

THE EFFECTS OF BIOPULPING ON CHEMICAL AND ENERGY CONSUMPTION DURING KRAFT PULPING OF HYBRID POPLAR

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ABSTRACT

Poplar wood chips were treated in a rotary bioreactor for 10 days with the white-rot fungus *Phanerochaete chrysosporium* KCCM 34740 prior to kraft cooking, in an attempt to improve the pulping and refining efficiency of the wood chips. It was apparent that fungal pretreatment could simultaneously increase screened pulp yield and reduce the kappa number (residual lignin content) of the hardwood pulps. Additionally, lower initial pulp freenesses were observed, while the water retention values of each pulp were elevated, suggesting increased external fibrillation of the pulp fibers. Scanning electron microscopy confirmed this hypothesis. It was also shown that the refining energy required to develop (to achieve a target freeness) the unbleached kraft pulp fibers was significantly lower in fungal pretreated wood, without any deleterious influence on paper quality. These findings clearly suggest that fungal pretreatment of hardwood chips with *P. chrysosporium* KCCM 34740 can reduce the chemical loading and energy consumption during kraft pulping, and concurrently reduce the energy required during pulp refining.

Keywords: Kraft pulping, *Phanerochaete chrysosporium*, poplar, biopulping, pulp yield, kappa number, freeness, water retention values, refining, handsheet properties.

INTRODUCTION

During the past decade, biological agents, such as microorganisms and proteins, have

been evaluated for a wide range of applications in the forest products industry, including modifications to virgin and recycled wood fiber, biobleaching, mill effluent remediation, and enzymatic deinking. Biological treat-

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ments, as compared to chemical reagents, offer many processing and environmental advantages, such as ease of degradation and disposal, as well as reaction by-products that are environmentally benign.

Pulping is the process by which the macroscopic structure of raw wood fiber is broken apart, rendering the fiber much more pliable, and thereby suitable for papermaking. Biopulping is the direct application of fungal cultures onto chip piles with the aim of enhancing both the production yield and processing of the pulp manufacture. This application has been directed by the need to alter and/or modify two separate target substrates: lignin for mechanical pulp production which improves both pulping and bleaching, and the lipophilic extractives, which limit pitch accumulation during processing (Pilon et al. 1982; Akamatsu et al. 1984; Blanchette et al. 1988; Sachs et al. 1989; Leatham et al. 1990a, b; Dawson-Andoh et al. 1991; Fujita et al. 1991; Blanchette et al. 1992; Fukui et al. 1992; Akhtar 1994; Fujita et al. 1993; Sykes 1993; Akhtar et al. 1993; Messner and Srebotnik 1994; Thornton et al. 1994; Chen et al. 1995; de Jong et al. 1997; Kohler et al. 1997; Breen and Singleton 1999; Gutierrez et al. 2001). Globally, mechanical pulping processes are rapidly growing primarily because of their high yields, relatively low capital investment, and the fact that these processes yield pulps with properties advantageous to certain products. However, there are also disadvantages, as they generate pulps of lower product strength and require greater input of electrical energy during processing. Most importantly, in mechanical pulping, pitch problems are often encountered during paper manufacture. Colloidal pitch can condense to form larger droplets that are subsequently deposited on the paper machine or found directly on the ensuing paper. These pitch deposits can cause large economic losses, from shutdown of equipment to contamination of the pulp, as well as the added cost of chemicals such as pitch control agents. In addition, the compounds that form pitch (resin and free fatty acids, sterols, and glycerides re-

leased from parenchyma cells and resin canals) can represent the primary source of toxicity in totally chlorine-free (TCF) mill effluents, and have a severe detrimental effect on the environment. The nature and chemical composition of the lipophilic extractives vary from mill to mill, and also between pulping and bleaching processes.

