

Biomechanical Pulping of Corn Stalk Rind with a White Rot Fungus – *Trametes hirsuta* – and the Use of Delignified Corn Stalk Pith as a Pulp Additive

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Corn stalk rind (CSR) was treated with *Trametes hirsuta* Ig-9 and then refined into pulp. The biotreatment resulted in loss of paper strength and brightness, but energy consumption during refining (ECR) was reduced. Meanwhile, multiple linear regression was carried out, for which ECR served as the dependent variable, and the yield and infrared relative absorbance intensities at 3414 cm⁻¹ and 1653 cm⁻¹ of the biotreated CSR served as independent variables. Results showed that the determining parameters of the biotreated CSR may be used to predict the ECR. In this work, delignified corn stalk pith (CSP) was added to aspen alkaline hydrogen peroxide mechanical pulp (APMP). The CSP enhanced the strength properties of the aspen APMP and inhibited yellowing. The biomechanical pulping of CSR has the potential to produce a low-cost green pulp, and the delignified CSP can serve as a pulp additive.

Keywords: Corn stalk rind (CSR); Delignified corn stalk pith (DCSP); *Trametes hirsuta* Ig-9; Biomechanical pulping; Aspen alkaline peroxide mechanical pulp

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INTRODUCTION

The existing wood resources are inadequate to meet the annual average increasing consumption rate of 2% to 3% for the paper and paper board industry, especially in some countries in the Asia-Pacific region, Middle East, and Eastern Europe (Ashori 2006; Szabó *et al.* 2009). In addition to paper and board production, unjustified logging consumes wood resources and is also coming under increasing environmental pressure (Parrotta and Agnoletti 2012). Meanwhile, an abundance of underutilized corn stalks are produced worldwide every year, and the low cost, abundance, and annual renewability of corn stalk render them a suitable feedstock for paper-making.

Using corn stalk as the raw material for chemical and semi-chemical-mechanical pulping and making dissolving pulp has been both investigated and patented (Behin and Zeyghami 2009; Latibari *et al.* 2010; Ryu 2011; Pang *et al.* 2012; Jarabo *et al.* 2013). These methods, however, either cause environmental pollution or do not utilize the value of the pith. The corn stalk rind is composed mostly of vascular bundles and cellulose, while the pith contains fewer vascular bundles and more xylan. The rind and pith account for approximately 50% of corn stalk by weight (Bootsma and Shanks 2005). One experiment investigated removing the pith from corn stalk and making the rind into soda-AQ pulp; however, the use of the removed pith was not considered in the research (Cheng *et al.* 2010).

Compared with the results of soda pulping of corn stalk, when the same active alkali was used, rind pulp had a better tensile index and burst index than corn stalk pulp (Latibari *et al.* 2010). Jahan and Rahman (2012) used pre-hydrolysis removal of pith and rind to making soda-AQ pulp and found that if the pre-hydrolysate liquor is employed as a source for fermentation, then phenolics from the degraded lignin become inhibitors to the downstream fermentation process. Presently, biomechanical pulping of corn stalk rind and the detailed application of the pith has not been reported.

In the current study, the fractional utilization of corn stalk was taken into account to achieve full use of this feedstock. The degradation experiments of corn stalk rinds screened the fungus *Trametes hirsuta* Ig-9 (CGMCC No. 2422), which can selectively degrade the lignin of corn stalk rind (CSR). Previous research found that the yellow laccase from *T. hirsuta* Ig-9 can oxidize some non-phenolic compounds in the absence of mediators (Zhang *et al.* 2009). Therefore, *T. hirsuta* Ig-9 was applied to produce corn stalk rind biomechanical pulp (CSRBMP). Simultaneously, the pith was delignified (DCSP) and then added to aspen alkaline hydrogen peroxide mechanical pulp (APMP). The study focused on the influence of biotreatment time during CSR biomechanical pulping with *T. hirsuta* Ig-9 and the effect of DCSP addition on the properties of the aspen APMP.

EXPERIMENTAL

Materials

Corn stalks were collected from a corn field near YaoQiang Airport (Jinan, Shandong province, China)

Strain-a (Sa), Strain-b (Sb), Strain-c (Sc), and Strain-d (Sd) were isolated from the soil of a corn field at Changqing in Jinan. Their mycelium morphology in PDA plate was the same as the basidiomycetes, and they produced the colored zone on the potato dextrose agar (PDA) plate that included tannic acid. However, the four basidiomycetes were not identified. *Trametes versicolor*, *Irpex lacteus*, *Trametes hirsuta* Ig-9, and *Phanerochaete chrysosporium* ME446 and its mutant *Phanerochaete chrysosporium*-14 were preserved on PDA slants in a laboratory.

