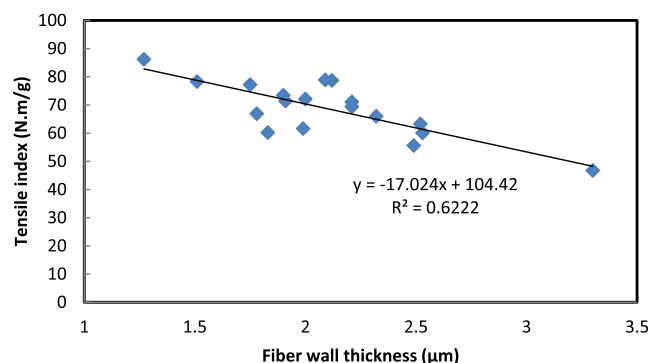


Figure 7. Relationship between the fiber wall thickness and tensile index of the refined pulp.

$$\begin{aligned} \text{BI} = & -7.603 - 0.895 \cdot \text{FL} - 0.102 \cdot \text{FW} - 0.310 \cdot \text{WT} \\ & + 0.032 \cdot \text{SR} + 4.862 \cdot \text{RR} + 0.159 \cdot \text{FC} \\ (R^2 = & 0.822, \text{ adjusted } R^2 = 0.675) \end{aligned} \quad (6)$$

$$\begin{aligned} \text{UTI} = & -7.499 + 1.659 \cdot \text{FL} - 0.104 \cdot \text{FW} + 0.030 \cdot \text{WT} \\ & + 0.019 \cdot \text{SR} + 4.725 \cdot \text{RR} + 0.160 \cdot \text{FC} \\ (R^2 = & 0.655, \text{ adjusted } R^2 = 0.428) \end{aligned} \quad (7)$$

$$\begin{aligned} \text{TI} = & -8.242 - 1.248 \cdot \text{FL} + 0.050 \cdot \text{FW} - 0.594 \cdot \text{WT} \\ & + 0.034 \cdot \text{SR} + 6.603 \cdot \text{RR} + 0.159 \cdot \text{FC} \\ (R^2 = & 0.526, \text{ adjusted } R^2 = 0.277) \end{aligned} \quad (8)$$

UTenI—unrefined tensile index, TenI—refined tensile index, UBI—unrefined burst index, BI—burst index, UTI—unrefined tear index, TI—refined tear index, WT—wall thickness, FL—fiber length, FW—fiber width, SR—slender ratio, RR—runkel ratio, and FC—flexibility coefficient.

The derived values from the morphological properties such as runkel ratio, flexibility coefficient, slenderness ratio, and so forth are considered significant parameters to evaluate the papermaking properties.¹¹ The fiber of the pulping raw material with a slenderness ratio less than 70 is not good for papermaking properties.³³ The slender ratio and flexibility coefficient had a positive correlation, and the runkel ratio had a negative correlation with papermaking properties (Table 4). The correlation of the tensile index of the refined pulp with a slender ratio was 42% (Figure 8).

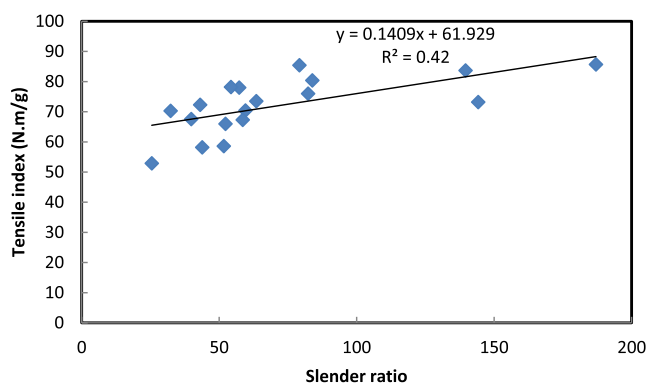


Figure 8. Relationship between the slender ratio and tensile index of the refined pulp.

