Chapter 2

Overview of Biomechanical and Biochemical Pulping Research

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The fungal pretreatment of wood chips prior to mechanical pulping saves electrical energy, improves paper strength properties, and reduces pitch content. Fungal pretreatment is also effective on nonwoody plants and benefits sulfite, organosolv, and dissolving pulp production. Preliminary results with biokraft pulping are encouraging, but an in-depth evaluation is required. The results of two pilot-scale outdoor chip pile experiments recently conducted at the Forest Products Laboratory were comparable IO those obtained using laboratory-scale bioreactors. The economics of the process are attractive, and the process appears to fit into existing pulp mill facilities with some modifications.

The pulp and paper industry utilizes mechanical or chemical pulping methods or a combination of these to produce pulps with desired characteristics. Mechanical pulping involves the use of mechanical force to separate the wood fibers. Mechanical processes are high yield (up to 95%) and produce paper with high bulk, good opacity, and excellent printability. However, these processes are electrical energy-intensive and produce paper with lower strength, higher pitch content, and higher color reversion rate (tendency IO turn yellow with time) compared to chemical processes. Chemical pulping involves the use of chemicals to degrade and dissolve lignin from the wood cell walls, releasing high-cellulose fibers. Chemical pulping processes yield pulps with higher strength; however, these processes are low yield (about 40% to 50%) and are very capital-intensive.

Biopulping, which is defined as the treatment of lignocellulosic materials with lignin-degrading fungi prior to pulping, appears to have the potential to overcome some problems associated with conventional mechanical and chemical pulping methods. The following text summarizes biomechanical and biochemical pulping research and describes key findings.

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Biomechanical Pulping of Wood

Background. The use of white-rot fungi for the biological delignification of wood was perhaps first seriously considered by Lawson and Still (*1*) at the West Virginia Pulp and Paper Company (now Westvaco Corporation). These researchers published a survey of the literature (72 lignin-degrading fungi), which pointed to the dearth of knowledge about the fungal degradation of lignin. In the 1970s, Eriksson at the Swedish Forest Products Laboratory (STFI) launched a fairly comprehensive investigation that demonstrated that fungal pretreatment could result in significant energy savings and strength improvements for mechanical pulping (*2-5*). That research also resulted in a U.S. patent that described a "method for producing cellulose pulp" (*6*). Although this research met with limited success-encountering difficulties in scale up-it provided valuable insights (*7,8*). Treatment of coarse mechanical pulp with enzymes such as cellulases and hemicellulases prior to secondary refining has also resulted in both electrical energy savings and improvements in paper strength properties (9). However, the information is scanty; details can be found in several review articles and the literature cited therein (*10-13*).

The literature cited in these review articles indicates that fungal pretreatment of wood chips for mechanical pulping can have certain benefits. Accordingly, a comprehensive evaluation of biomechanical pulping was launched in 1987 at the USDA Forest Service, Forest Products Laboratory (FPL), under the auspices of a Biopulping Consortium. The Consortium involved the FPL, the Universities of Wisconsin and Minnesota, end up to 22 pulp and paper and related companies. The overall goal was to comprehensively evaluate the technical and economical feasibility of fungal pretreatment with mechanical pulping to save energy and/or improve paper strength. The consortium research was conducted by several research teams (*12*). In this chapter, we focus only on the work conducted by the fungal, pulp and paper, and engineering scale-up teams. Key findings arc described in the following sections.

Selection of Lignin-Degrading Fungi. The screening of white-rot fungi followed procedures for selecting fungi that preferentially degrade lignin. One of the most appropriate methods appeared to be an assessment of decay (chemical analyses of lignin and wood sugar content) using wood blocks in accelerated decay chambers (14). Fast-growing species that rapidly colonize wood with a preference for degrading lignin were selected. These fungi with selective lignin-degrading ability showed promise for biomechanical pulping. Recently, a new and relatively easier and faster method was developed using Simons stain that predicts the efficacy of fungal pretreatments during biomechanical pulping by staining selectively for fibrillated fibers in coarse pulps (*15*). This method is now being used routinely to help optimize the biopulping process as well as to select new species and strains. After screening more than 400 species and strains. The best fungi found to date are *Ceriporiopsis subvermispora, Phanerochaete chrysosporium, Phlebia tremellosa, Phlebia subserialis, Phlebia brevispora, Dichomitus squalens, and Hyphodonitia setulosa.*

Evaluation of Selected Fungi for Mechanical Pulping. White-rot fungi screened as described were evaluated for their ability to decrease the electrical energy requirement and to improve paper strength properties during refiner mechanical pulping. The process involved treatment of wood chips with fungi in bioreactors on a bench scale at appropriate temperature and humidity, followed by mechanical pulping of control and fungus-treated chips in a single-disk atmospheric refiner, preparation of paper, and testing of paper for physical properties (*12*).