It has been well recognized that many microorganisms, particularly the white-rot fungi *Phanerochaete chrysosporium* and *Ceriporiopsis subvermispora*, attack and degrade lignin in wood (Kirk et al. 1994; Akhtar et al. 1996). Most studies of biological pulping were carried out with laboratory- or pilot-scaled facilities; but during the last 10 years, the scaled-up applications to industrial operation have been conducted in Canada, United States, and Europe (Trotter 1990). It has been suggested that biopulping can be successfully employed to generate chips suitable for sulfite, kraft, and biomechanical pulping. Furthermore, it has been suggested that this process can generate superior quality dissolving pulp.

This work was carried out to investigate the effectiveness of biological treatment for savings in chemicals during kraft pulping and energy during refining of hybrid poplar wood chips treated with *P. chrysosporium*.

MATERIALS AND METHODS

Strain and growth medium

The white-rot fungus strain, *Phanerochaete chrysosporium* KCCM 34740, was obtained from KCCM (Korean Culture Center of Microorganisms, Seoul, Korea). This strain was inoculated and grown in YM broth (Difco 271120) at $29 \pm 1^\circ\text{C}$, RH $70 \pm 1\%$ for 7 days with shaking. Following growth, the mycelium were collected by filtration, and homogenized in a Waring blender and used as an inoculum for fungal treatment of wood chips.

Wood chips

Twenty year old hybrid poplar (*Populus alba* \times *glandulosa*) was obtained from Dongguk University Research Forest in Nam-

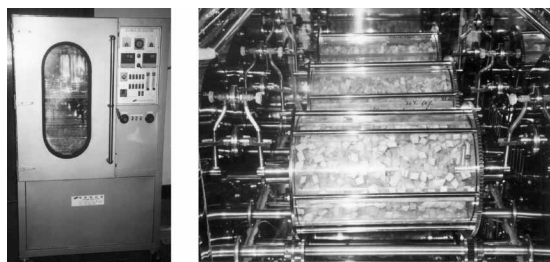


FIG. 1. Bioreactor employed for fungal pretreatment of wood.

yangju, Korea, in January 2001. The logs were debarked and then chipped in a 14-in. (internal diameter) disc chipper (Abraham Co., Finland) immediately after felling. The ensuing wood chips were subsequently screened to collect a homogenous chip class ($20 \times 15 \times 3$ mm), and gas sterilized with ethylene oxide for 24 h prior to fungal treatment.

Bioreactor

A specially designed and manufactured biopulping reactor was employed for all lab-scale experiments. The reactor is equipped with a rotating chamber, housing three independently controlled (temperature and humidity) bioreactors (Fig. 1). Each bioreactor was supplied with humid air sterilized by membrane filter during incubation.

Fungal treatment of wood chips

Wood chips were spray treated with an inoculum of *P. chrysosporium* (0.005 g of mycelium per 1 g of oven-dried wood chip), under sterile conditions, and incubated in the bioreactor (Fig. 1) at $29 \pm 1^\circ\text{C}$, RH $70 \pm 1\%$ for 10 days—conditions that were previously shown to be the most effective conditions for fungal treatment of wood (Kang et al. 2001).

Control (untreated wood chips) were incubated concurrently, under the same conditions, without the addition of fungi.

Kraft pulping

Control and fungal-treated wood chips were chemically pulped at three different cooking

TABLE 1. *Kraft pulping conditions for control and fungal pretreated poplar chips.*

Variables	Untreated (Control)	Fungal treated		
		KP-I	KP-II ^a	KP-III ^b
Active alkali (%)	17		12	17
Sulfidity (%)	20		15	20
Liquor-to-wood ratio	5 : 1		5 : 1	5 : 1
Max. cooking temp. ($^\circ\text{C}$)	170		170	165
Time to max. temp. (hr)	1.0		1.0	1.0
Time at max. temp. (hr)	2.0		2.0	1.5

^a For saving of cooking chemicals.