Fibers having the runkel ratio less than 1.0 are considered to be thin-walled fibers, which facilitate fibers that collapse easily and form a paper sheet with a large bonded area. If the runkel ratio is more than 1.0, the fibers are stiff and difficult to collapse and form bulkier paper with a less bonded area.³⁴ As shown in Table 4, the runkel ratio was negatively correlated with papermaking properties. The correlation of the tensile index of the refined pulp with a runkel ratio was 62.2%.

The flexibility coefficient describes the extent of fiber bonding in the paper sheet.^{35,36} The flexibility coefficient showed a positive correlation with papermaking properties (eqs 3–8).

3.2. Correlation of Papermaking Properties with Pulp Fiber Quality. Pulp fines, curl and kink indexes, external fibrillation, and coarseness were measured in the unrefined pulp, and a multiple regression of these properties of pulp with papermaking properties was developed. The fiber quality parameter and papermaking properties are given in Table 5. As shown in eq 9, multiple regressions of the tensile index of the unrefined pulp with fines, curl and kink indexes, external fibrillation, and coarseness accounted for 41.9%, while the same for the refined pulp was 70.4% (eq 10). Similarly, multiple regression correlations for the burst index were 55.8% (eq 11) and 69.5% (eq 12), and those for the tear index were 44.7% (eq 13) and 84.9% (eq 14) for unrefined and refined pulps, respectively.

Pulp fines increase wet web strength, leading to a denser and better bonded sheet.³⁴ These 22 non-wood pulps contain a wide variation of fines, for example, 16.1% in dhaincha to 66.8% in banana leaf pulp. Fines consist mainly of cellulose such as ray cells, vessel fragments, and broken cell wall material, which are 0.2 mm less in length. Fines can play a determining role in many surface-related interactions before sheet consolidation, and they also affect final sheet properties. Equation 9 showed a positive influence on the tensile index of the unrefined pulp with pulp fines, while the refined pulp showed a negative influence (Table 3). The literature study reveals that primary fines have little effect in sheet bonding.^{37–39} Fines from kraft and recycled paper are quite effective, while those from TMP are ineffective in increasing handsheet density, breaking length, and burst index. Different non-wood fines behaved quite differently, some of them facilitated fiber bonding and some of them did not.

Another important property that has an impact on strength and optical properties of paper sheets is coarseness. The coarseness is the mass of the fiber per unit length. Coarseness and cell wall thickness are different properties but are often

Table 4. Correlation between Papermaking Properties and Morphological Properties

	FL	FW	WT	SR	RR	FC	UTenI	TenI	UBI	BI	UTI	TI
FL	1	0.116	−0.247	0.806 ^a	−0.160	0.254	0.267	0.407	0.668 ^a	0.574 ^b	0.612 ^a	0.399
FW	0.116	1	−0.430	−0.429	−0.650 ^a	0.739 ^a	−0.171	−0.205	−0.192	−0.243	−0.022	0.124
WT	−0.247	−0.430	1	0.024	0.856 ^a	−0.814 ^a	−0.294	−0.251	−0.330	−0.284	−0.198	−0.254
SR	0.806 ^a	−0.429	0.024	1	0.217	−0.196	0.375	0.461	0.694 ^a	0.660 ^a	0.548 ^b	0.310
RR	−0.160	−0.650 ^a	0.856 ^a	0.217	1	−0.954 ^a	−0.101	−0.152	−0.072	−0.112	−0.115	−0.174
FC	0.254	0.739 ^a	−0.814 ^a	−0.196	−0.954 ^a	1	0.113	0.191	0.120	0.177	0.191	0.266
UTenI	0.267	−0.171	−0.294	0.375	−0.101	0.113	1	0.776 ^a	0.712 ^a	0.728 ^a	0.265	0.356
TenI	0.407	−0.205	−0.251	0.461	−0.152	0.191	0.776 ^a	1	0.666 ^a	0.860 ^a	0.563 ^b	0.577 ^b
UBI	0.668 ^a	−0.192	−0.330	0.694 ^a	−0.072	0.120	0.712 ^a	0.666 ^a	1	0.836 ^a	0.740 ^a	0.618 ^a
BI	0.574 ^b	−0.243	−0.284	0.660 ^a	−0.112	0.177	0.728 ^a	0.860 ^a	0.836 ^a	1	0.699 ^a	0.680 ^a
UTI	0.612 ^a	−0.022	−0.198	0.548 ^b	−0.115	0.191	0.265	0.563 ^b	0.740 ^a	0.699 ^a	1	0.822 ^a
TI	0.399	0.124	−0.254	0.310	−0.174	0.266	0.356	0.577 ^b	0.618 ^a	0.680 ^a	0.822 ^a	1