Energy Savings and Physical Properties. The test fungi saved significant amounts of electrical energy and improved paper strength (*12*). Unfortunately, the most effective fungi on aspen (hardwood) were found to be relatively ineffective on loblolly pine (softwood). However, we discovered that a relatively uncommon fungus, *C. subvermispora,* was effective on both wood species (*16*). Our results indicate that *C. subvermispora* pretreatment of different wood species saves energy during both initial fiberization and subsequent refining (*17*). A U.S. patent was issued on the use of *C. subvermispora* for biomechanical pulping (*18*).

We recently discovered that *Phlebia subserialis* gives results comparable to those obtained with *C. subvermispora.* importantly, *P. subserialis* has a broader temperature range (27°C-39°C) than *C. subvermispora* (27°C -32°C). *P. subserialis* produces fewer aerial hyphae than *C. subvermispora* on wood chip surfaces. Also, *P. subserialis-treated* chips are not as soft (and presumably not as compressible) as those treated with *C. subvermispora*. These advantages of *P. subserialis* should reduce the cost of biotreatment significantly during scale up (i.e., decreased need for temperature control and greater ease of ventilation). A U.S. patent has been filed on the use of *P. subserialis* for mechanical pulping.

Optimization Studies. Many variables can affect biopulping. In our initial work, we simply made best guesses based on the literature, knowledge of fungal growth, and past experience. However, as in any industrial microbial process, the opportunity to increase the effectiveness and efficiency of biopulping and decrease its cost through optimization of variables is great. Consequently, we selected certain variables, such as rate of ventilation, addition of nutrients, and wood species, for initial optimization studies; details can be found in a previous publication (*12*). Some of the key variables are described in the following text.

Wood Chip Decontamination. In general, white-rot fungi are not able to outcompete indigenous microorganisms in unsterilized wood chips, which often are quite dirty. Even with the most aggressive while-rot fungi, maintaining reproducible results on a routine basis requires some decontamination. In bench-scale studies, wood chips were sterilized by autoclaving prior to fungal inoculation to maintain control. However, recent experiments have shown that surface decontamination achieved by brief atmospheric steaming (as short as 15 s) is sufficient to give *C. subvermispora and P. subserialis* the competitive advantage, even in heavily contaminated chips. After steaming, the temperature of the chips is near 100°C, at least at the surface.

Inoculum. In any industrial microbial process, the inoculum is of key importance. in early experiments, precolonized wood chips were used as inoculum. In recent experiments, we evaluated a liquid inoculum of *C. subvermispora* on loblolly pine chips. Since this fungus does not produce spores, fragmented mycelium was used (*19*). Three kg/ton of inoculum (dry weight basis) was required to achieve acceptable results, which is probably too high to be practical (*20*). A remarkable reduction was achieved by adding corn steep liquor, a byproduct of the corn wet-milling industry, to the inoculum suspension. Addition of only 0.5% unsterilized corn steep liquor (dry weight basis) reduced the amount of inoculum to ≤ 5 g/ton of wood (dry weight basis) without sacrificing biopulping efficacy of the fungus (Table I). Corn steep liquor is relatively inexpensive ($110/ton corn steep liquor on dry weight basis). This amount of inoculum is probably well within a commercially attractive range.

Since corn steep liquor is produced widely in the United States and its composition (despite the variation) from one source to another or from one batch to another does not seem to affect the biopulping efficacy of the fungus, pulp and paper companies should be able to obtain a regular supply from the nearest location and minimize transportation costs. The component or components of corn steep liquor responsible for the beneficial effect are not known. A U.S. patent has been issued on the use of corn steep liquor in biopulping (*21*).

Table I. Energy Savings and Tear Index Improvement From Biomechanical Pulping of Aspen Chips With Lignin-Degrading Fungi With and Without Corn Steep Liquor[a]

		Savings or Improvement Over Control (%)	
Fungus	*Corn Steep Liquor*	*Energy*	*Tear Index*
Ceriporiopsis subvermispora L- 14803 SS-3	-	0	0
	+	33	22
Phlebia brevispora HHB 7099	-	0	0
	+	38	19
Phlebia subserialis RLG 6074-sp	-	0	0
	+	40	0
Phlebia tremellosa FP 102557-sp	-	0	0
	+	27	24
Hyphodontia setulosa FP 106976	-	0	0
	+	36	16

[a]Chips steamed, cooled, aud inoculated with 5 g fungus/ton of wood (dry weight basis); ±0.5% unsterilized corn steep liquor (dry weight basis); 2-week incubation.