The aspen APMP of 29 °SR was provided by Shandong Zhong Mao Sheng Yuan Paper Co. Ltd (China).

Tween 80®, Carboxymethylcellulose sodium, beechwood xylan, 2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid (ABTS), and veratryl alcohol were purchased from Sigma (China).

Manganese sulfate monohydrate, Sodium hydroxide, Sodium hypochlorite, and hydrogen peroxide were obtained from Aladdin Industrial Inc. (China).

Schematic Overview of Experiment

The schematic overview of the experiment is shown in Fig. 1.

Separation of Rind and Pith

The corn stalk was separated into the rind and the pith. The rind was cut into 2.0 to 3.0 cm × 1 to 1.5 cm sticks, soaked in water for 12 h, and then drained. The pith was pulverized and passed through a 20-mesh sieve for use.

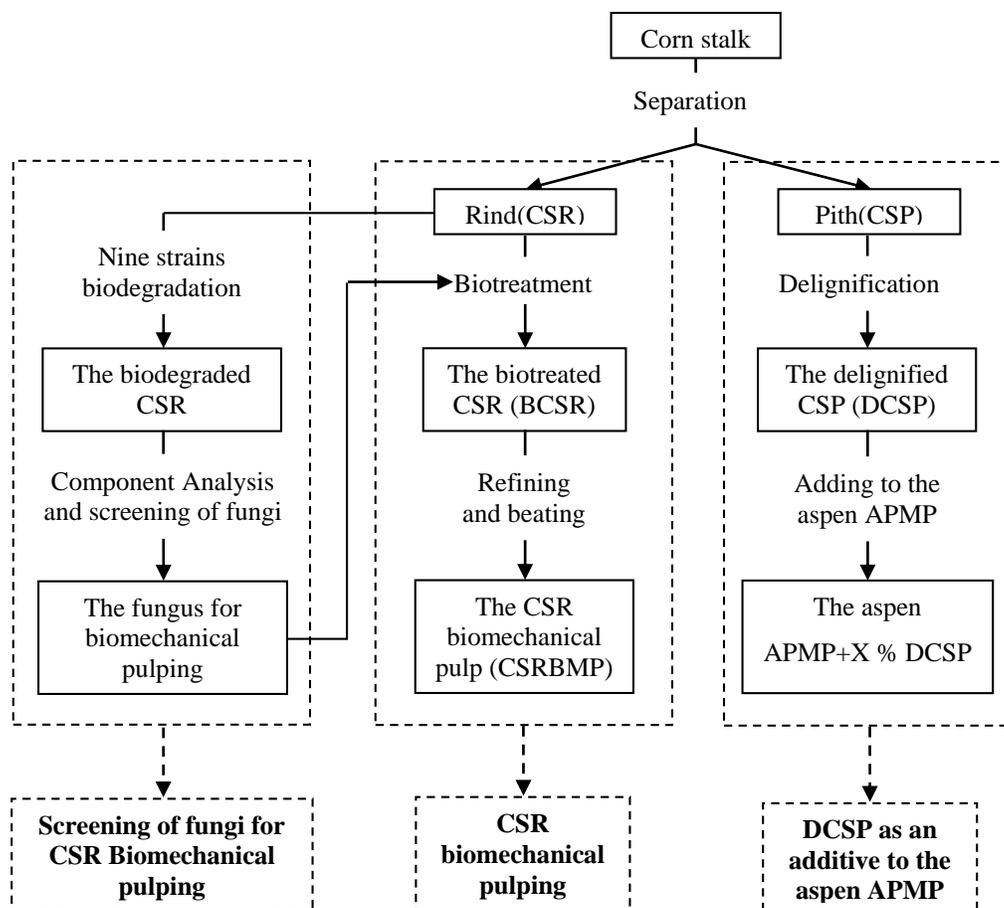


Fig. 1. The schematic overview of the experiment

Screening of Fungal Strains

Sa, Sb, Sc, Sd, *Trametes versicolor*, *Irpex lacteus*, *Trametes hirsuta* Ig-9, and *Phanerochaete chrysosporium* ME446 and its mutant *Phanerochaete chrysosporium*-14 were maintained on PDA slants at 4 °C and pre-cultivated on a PDA plate at 28 °C and 80% relative humidity (RH) before use.

The pre-cultivated strains inoculated on the surface of 50 mL of PDA medium in a 500-mL Erlenmeyer flask with a 1-cm plug and 10 g of autoclaved CSR (oven dry weight (o.d.)) were added after the surface of the medium was full of mycelia. After 30 days of cultivation, the rind was harvested, air-dried, weighed, pulverized, and passed through a 20-mesh sieve. The holocellulose, Klason lignin, and pentosan contents of the biodegraded rind were determined according to Shi and He's method (2003). The content of cellulose was calculated as the holocellulose content minus the pentosan content. The non-inoculated culture containing sterilized rind served as a control. There were three replicates for all cultures.