^aCorrelation is significant at the 0.01 level (2-tailed). ^bCorrelation is significant at the 0.05 level (2-tailed). UTenI—unrefined tensile index, TenI—refined tensile index, UBI—unrefined burst index, BI—burst index, UTI—unrefined tear index, TI—refined tear index, WT—wall thickness, FL—fiber length, FW—fiber width, SR—slender ratio, RR—runkel ratio, and FC—flexibility coefficient.

Table 5. Pulp Fiber Quality and Its Papermaking Properties

raw materials	fines	curl index	kink index	fibrillation	coarseness	tensile index (N·m/g)		burst index (kPa·m ² /g)		tear index (mN·m ² /g)	
						unrefined	refined	unrefined	refined	unrefined	refined
bagasse	30	0.112	1.695	1.36	0.131	58.96	85.41	3.41	4.9	6.6	5.98
banana pseudo stem	54.35	0.191	2.74	2.02	0.081	44.64	76	3.59	5.16	10.1	6.85
banana leaf	66.8	0.194	2.485	0.62	0.091	48.74	83.7	3.69	5.93	10.58	7.6
banana peduncle	33.05	0.103	1.59	1.995	0.097	48.5	70.4	3.11	4.54	7.47	7
cassava stalks	53.2	0.04	0.938	1	0.034	38.1	52.9	1.2	2.43	4.6	5
chia stalks	31.25	0.093	1.72	1.17	0.149	43.3	72.3	1.7	3.8	5.9	4.4
corn stalks	58.6	0.127	1.92	1.49	0.092	52.39	78	2.82	4.15	6.85	5.36
cotton stalks	28.9	0.138	2.11	1.43	0.089	25.2	66	1	3.3	5.6	5
dhaincha stalks	16.13	0.059	1.145	1.13	0.083	55.6	93.7	2.2	5.6	8.1	8.1
eggplant stalks	18.2	0.067	1.4	1.7	0.058	34.1	58.2	1.9	3.5	6.65	6.85
jute fiber	17.9	0.1365	1.21	0.985	0.08	28.9	85.7	2.2	6.8	18.7	20.8
jute stick	73.4	0.077	1.39	2.57	0.051		72.9		4.7		4.9
kash stalks	43.43	0.152	1.703	1.41	0.119	64.71	87	3.31	5.26	6.85	6.6
kaun straw	51.55	0.132	2.38	0.78	0.106	42.8	67.3	2.3	3.7	6.23	4.98
mulberry	36.7	0.064	1.35	1.4	0.04	33.59	67.6	2.24	3.79	7.47	6.9
mustard stalks	48.17	0.105	1.827	2.07	0.167	43	73.5	1.7	3.2	5.9	5.4
okra stalks	31.6	0.101	1.75	1.4	0.143	40.1	78.2	2.14	4.04	7.47	7.06
red lentil stalks	37.7	0.138	2.15	2.62	0.128	36.1	58.6	1	3.3	2	3
rice straw	47.2	0.181	2.77	1.83	0.0863	60.5	80.4	2.9	5.1	5.7	6.4
wheat straw	42.9	0.15	2.45	1.53	0.095	36.1	53.5	2.14	3.11	5.6	4.98