Bleaching Studies. Fungal pretreatment significantly reduced the brightness of the resulting mechanical pulps. However, experiments showed that the pulps can easily be bleached with either alkaline hydrogen peroxide or sodium hydrosulfite. Biomechanical pulp was readily bleached to about 60% Elrepho brightness with 3% hydrogen peroxide and 1% sodium hydrosulfite-a brightness suitable for newsprint (*22*); brightness values approaching 80% were achieved with a two-step bleach sequence. Thus, bleachability of biomechanical pulps does not appear to be a problem.

Analyses of Effluents: Samples of the wastewater from the first refiner passes of fungus-treated aspen chips were analyzed for Microtox toxicity, biochemical oxygen demand (BOD), and chemical oxygen demand (COD). Fungal pretreatment decreased effluent toxicity substantially, decreased or increased BOD values slightly depending on experimental conditions, but somewhat increased COD values compared to that of values for control effluents (23). Increased COD values may be due to the release of biorecalcitrant lignin-related products from fungal action.

Microscopic Studies. To gain insight into the mechanism of biopulping, we examined the fungal growth patterns of *P. chrysosporium and C. subvermispora in* aspen wood chips at the microscopic level. *P. chrysosporium* (used in our early experiments) grew well across the chip surfaces and throughout the cell walls. The hyphae penetrated the chips through the lumens of wood vessels and fiber cells as well as through natural wood cell pits and fungal bore holes. Partial degradation of the cell lumen walls was evident. Erosion troughs and localized wall fragmentation or thinning was clearly visible as was generalized swelling and relaxing of the normally rigid wood cell wall structure.

Interestingly, some fungi, including *C. subvermispora,* produced abundant calcium oxalate crystals on their hyphae as well as manganese deposits in localized areas on the wood cell walls. The deposition of calcium and manganese occurred in wood after a relatively short incubation with *C. subvermispora* (*24*).

Our observations suggest that the physical basis for the biopulping efficacy of the fungal treatment is likely to involve an overall softening and swelling of the cell walls as well as thinning and fragmentation in localized areas (25). Further studies showed that the biopulped fibers have increased fibrillation compared with that of conventional mechanically pulped fibers (*26*) and that chip size has only a minor effect on biopulping efficacy of the fungus (*27*).

Pitch Reduction. Pitch refers to the mixture of hydrophobic materials that cause a number of problems in pulp and paper manufacture, including downtime for cleaning, breakage of papers on the paper machine, and holes in the paper (*28*). Treatment of wood chips with different fungi has shown promise in reducing significant amounts of pitch (29). In our laboratory studies, we have shown that the best biopulping fungus, *C. subvermispora,* can remove as much as 30% of the extractives compared to the control (*19*).

Biomechanical Pulping of Nonwoody Plants

The preservation of forests and increasing environmental awareness have focused research on exploration of agro-based resources for papermaking. In particular, developing countries are using such resources for papermaking on a commercial scale. However, in the United States, their use is almost negligible, although nearly 330 million tons of various agricultural biomass is available (30).

Standard chemical pulping processes are typically used for making pulp from agro-based fibers; however, these processes are energy-intensive, require large capital investments, and contribute to air and water pollution. Studies in collaboration with the University of Wisconsin Department of Forestry showed that fungal *(C. subvermispora)* pretreatment of kenaf prior to mechanical pulping saved a! least 30% of the electrical energy normally used during refining and improved paper strength properties; values approaching those for hardwood kraft pulps were observed (Table II) (*31*). Biopulping of bagasse has also shown very promising results (*4*). These findings suggest that biopulping technology also has potential for papermaking from nonwoody plants.

Table II. Comparison of Paper Strength Properties

Pulping Process	*Burst Index (kNIg)*	*Tear Index (mNm^2lg)*
	Aspen[a]	
Stone groundwood	1.00	1.85
Refiner mechanical pulping	0.85	2.38
Thermomechanical pulping	1.18	2.50
Chemithermomechanical pulping	2.35	6.28
Semichemical pulping	4.45	6.00
Kraft pulping	4.60	8.00
	Kenaf[b]	
Control	2.00	6.00
Fungus-treated (2-week)	3.35	9.50

[a]Paper made by various pulping processes without fungal pretreatment.
[b]Paper made by mechanical pulping process (*31*).