^b For saving of cooking energy.

conditions to evaluate both savings in cooking chemicals and energy required to effectively delignify the hardwood pulp (Table 1). One condition (KP-I) was identical to the control treatment, with the exception of fungal treatment, while KP-II was employed as a comparison to the control pulp to evaluate savings in cooking chemicals (decreased active alkali and sulfidity), and KP-III evaluated potential energy savings by reducing H-factor (decreased cooking temperature and time).

Pulp and paper evaluation

Following kraft cooking, wood chips were extensively washed with distilled water, disintegrated, and screened on a flat Parker screen (Toyoseiki, Japan) to determine pulp yield. After screening, the pulps were refined in a Valley beater to evaluate energy consumption to attain target freeness, by determining Canadian standard freeness (Tappi Test Method T227 om-94) values at 5-min intervals during the course of refining. Nominal 60 g/m² handsheets were prepared from the unrefined pulp using whitewater recirculation and evaluated based on Tappi Test Methods. The oven-dry basis weight was used to calculate handsheet strength parameters.

Both the control and fungal treatments were done in duplicate, whereby sheet preparation and sheet testing were done on each of the independent replicates (each replicate contained 10 samples).

Water retention values (WRV) were measured by centrifugation using 0.5 g oven-dried

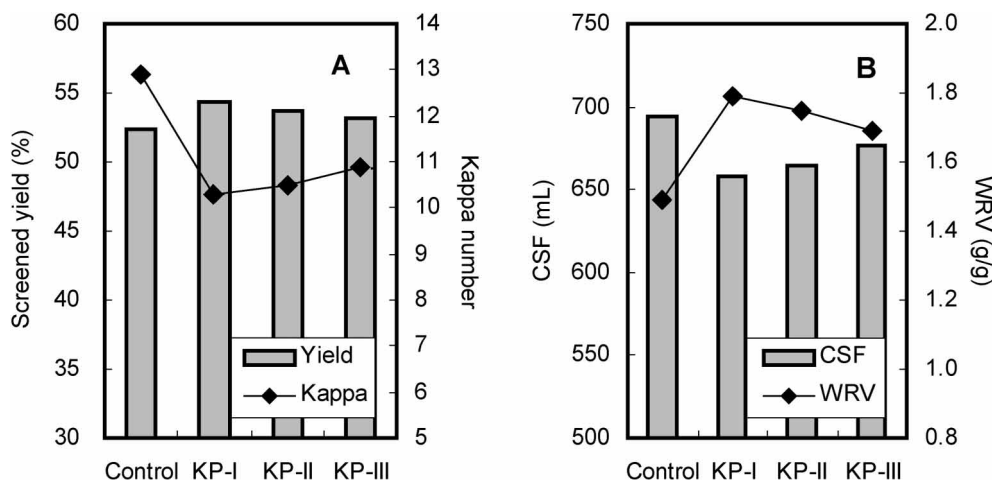


FIG. 2. Changes in (A) screened yield and kappa number, and (B) freeness and water retention values for control and *P. chrysosporium* pretreated hybrid poplar wood chips at different kraft pulping conditions.

fiber. In short, samples were weighed, centrifuged at $900\times g$ for 30 min, and then transferred to a weighing vessel. The samples were then dried overnight at 105°C and reweighed. The change in weight of samples represents the capacity for the pulp to retain water. Kappa numbers were measured according to Tappi Test Method T236 om-99.

SEM observation of pulp fiber

In an attempt to visualize the biological effect of fungal treatment on the wood chips, scanning electron microscopic (Hitachi S-300N, Japan) analysis of the kraft pulp fiber was conducted. Imaging was performed at $4,000\times$ magnification.