Biomechanical Pulping of CSR

Biotreatment of CSR with Trametes hirsuta Ig-9

Autoclaved potato dextrose broth (PDA without agar) was inoculated with two *T. hirsuta* Ig-9 mycelia plugs of 1 cm and then kept at 28 °C and 80% RH. The mycelium suspension was prepared (Souza-Cruz *et al.* 2004) and was used as the inoculum.

A 3-L Erlenmeyer flask containing 100 g of autoclaved CSR (o.d.) was inoculated with 1.3 mg of mycelia per gram of CSR (o.d.). The flask was maintained at 28 °C and 80% RH. After given periods of incubation, 1 L of 50 mM sodium acetate (pH 5.5) with 0.1 g of surfactant (Tween 80®) was added to the 3 L of culture. The extraction was performed at 120 rpm for 5 h at 10±1 °C. The liquor was filtrated and centrifuged (10,000 g, 4 °C, 5 min). The supernatant was used for the assay of enzyme activity. The biotreated CSR (BCSR) was then subjected to refining.

FPase (filter paper enzyme activity), CMCase (carboxyethylcellulose enzyme activity), and xylanase activity were determined with Whatman No. 1 filter paper (50 mg), carboxymethylcellulose sodium, and aspen xylan (Rickard and Laughlin 1980; Ghose 1987), respectively, by measuring the amount of reducing sugar released. One unit of enzyme activity was defined as the amount of enzyme releasing 1 µmol of glucose or xylose per minute.

Laccase, manganese peroxidase (MnP), and lignin peroxidase (LiP) were determined with 2,2-azinobis(3-ethylthiazoline)-6-sulphonate (ABTS), Mn²⁺, and veratryl alcohol (Hofrichter *et al.* 1998; Johannes and Majcherzyk 2000; Arora and Gill 2001) by monitoring the absorbance change at 420 nm, 270 nm, and 310 nm, respectively ($\epsilon_{420\text{nm}}=3.6\times 10^4 \text{ mol}^{-1} \cdot \text{L} \cdot \text{cm}^{-1}$, $\epsilon_{270\text{nm}}=11590 \text{ mol}^{-1} \cdot \text{L} \cdot \text{cm}^{-1}$, and $\epsilon_{310\text{nm}}=9300 \text{ mol}^{-1} \cdot \text{L} \cdot \text{cm}^{-1}$). One unit of enzyme activity was defined as the amount of enzyme oxidizing 1 µmol of the substrate per minute.

Refining and beating of BCSR

The biotreated rind was refined with a KRK continuous high-concentration disk refiner No. 2500-II (Kumagai Riki Kogyo Co. Ltd., Tokyo, Japan) for three stages: (1) 0.50 mm interval, 15.0% concentration, 90 g/min feeding speed; (2) 0.30 mm interval, 19.2% concentration, 80 g/min feeding speed; and (3) 0.18 mm interval, 21.0% concentration, 70 g/min feeding speed. The watt-hour meter on the disk refiner recorded the electrical energy at the start and end of feeding. The energy consumption during refining (ECR) was calculated by dividing the electrical energy difference between the start and end of feeding by the yield (o.d.) of the pulps produced. The beating degree was reported as the sum of the three-stage refining.

After refining, the crude rind biomechanical pulp was passed through a 0.3 mm-slot sieve and was beaten on PFI mill (Shanxi University of Science and Technology Machinery Manufacturer, XianYang, Shanxi Province, China), resulting in corn stalk rind biomechanical pulp (CSRBMP).

DCSP as an Additive in Aspen APMP

Delignification of CSP

The pulverized pith was first extracted with benzene-alcohol (v/v, 2:1) for 6 h, and then was extracted with 5% NaOH for 3 h at 60 °C at 8% pith concentration. The extracted pith was bleached with hypochlorite (5% effective chlorine, pH < 2) for 45 min at room temperature. The pith was then bleached again with 6% H₂O₂ at a pH of 11.5 and 50 °C for 5 h. The pith concentration was 5% for bleaching. After H₂O₂ bleaching, the pith was thoroughly washed to a neutral pH, resulting in delignified corn stalk pith (DCSP).

Addition of DSCP to the aspen APMP

The aspen APMP was produced through the first stage extrusion, the first stage chemical impregnation, the second stage extrusion, the second stage chemical

impregnation, and refining. Aspen APMP of 48 °SR was produced using a PFI mill from the 29 °SR aspen APMP.