Table 6. Correlation between Papermaking Properties with Pulp Fiber Quality

	fines	curl index	kink index	fibrillation	coarseness	UTenI	TenI	UBI	BI	UTI	TI
fines	1	0.486 ^a	0.559 ^a	−0.069	−0.005	0.248	−0.134	0.384	−0.009	0.336	−0.380
curl index	0.486 ^a	1	0.858 ^b	0.114	0.222	0.234	0.258	0.492 ^a	0.465 ^a	0.188	0.068
kink index	0.559 ^a	0.858 ^b	1	0.236	0.252	0.146	−0.049	0.365	0.168	0.255	−0.330
fibrillation	−0.069	0.114	0.236	1	0.251	−0.034	−0.285	−0.121	−0.234	−0.233	−0.340
coarseness	−0.005	0.222	0.252	0.251	1	0.255	0.252	0.018	0.026	−0.091	−0.244
UTenI	0.248	0.234	0.146	−0.034	0.255	1	0.616 ^b	0.715 ^b	0.626 ^b	0.368	−0.077
TenI	−0.134	0.258	−0.049	−0.285	0.252	0.616 ^b	1	0.539 ^a	0.873 ^b	0.322	0.551 ^a
UBI	0.384	0.492 ^a	0.365	−0.121	0.018	0.715 ^b	0.539 ^a	1	0.749 ^b	0.721 ^b	0.136
BI	−0.009	0.465 ^a	0.168	−0.234	0.026	0.626 ^b	0.873 ^b	0.749 ^b	1	0.496 ^a	0.520 ^a
UTI	0.336	0.188	0.255	−0.233	−0.091	0.368	0.322	0.721 ^b	0.496 ^a	1	−0.077
TI	−0.380	0.068	−0.330	−0.340	−0.244	−0.077	0.551 ^a	0.136	0.520 ^a	−0.077	1

^aCorrelation is significant at the 0.05 level (2-tailed). ^bCorrelation is significant at the 0.01 level (2-tailed). UTenI—unrefined tensile index, TenI—refined tensile index, UBI—unrefined burst index, BI—burst index, UTI—unrefined tear index, and TI—Refined tear index.

found to be correlated. Equations 11–14 show that fiber coarseness had a positive impact on the tensile index and a

negative impact on burst and tear indexes. Seth described that coarser fibers have thicker walls and have a smaller specific

surface area because of smaller per unit pulp mass.⁴⁰ Retulainen observed a strong dependence of the light scattering coefficient of paper on fiber coarseness.⁴¹

As shown in Table 6, external fibrillation had a slight negative effect on papermaking properties.

A large number of external fibrils produced after beating increased the retention of the filler and contributed to fiber bonding, resulting in improved tensile strength and internal bond strength.⁴² However, this investigation showed a negative correlation with papermaking properties (Table 6).

A curl index of about 10% is considered straight fibers, an index of about 20% curly fibers.⁴³ The curl index is the ratio of the true contour length of the fiber divided by the projected length. As shown in Table 6, the curl index varied from 6% in the Mulberry plant pulp to 19% in the banana leaf pulp. Most of these pulps were straight fibers. Beating of pulp provided externally fibrillated fibers, which facilitated restoring, swelling, and straightening of fibers. However, in this study, the curl index had a positive correlation with papermaking properties (Table 6). According to Page, the curled fibers have a low tensile index but can have high tear strength.⁴³ The discrepancy in the present study can be explained by different anatomical properties of different non-woods, for example, primary fines, initial external fibrillation, and so forth in some non-wood contribute to bonding potential, which affect papermaking properties. In case of other raw materials, fiber length, slender ratio, and so forth affect papermaking properties. Therefore, it is hard to predict papermaking properties from the model of different non-woods.