RESULTS AND DISCUSSION

The forestry industry constitutes one of the largest economic sectors in the world. With continuous and steady growth expected in the demand for wood and fiber, accompanied by stricter environmental regulations, it is crucial that the processing of wood and wood fiber be undertaken in an environmentally benign and energy-efficient manner. It is anticipated that, in the future, a large percentage of wood, more specifically hardwood-derived wood, will come from intensively managed, fast-rotation

plantation forests. In the Northern Hemisphere, hybrid poplar is the most likely candidate to complement the expensive breeding programs and *Eucalyptus* plantations of the Southern Hemisphere. *Populus* has an unusual mode of asexual reproduction, which is referred to as “suckering.” This reproductive mechanism generates several genetically identical stems, known as ramets that originate from a common root system, and *Populus* is therefore an ideal species for reforestation. This pattern promotes the occurrence of natural genetic clones in highly concentrated geographic stands. *Populus*’s rapid growth rate ($\sim 30\text{ m}^3/\text{ha}/\text{yr}$) and inherent lower age of maturity result in shorter rotation times compared to other hardwood species grown in similar environments (Cisneros et al. 1996).

Screened yield and pulp properties

Following 10 days’ incubation in the bioreactor, it was apparent that chips treated with fungi (KP-I) demonstrated higher screened pulp yields ($\sim 1.3\%$) when compared to chips that were untreated (Fig. 2A). Additionally, chips treated concurrently at milder pulping condition (Table 1): either at a reduced chemical loading (KP-II), or at a similar chemical loading but at reduced H-factor (KP-III), also



FIG. 3. Scanning electron micrographs (SEM) at 4,000 \times magnification of pulp fibers generated from (A) control wood chips and (B) fungal pretreated wood chips.

demonstrated improved screened pulp yield ($\sim 0.7\%$) when compared to the control wood chips. However, the improvements in screened pulp yield were not as great as the KP-I pulp, as both of the milder pulping conditions resulted in more shives (rejects) compared to the KP-I pulps (1.2%). The shive contents of the KP-II and KP-III were 1.7% and 2.0%, respectively; however, this is still lower than that of the corresponding control pulp, 2.5%.

An evaluation of pulp kappa clearly illustrated that fungal pretreatment significantly reduced the residual pulp kappa (~ 8 kappa) when compared to the control pulps. These findings concur with previous findings, which have shown that biopulping results in substantially lower residual pulp lignin content (Blanchette et al. 1988; Leatham et al. 1990b; Blanchette et al. 1992; Akhtar et al. 1993; Akhtar 1994). As expected, the two milder cooking conditions did not remove lignin to the same extent as the KP-I condition, but still demonstrated a greater efficiency at delignification compared to the corresponding control wood (Fig. 2A).

A measurement of the pulp freeness of the unrefined furnishes indicated that fungal pretreatment results in lower initial freeness values, regardless of pulping condition, compared to the control pulp (Fig. 2B). However, it is clear that the chips cooked at comparable conditions to the control chips (KP-I) showed the

greatest improvements, demonstrating a ~ 35 -mL drop in initial freeness, while chips cooked at a lower active alkali and sulfidity, and at a lower H-factor resulted in a ~ 20 and ~ 10 -mL, respectively, lower freeness when compared to the same control (Fig. 2B). An evaluation of these same pulp samples clearly demonstrated that the water-carrying capacity (water retention values) were significantly greater than the control pulp. This increased water retention indicates that the pulps were more heavily fibrillated, as fines and fibrils have the propensity to retain water in the pulp matrix. A qualitative, visual evaluation by SEM clearly supports these findings, demonstrating substantially elevated levels of external fiber fibrillation (Fig. 3). Similar findings have also been shown by Messner and Srebotnik (1994).