The amount of DCSP that was added to the aspen APMP was based on paper basis weight, area of paper-making, and the water content of the DCSP. Aspen APMP without DCSP was used as the control.

Determination of Pulp and Paper Properties

The α -cellulose content was determined according to Ferraz *et al.* (2003). Handsheets of 60 g/cm² were produced by a Rapid Köthen sheet former (PTI GmbH, Vorchdorf, Austria). Handsheets preparation, the tightness, tensile index, and tear index were determined according to TAPPI standard methods T205 and T220, T500, T404, and T414, respectively. The opacity and brightness were determined using a L&W Elrepho spectrophotometer (Lorentzen & Wettre; Kista, Sweden) according to ISO standard 2471 and 2470. The yellowing value was determined according to TAPPI standard method T260.

SEM and FT-IR Analysis

The aspen APMP with DCSP and the control were visualized using a scanning electron microscope (Quanta 200, FEI, The Netherlands) at 10 kV.

The infrared spectra of the BCSR, CSRBMP, CSP, and DCSP were obtained using a Shimadzu IR Pretige-21 FT-IR spectrometer (Japan). The base between 1800 and 700 cm⁻¹ was constructed by connecting the point at 780 cm⁻¹ and the point at 1780 cm⁻¹, while the base between 3800 cm⁻¹ and 2750 cm⁻¹ was constructed by connecting the point at 2750 cm⁻¹ and the point at 3800 cm⁻¹ on the FTIR spectra. The absorbance intensity located at 1605 cm⁻¹ was used as an internal reference band in FT-IR spectra to calculate the relative absorbance.

Data Analysis

All data were the mean value of three times repetitions except for the FTIR analysis, and the results are expressed as the mean value \pm SEM (standard error of the mean). The Pearson correlation analysis between ECR and enzyme activities in biotreatment, the yield of BCSR after biotreatment, or the relative absorbance at wavenumber of peak on FTIR spectra and the multiple regressions between ECR and yield of the BCSR (Y), the relative absorbance intensity at 3414 cm⁻¹ (A_{3414}), and the relative absorbance intensity at 1653 cm⁻¹ (A_{1653}) were performed with Origin 8.0.

RESULTS AND DISCUSSION

Screening of Fungi

The ratio of the lignin loss to the cellulose loss and the ratio of the lignin loss to the weight loss can be used to indicate the selectivity of white rot fungi in the degradation of pulps, wheat straws, and rice straws (Martínez *et al.* 1994; Chang *et al.* 2012). A high $\Delta L/\Delta H$ (lignin loss/ holocellulose loss) or $\Delta L/\Delta C$ (lignin loss/ cellulose loss) value of a fungal strain indicates that the strain experienced high lignin removal with little holocellulose attack. IS represents the ratio of lignin loss to weight loss (Fackler *et al.* 2007). Table 1 shows the component analysis of the nine strains. The highest value of $\Delta L/\Delta H$ and $\Delta L/\Delta C$ was obtained with *T. hirsuta* Ig-9, and its IS was the closest to 1. This

indicates that it had the strongest ability to selectively degrade lignin of CSR; therefore, *T. hirsuta* Ig-9 was applied to produce CSR biomechanical pulp in the subsequent experiment.

Table 1. Component Analysis of CSR after 30 days of Biodegradation

Fungi	ΔW	Klason lignin (%)	Acid soluble lignin (%)	Gross lignin (%)	Holo-cellulose (%)	Cellulose (%)	Index of selectivity		
							$\frac{\Delta L}{\Delta H}$	$\frac{\Delta L}{\Delta C}$	IS
Control	1.50 (0.40)	17.69 (0.80)	2.41 (0.08)	20.10	75.07 (0.80)	52.84 (0.56)	-	-	-
<i>T. versicolor</i>	32.76 (3.96)	17.37 (0.91)	2.38 (0.14)	19.75	73.76 (1.08)	51.62 (0.28)	0.27	0.25	0.21
<i>I. lacteus</i>	24.81 (2.58)	17.14 (1.06)	2.99 (0.06)	20.13	66.91 (0.35)	44.77 (0.59)	-	-	0.20
<i>T. hirsuta</i> Ig-9	3.86 (0.65)	15.40 (0.69)	2.47 (0.22)	17.87	74.69 (0.36)	52.66 (0.21)	5.78	12.20	0.76
<i>P. chrysosporium</i> ME 446	26.69 (2.76)	17.06 (1.20)	2.22 (0.19)	19.28	70.78 (1.45)	50.11 (1.46)	0.19	0.30	0.22
<i>P. chrysosporium</i> -14	17.36 (1.44)	16.52 (0.38)	2.22 (0.19)	18.74	72.66 (1.22)	51.01 (0.83)	0.56	0.75	0.27
Sa	16.25 (1.69)	18.74 (0.57)	2.67 (0.04)	21.41	70.84 (0.69)	50.25 (0.47)	-	-	0.13
Sb	25.70 (2.22)	20.17 (0.29)	2.42 (0.08)	22.60	68.48 (0.81)	46.07 (0.35)	-	-	0.13
Sc	3.88 (0.35)	17.67 (0.14)	2.40 (0.17)	20.07	71.46 (0.22)	50.82 (0.43)	0.01	0.02	0.21
Sd	12.36 (1.50)	16.69 (0.09)	2.17 (0.05)	18.86	73.38 (0.59)	52.23 (0.93)	0.74	2.04	0.29