Biochemical Pulping

In chemical pulping, the goal is to remove lignin from wood and leave the cellulose and hemicelluloses. However, the chemical processes are not completely selective and they tend to degrade the polysaccharides to some extent. Fungal pretreatment of wood chips removes some of the lignin and modifies other lignin; these changes might make it easier to remove lignin in the subsequent pulping process. As mentioned earlier, fungal treatment causes softening and swelling of wood cells. It is possible that these fungus-

induced changes and the removal/modification of lignin may result in improved chemical penetration during pulping operations, which could result in more easily bleachable, lower kappa pulps; reduced cooking times and temperatures; reduced pulping chemical needs; and reduced effluent waste load.

Biosulfite Pulping. Sulfite pulping processes include several that differ in the base used for the pulping chemicals as well as the pH of the pulping liquor. Historically, sulfite pulping has been dependent on calcium-based liquor of high acidity (pH 1-2). However, in the last half-century, the more soluble bases of sodium, magnesium, and ammonium have come into use. The use of these bases has extended the possible pH range to less acidic conditions so that sulfite pulping is now done at pH of 3-5 and neutral sulfite semichemical (NSSC) pulping is done at pH 7-9. In the United States, 14 sulfite mills are in operation (*32,33*). Recent Environmental Protection Agency (EPA) regulations propose dramatic reductions in air and waler discharges, and new technologies are required to meet these regulations. Recent studies suggest that biopulping technology can help in complying with these regulations; the results are summarized below.

Magnesium-Based Sulrite Pulping. In an experiment on magnesium-based sulfite pulping, Fischer et al. (*19*) showed that 2-week treatment with *C. subvermispora* of birch and spruce wood led to kappa reduction of approximately 30% with both woods. Longer fungal treatment led to greater kappa reduction. These authors also reported a significant reduction in cooking time with fungal pretreatment.

Sodium- and Calcium-Based Sulfite Pulplng. Using loblolly pine and *C. subvermispora* Scott et al. (*32,33*) obtained results (Table III) similar to those of Fischer et al. (19). Scott et al. also observed lower shives content in treated pulp samples compared to the control, indicating a more complete pulping with fungal pretreatment (unpublished results). Effluents from fungus-treated samples showed substantial reduction in toxicity with no increases in BOD and COD values. These results suggest the potential of biopulping technology for sulfite pulping.

Table III. Yield and Kappa Number of Loblolly Pine After Calcium-Acid Sulfite Pulping[a]

Treatment	*Yield (%)*	*Kappa Number*
Control	47.6	26.8
Strain CZ-3[b]	47.7	13.7
Strain SS-3[b]	47.8	21.1

[a]Source: Ref. *32.*
[b]Chips steamed, cooled, and inoculated with either strain of *C. subvermispora;* 2-week incubation. Data are average of three replicates.

Biokraft Pulping. Very few studies have shown that fungal pretreatment is effective for increasing pulp yield and strength and for reducing kappa number and cooking time during kraft pulping (*34,35*). Recent studies have indicated that fungal pretreatment can reduce the amount of pulping liquor and cooking time, and it can improve paper strength properties with increased brightness (unpublished results). However, an in-depth evaluation is required; all studies to date must be regarded as preliminary.

Fungal Pretreatment for Organosolv Pulping. Technologies are currently in development that would reduce the environmental impact of kraft pulping. The problem of emission of volatile sulfur compounds and high chemical oxygen demand bleaching effluents is yet to be solved. Organosolv pulping circumvents the environmental problems related to sulfur emissions, and it has been found to be effective on several wood species with a broad range of organic solvents in acid or alkaline media (*36,37*). In addition to the high delignification efficiency of several organic solvent systems, the acidic conditions can also result in carbohydrate degradation. As a result, pulps with low papermaking quality are obtained. Therefore, selective delignification without carbohydrate degradation is required.

With the use of selective lignin-degrading fungi, increases in delignification rates have been noted even at low pulp weight losses in organosolv pulping (*38*). Alternatively, the same residual lignin contents could be achieved in shorter reaction times with fungus-pretreated samples, thus providing energy savings in the organosolv process.