It is well known that white-rot fungi preferentially degrade the lignin in the wood cell wall, making the pulp fiber more porous (Oriaran et al. 1990). The altered pulp morphology (porosity) facilitates a greater ease of penetration of chemical cooking by increasing accessibility to lignin in the wood cell wall. Furthermore, it also enhances the dispersion of cooking chemicals into wood fibers. Clearly, fungal pretreatment of wood chips can generate significant savings in pulping chemicals

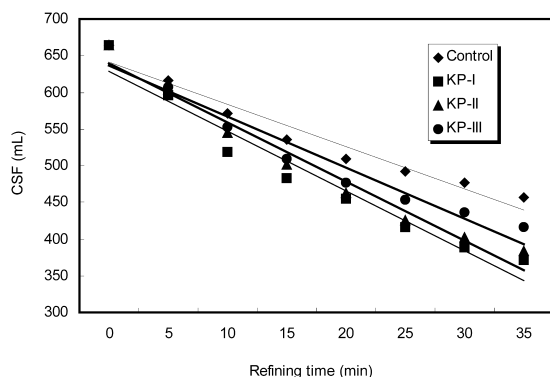


FIG. 4. Changes in freeness as function of refining time in a Valley beater of unbleached kraft pulp generated from control and fungal pretreated hybrid poplar wood chips at three different cooking conditions.

and/or energy during kraft pulping to achieve a target kappa.

Refining energy and paper properties

All pulps (control and three fungal pretreated pulps) were initially adjusted to a freeness of 660 to avoid any effects of the initial freeness gain, and then subjected to refining in a Valley beater for 35 min. At exactly 5-min intervals, pulp samples were removed for freeness determination. It was apparent that the wood chips subject to fungal pretreatments respond to refining differently than the corresponding control, demonstrating significantly greater drops in freeness at all time intervals. As was previously shown, the KP-I pulp demonstrated the greatest drop in freeness (Fig. 4). This would suggest that fungal pretreatment is an effective means of also reducing the amount of refining energy required to achieve target freeness values, and therefore represents an effective means of improving the efficacy of both the chemical pulping and papermaking process. The improved refining is likely a result of the improved lignin removal, as well as lignin depolymerization as has been previously suggested (Blanchette et al. 1992; Fukui et al. 1992), both of which will facilitate the effective softening of the fibers and alter the degree of fibrillation compared to the control pulp.

An evaluation of handsheets produced from

TABLE 2. Handsheet properties of control and *P. chrysosporium* treated poplar.

Unrefined physical properties	Untreated (Control)	Fungal-treated		
		KP-I	KP-II	KP-III
Tensile index (N·m/g)	43.16	55.03	53.75	52.28
Tear index (mN·m ² /g)	2.37	2.03	2.18	2.21
Folding endurance (times)	21.20	32.17	29.99	26.65
Burst index (kPa·m ² /g)	0.61	0.73	0.66	0.63

the unrefined pulp fibers, adjusted to the same initial freeness, clearly demonstrated that tensile and burst indices were both improved, while tear index was reduced as a result of biopulping with *P. chrysosporium* KCCM 34740 (Table 2). Furthermore, the improvements in paper properties were observed at less severe cooking conditions (lower sulfidity and active alkali), as well as at a reduced H-factor (lower cooking conditions and residence time at temperature).

CONCLUSIONS

It was clearly shown that the pretreatment of hardwood (hybrid poplar) wood chips with *P. chrysosporium* KCCM 34740 in a bioreactor controlling both temperature and humidity can improve the efficacy of pulping the chips, generating improved pulp yield and reduced residual kappa, and concurrently maintaining or improving the papermaking performance of the ensuing fiber. Furthermore, during refining, it was clear that chips pretreated with fungi required less refining energy to attain target pulp freeness, suggesting that this application could be used to reduce overall energy required to develop papermaking fibers. It was also apparent that improvements were greatest when pretreated chips were pulped at similar conditions to the control. However, improvements were also apparent at reduced chemical loadings (lower sulfidity and active alkali) and H-factor (temperature and residence time).

An analysis of water retention values (WRV) suggests that the pretreated fibers displayed increased porosity, likely a function of

increased fiber fibrillation, a conclusion supported by SEM observation.

In conclusion it is fair to say that fungal treatment of hardwood chips with *P. chrysosporium* KCCM 34740 prior to kraft pulping can reduce chemicals and energy consumption during pulping and subsequently reduce the refining energy required during fiber processing.

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