ΔW , the weight loss/% = $\frac{\text{the o.d.weight of CSR before biodegradation} - \text{the o.d.weight of CSR after biodegradation}}{\text{the o.d.weight of CSR before biodegradation}}$;

ΔL , the lignin loss = the lignin content of the control – the lignin content of CSR biodegraded;

ΔH , the holocellulose loss = the holocellulose content of the control – the holocellulose content of CSR biodegraded;

ΔC , the cellulose loss = the cellulose content of the control – the cellulose content of CSR biodegraded;

L_1 , the lignin content of the control;

L_2 , the lignin content of the biodegraded CSR;

$IS = \frac{L_1 - L_2 \times (100 - \Delta W) / 100}{\Delta W}$;

*standard deviation is shown in parentheses

Biomechanical Pulping of CSR with *T. hirsuta* Ig-9

Enzyme activity during CSR biotreatment

The type and quantity of enzyme produced by the white rot fungi during biopulping varies with the type of strain, substrate, and treatment conditions (Souza-Cruz *et al.* 2004), which may influence subsequent pulping processes and paper properties (Maijala *et al.* 2008).

Figure 2 shows the enzyme activity during the CSR biotreatment. During biotreatment of CSR with *T. hirsuta* Ig-9, neither LiP nor MnP were detected. Laccase was detected and peaked on day 21. The FPase, CMCase, and xylanase activities peaked on day 28, with the maximum activity being 11.30, 2.73, and 41.11 IU/g, respectively. The high xylanase activity was similar to the results of a previous work, which showed that xylanase

was the main hydrolytic activity during the biodegradation process of *Eucalyptus grandis* wood by *Ceriporiopsis subvermispota* (Ferraz *et al.* 2003).

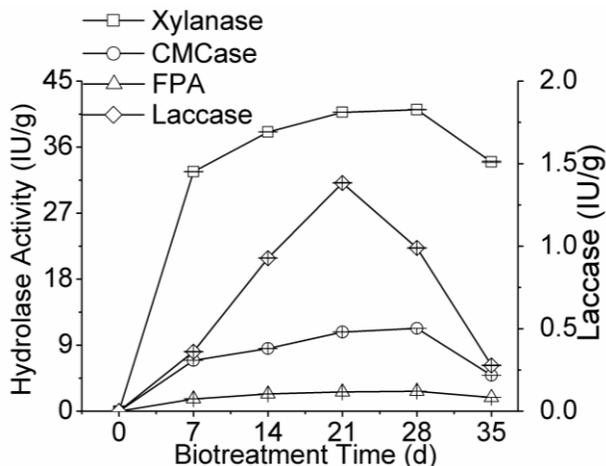


Fig. 2. Enzyme activity during CSR biotreatment

CSR biomechanical pulp and paper properties

The beating degree of the CSR biomechanical pulp with *T. hirsuta* Ig-9 was from 40 to 46 °SR. Figure 3 shows the resulting paper properties of sheets made with the CSR BMP. After 7 days of treatment, the tensile index and tear index of the paper produced from the CSR BMP were decreased by 24% and 33%, respectively (Fig. 3A). The strength property of paper reached a minimum after 28 days of treatment. These results are the opposite of those reported for aspen, eucalyptus, and spruce biomechanical pulp, which all experienced improvement in tensile and tear index (Akhtar 1994; Akhtar *et al.* 2004; Majjala *et al.* 2008). This may be due to the omission of the glucose medium that was considered to suppress cellulose degradation and increase fungal biomass.