Kink is the abrupt change in the fiber curvature. As shown in eqs 9–12 and 14, the kink index had a negative effect with papermaking properties. Mohlin and Alfredsson also exhibited a negative effect of fiber deformation (curl and kink) on paper making properties.⁴⁴

$$\begin{aligned} \text{UTenI} = & 32.170 + 0.215*\text{fines} + 93.994*\text{curl index} \\ & - 8.199*\text{kink index} - 0.690*\text{fibrillation} + 85.978 \\ & * \text{coarseness} \quad (R^2 = 0.419, \text{ adjusted } R^2 = 0.175) \end{aligned} \quad (9)$$

$$\begin{aligned} \text{TenI} = & 80.868 - 0.156*\text{fines} + 283.637*\text{curl index} \\ & - 18.985*\text{kink index} - 7.237*\text{fibrillation} + 105.937 \\ & * \text{coarseness} \quad (R^2 = 0.704, \text{ adjusted } R^2 = 0.495) \end{aligned} \quad (10)$$

$$\begin{aligned} \text{UBI} = & 1.478 - 0.013*\text{fines} + 12.249*\text{curl index} - 0.431 \\ & * \text{kink index} - 0.186*\text{fibrillation} - 0.632*\text{coarseness} \\ & (R^2 = 0.558, \text{ adjusted } R^2 = 0.311) \end{aligned} \quad (11)$$

$$\begin{aligned} \text{BI} = & 4.620 - 0.016*\text{fines} + 25.591*\text{curl index} - 1.157 \\ & * \text{kink index} - 0.457*\text{fibrillation} - 0.38 \\ & * \text{coarseness} (R^2 = 0.695, \text{ adjusted } R^2 = 0.483) \end{aligned} \quad (12)$$

$$\begin{aligned} \text{UTI} = & 5.732 + 0.027*\text{fines} - 9.984*\text{curl index} + 1.620 \\ & * \text{kink index} - 1.167*\text{fibrillation} - 4.710*\text{coarseness} \\ & (R^2 = 0.447, \text{ adjusted } R^2 = 0.20) \end{aligned} \quad (13)$$

$$\begin{aligned} \text{TI} = & 13.814 - 0.077*\text{fines} + 80.615*\text{curl index} - 5.743 \\ & * \text{kink index} - 1.138*\text{fibrillation} - 15.95*\text{coarseness} \\ & (R^2 = 0.849, \text{ adjusted } R^2 = 0.702) \end{aligned} \quad (14)$$

UTenI—unrefined tensile index, TenI—refined tensile index, UBI—unrefined burst index, BI—burst index, UTI—unrefined tear index, and TI—refined tear index.

From the abovementioned discussion, it can be deduced that bagasse, corn stalks, cotton stalks, dhaincha stalks, kash stalks, and wheat straw had a higher pulp yield with a good tensile index and high fines content. The tear index of these non-wood pulps was inferior due to shorter fiber length and are suitable fine paper. Samples containing a longer fiber such as jute, banana peduncle, and bamboo pulps had a superior tear index and lower fines, and such a property allows these samples to be used in the manufacture of kraft liner and specialty papers. Also, the long fiber pulp could be mixed with the above-mentioned short fiber non-wood pulps and could be used as raw materials for tissue paper. Thus, when using different non-woods from Bangladesh, the abovementioned modeling can help predict the pulp yield with the papermaking properties and their potential use in different types of papers.

4. CONCLUSIONS

The relationships between pulp and papermaking properties with 22 non-wood fiber characteristics were established. The pulp yield was positively correlated with holocellulose and α -cellulose. Lignin had a negative effect on the pulp yield and a positive effect on the kappa number. The fiber length showed a positive effect in tensile and burst indexes of the refined pulp, while the tear index of both refined and unrefined pulps was found to be related directly to the fiber length. Pulp fines had a positive influence on the tensile index of the unrefined pulp, while the refined pulp showed a negative influence. It is difficult to predict papermaking properties from the pulp fiber quality parameter from multiple regression analysis of different non-wood pulps. Therefore, multiple factors affecting the bond depended on paper properties in different non-wood pulps.

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Notes

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