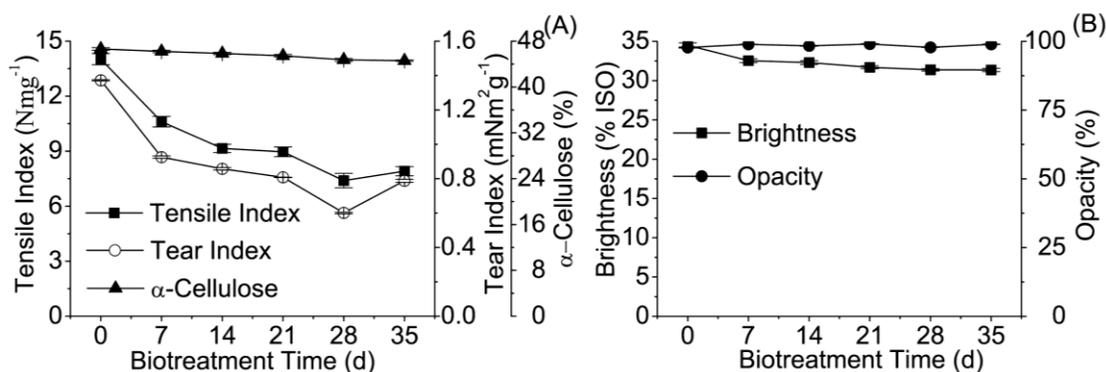


Fig. 3. Properties of CSRBMP and paper made from CSRBMP, (A) the strength properties and α -cellulose content, (B) the optical properties

The α -cellulose in the pulp represents the high polymerization degree of the cellulose. The decrease in α -cellulose content and paper strength of the CSRBMP shown in Fig. 3A indicates that the decrease in paper strength may be due to the reduction of the high polymerization degree of cellulose caused by cellulase that *T. hirsuta* Ig-9 produced during biotreatment (Fig. 2).

The opacity changed from 97.76% to 99.01% with a small variation, while the brightness slightly decreased with the increase in biotreatment time as shown by Fig. 3B. The biotreatment had the same effect on the brightness and opacity as results reported in a previous work (Maijala *et al.* 2008).

Energy consumption during refining of CSRBMP

The energy consumption during refining (ECR) and the yield of the BCSR decreased with the increase in biotreatment time, as shown in Table 2.

Table 2. Energy Consumption during Refining and Yield of BCSR

Biotreatment Time (d)	Energy Consumption during Refining (kwh · kg ⁻¹ · °SR ⁻¹)	Yield After Biotreatment (%)
0	0.2923(0.006)	93.56(0.29)
7	0.2841(0.005)	90.92(0.28)
14	0.2801(0.003)	89.17(0.23)
21	0.2763(0.007)	89.01(0.38)
28	0.2721(0.004)	83.29(0.25)
35	0.2523(0.007)	82.01(0.34)

*The standard deviation is shown in parentheses

Table 3. Pearson Correlation Analysis

Enzyme Activity, Yield, or Wavenumber of Peak on FTIR Spectra (cm ⁻¹)	Energy Consumption during Refining	
	Coefficient of Pearson Correlation	Significance ^a
Xylanase	-0.53646	0.27251
CMCase	-0.25832	0.62114
FPase	-0.48641	0.32792
Laccase	-0.11481	0.82854
BCSR Yield	0.92017	0.00930
3414	0.73114	0.09871
2900	-0.05007	0.92595
1735	-0.63011	0.17992
1653	-0.76441	0.07672
1631	-0.43657	0.38675
1514	-0.57816	0.22939
1458	-0.35571	0.48894
1425	-0.39511	0.43818
1372	-0.53026	0.27915
1327	-0.24172	0.64448
1246	-0.35478	0.49016
1203	-0.31649	0.54111
1165	-0.01814	0.97279
1107	0.07456	0.88836
1055	0.07456	0.88836
896	-0.43797	0.38505

^a 2-tailed test of significance was used and level of significance $\alpha=0.1$

To predict the ECR, Pearson correlation analysis was performed. The results in Table 3 indicate that at a significance level of $\alpha=0.1$, the yield of the BCSR (Y), the relative absorbance intensity at 3414 cm⁻¹ (A_{3414}), and the relative absorbance intensity at 1653

cm^{-1} (A_{1653}) had good linear correlations with the ECR. The ECR was positively proportional to Y and A_{3414} , and negatively proportional to A_{1653} .

Further multiple linear regressions were performed with Origin 8.0, where Y , A_{3414} , and A_{1653} served as independent variables and ECR as the dependent variable. The regression results were:

$$ECR = 0.00522 Y + 0.03131 A_{3414} + 0.50939 A_{1653} - 0.67695 \quad (1)$$

The regression coefficient of determination R^2 was 0.99334 and prob (>F) was 0.00998; thus, the regression was significant at a 95% confidence interval.

The fungal biotreatment of CSR before refining permits energy savings, which was also found for biomechanical pulping of other wood and non-wood materials (Akhtar *et al.* 2004; Ramos *et al.* 2004; Hernández *et al.* 2005). In a previous study, no apparent correlation was found between the removal of lignin of wood chips and energy savings (Ferraz *et al.* 2008). Reducing energy consumption during refining may be the synergistic result of the modification of lignin, cellulose, and hemicellulose by the fungal oxidant/radical and hydrolytic mechanism. The results of the multiple linear regression reveal that the ECR may be predicted by determining the parameters of BCSR such as Y , A_{3414} , and A_{1653} .

DCSP as an Additive in the Aspen APMP

Addition of DCSP to the aspen APMP

Table 4. Effect of DCSP Addition on the Aspen APMP

Addition Amount (%)	Beating Degree (°SR)	Brightness (%ISO)	Tightness (g/cm ³)	Tensile Index (N·m·g ⁻¹)	Tear Index (mN·m ² /g)	Opacity (%)	Yellowing Value
0	29	78.3 (0.34)	0.469 (0.11)	21.31(0.12)	4.22(0.25)	83.60 (0.12)	0.589(0.08)
10	29	78.1 (0.32)	0.492 (0.06)	31.68(0.22)	4.69(0.23)	82.80 (0.22)	0.520(0.06)
20	29	78.2 (0.38)	0.500 (0.09)	38.63(0.24)	5.18(0.25)	81.60 (0.25)	0.486(0.06)
30	29	78.0 (0.29)	0.514 (0.08)	49.35(0.31)	5.87(0.24)	79.90 (0.19)	0.464(0.05)
40	29	78.1 (0.30)	0.526 (0.10)	57.55(0.27)	6.52(0.23)	77.10 (0.14)	0.467(0.08)
50	29	78.0 (0.40)	0.552 (0.07)	66.83(0.32)	6.44(0.13)	75.14 (0.21)	0.468(0.07)
60	29	78.2 (0.37)	0.573 (0.06)	72.91(0.29)	6.27(0.23)	74.14 (0.20)	0.470(0.09)
0	48	ND ^a	ND	28.93(0.30)	4.58(0.25)	ND	0.592(0.07)
10	48	ND	ND	29.61(0.29)	4.68(0.18)	ND	0.537(0.06)
20	48	ND	ND	32.79(0.33)	4.96(0.13)	ND	0.491(0.08)
30	48	ND	ND	33.91(0.24)	4.72(0.22)	ND	0.453(0.05)
40	48	ND	ND	36.20(0.28)	4.69(0.25)	ND	0.463(0.07)

^aND - not determined. The standard deviation is in parentheses.

The alkaline extraction, hypochlorite, and hydrogen peroxide pretreatment produced 70% to 75% delignified corn stalk pith (DCSP). The tensile index and tightness of paper made from the 29°SR aspen APMP synchronously increased with the increase in DCSP as shown in Table 4. The result of DCSP addition to aspen APMP was similar to that of the extraction of hemicellulose prior to aspen chemithermomechanical pulping in that it reduces the tensile index of paper (Liu *et al.* 2012). The effect of DCSP on the APMP may be similar to the impact of fines on mechanical pulp (Moss and Retulainen 1997). The tensile index of paper made from the 48°SR aspen APMP also increased with increasing DCSP addition. The tear index of paper produced from the 29°SR and 48°SR aspen APMP peaked with the addition of 40% and 20% DCSP, respectively. The DCSP addition did not affect the brightness of the aspen APMP, but caused a decrease in opacity, with the highest decreasing rate occurring between 30% and 40% addition amount (Table 4). Additionally, DCSP addition inhibited APMP yellowing, especially at 30% addition (Table 4). The results show that DCSP has potential to serve as an adding agent for strengthening pulp and inhibiting yellowing.

Analysis of the aspen APMP with DCSP and DCSP by FTIR and SEM

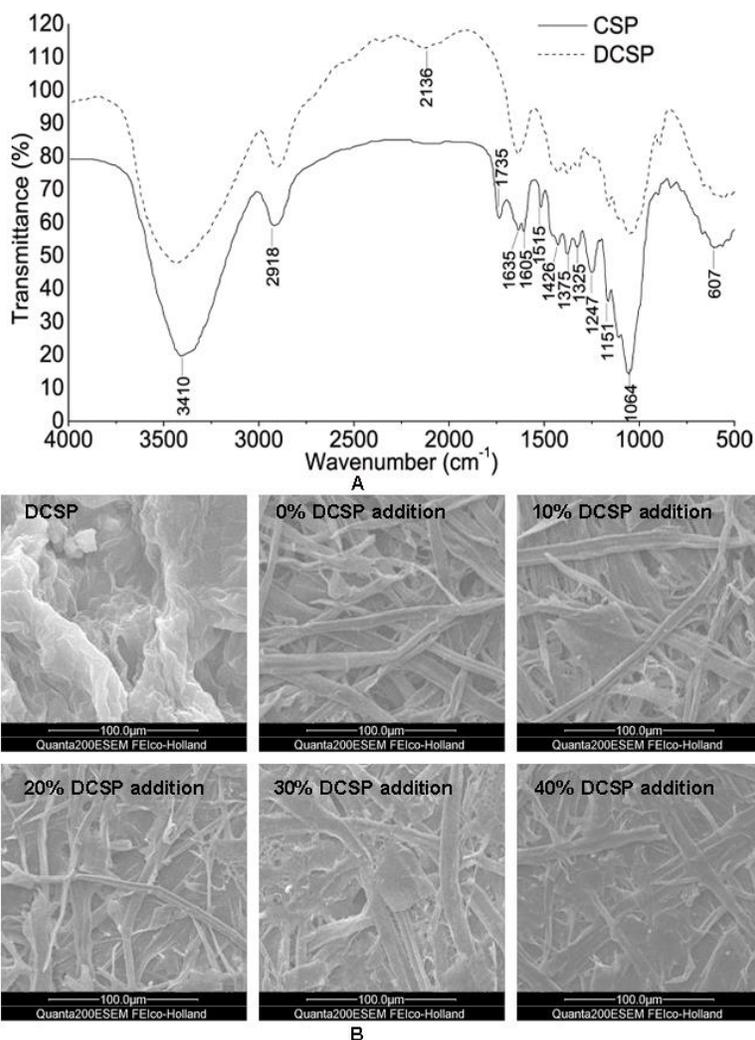


Fig. 4. FTIR spectra of CSP and DCSP (A), and SEM images of DCSP and the aspen APMP with DCSP (B)

The FTIR spectra of the DCSP are shown in Fig. 4A. Compared with CSP, the peaks of DCSP at 1605 and 1514 cm^{-1} assigned to lignin (Faix 1992; Schwanninger *et al.* 2004) disappeared, and the peaks at 1372, 1107, and 1055 cm^{-1} assigned to holocellulose (Popescu *et al.* 2010; Sene *et al.* 1994) became weak. The band at 1735 cm^{-1} associated with the acetyl group of xylan (Pandey and Pitman 2003) disappeared, while the band at 1635 cm^{-1} related to the carboxylate group (Bao *et al.* 2011) appeared. The SEM of the DCSP (Fig. 4B) reveals a loose and soft appearance of the DCSP. When added to the aspen APMP, the DCSP penetrated into and filled in the space of the aspen APMP fibers and some absorbed onto the surface of the aspen APMP fibers (Fig. 4B). With the increase in DCSP addition amount, the SEM show that as the adhesion increased the space between the fibers became reduced.

The FTIR spectra of the DCSP affirmed that the lignin of the CSP was indeed removed and that the holocellulose partly decomposed into a smaller molecule or oxidized to generate the carboxylate group. A decomposed fiber can more easily access the space between the aspen APMP fibers. The generated carboxylate group is able to bond to the hydroxyl group of the aspen APMP fibers. The dissolved xylan molecule deposits and absorbs on the fiber surfaces (Schönberg *et al.* 2001); thus, resulting in the improvement in the aspen APMP strength and is the comprehensive effect of fines, the carboxylate of holocellulose, and xylan in DCSP.

CONCLUSIONS

1. Corn stalk rind (CSR) after seven days of biotreatment with *T. hirsuta* Ig-9 was refined to produce corn stalk rinds biomechanical pulp (CSRBMP), with a CSRBMP yield of approximately 77% and a 2.7% reduction in energy consumption during refining. After the CSP was delignified, approximately 73% delignified corn stalk pith (DCSP) was obtained. When 30% DCSP was added to the unbeaten aspen APMP, the tensile index doubled, the tear index increased by 39%, and the yellowing value decreased by 21%.
2. The biotreatment conditions not optimized resulted in a decline in strength and brightness of the resulting paper made from CSRBMP. Additionally, the increase in biotreatment time decreased the energy consumption during refining. Multiple regression was carried out, where Y , A_{3414} , and A_{1653} served as independent variables and ECR (energy consumption during refining) served as the dependent variable. The regression showed that the determining parameters of the biotreated rind may be used for predicting the energy consumption during refining.
3. Because the carboxylate of the holocellulose and xylan in the DCSP increased the bond between the aspen APMP fibers, the tensile index of the resulting paper from the aspen APMP increased with the increase in DCSP addition amount.

ACKNOWLEDGMENTS

The authors wish to thank the Key Lab of Pulp and Paper Science and Technology of the Ministry of Education of Qilu University of Technology for providing the equipment used for pulping and paper-making.

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Article submitted: May 26, 2015; Peer review completed: September 19, 2015; Revised version received and accepted; September 28, 2015; Published: November 4, 2015.

DOI: 10.15376/biores.10.4.8565-8579