Fungal Pretreatment for Dissolving Pulp Production. Dissolving pulp is a low yield chemical pulp (30%-35%) with a high cellulose content (95%-98%) and relatively low hemicellulose (1%-10%) and lignin (< 0.05%) contents. Dissolving pulp is manufactured by both prehydrolysis-kraft and acid sulfite methods. The end uses of dissolving pulp include cellophane and rayon, cellulose esters, cellulose ethers, graft derivatives, and cross-linked cellulose derivatives. The bleaching of both sulfite and prehydrolysis-kraft pulps is achieved by removing residual lignin to increase final brightness and (α-cellulose content of the dissolving pulp. Although bleaching chemicals are selective and cost-effective, they cause environmental problems. The use of fungal pretreatment might result in savings of chemicals in pulping and bleaching and improvement of the quality of dissolving pulps.

Biobleaching of sulfite pulp from eucalyptus wood chips with *C. subvermispora* enhanced brightness significantly, but it reduced the cellulose content of the resulting dissolving pulp. A combined fungus and xylanase pretreatment of sulfite pulps led to the production of dissolving pulp using 63% less active chlorine and having a brightness of over 93% ISO (*39*). Subsequent studies showed that *C. subvermispora* pretreatment of eucalyptus wood chips not only increased lignin removal during sulfite pulping and increased brightness of the dissolving pulp, but also improved the selectivity of the bleaching process, thereby increasing the final pulp yield (Christov et al., personal communication).

Table IV. Energy Savings and Improvements in Strength Properties From Biomechanical Pulping of Spruce Chips With *C. subvermispora* L-14807 SS-3 at Laboratory and Pilot Scales[a]

Parameter[b]	*Laboratory Scale (1.5 kg, Dry Weight Basis)*	*Pilot Scale (50-ton, Dry Weight Basis)*
Energy savings	24	38
Burst index	35	22
Tearindex	52	35
Tensileindex	27	9

[a]Two-week incubation.
[b]Perccritage of energy savings or strength improvements calculated on basis of untreated control values. Data are average of the replicates.

Engineering and Scale-Up

Our recent work involved engineering and scale-up of the biopulping process towards economic evaluation. Several engineering challenges were met, which involved redesigning a successfull laboratory procedure to be practical on a larger scale. We developed methods for decontaminating wood chip surfaces, cooling the chips, and inoculating them with *C. subvermispora* on a continuous basis Methods were also developed to maintain the optimum growth temperature of the fungus (27°C-32°C) and the moisture in the chip pile (50%-60%, wet weight basis) so that the fungus could perform biopulping effectively on a larger scale.

The goal of maintaining proper temperature and moisture in the chip pile was accomplished by ventilating the pile with conditioned and humidified air. We found that ventilation was necessary; when a 1-ton chip pile was biopulped without forced ventilation, the center of the pile reached about 42°C within 48 h as a result of the metabolic heat generated by the fungus. No biopulping action was noted in that region.

In October 1996, we conducted a 50-ton (dry weight basis) outdoor chip pile experiment at FPL to test our large-scale design in a cold climate. In this experiment, the decontamination of chips using low-pressure steam, subsequent cooling, and inoculation were performed sequentially in screw conveyers. Inoculated chips were then incubated for 2 weeks to allow the fungus to grow and “soften” the chips. During incubation, the chip pile was ventilated with conditioned air During subsequent mechanical pulping, significant energy savings and improvements in paper strength properties were noted (Table IV); variation among different regions of the pile was insignificant. In July 1997, another outdoor chip pile experiment was conducted at FPL to test our large-scale design in a hot climate. Similar results were obtained. The fungus-treated chips from this trial were also refined at a thermomechanical pulp (TMP) mill, and a 30% savings in electrical energy and significant improvements on paper strength properties were realized.

Process Economics

The economic attractiveness of the biopulping process was evaluated on the basis of the process studies and engineering data obtained to date. The economic benefits gained through the use of the process result from the following effects.

Refiner Energy Savings. For a 2-week process, the savings should be a minimum of 25% under Ihe worst-case conditions, whereas up to nearly 40% can be achieved under optimized conditions.

Process Debottlenecking. The reduction in the specific refiner power is coupled to higher refiner throughput. Mills that are currently limited by refiner capacity may assign substantial value to the debottlenecking effect that the fungal pretreatment can provide.

Furnish Blend Advantages. The biopulping process results in pulps with improved paper strength. This is advantageous in situations where the product is a blend of mechanical pulps and more expensive kraft pulps. The improved strength of the biomecanical pulps may allow the required strength of the blend to be achieved with a lower percentage of the kraft pulp.

An economic evaluation was performed for a 600 ton/day TMP mill. The storage time was 2 weeks in a flat-pile geometry. Capital costs to incorporate biopulping technology into this paper mill are estimated to be between $5 and $7 million. Savings of about $ 10/ton pulp may be realized with 30% savings in electrical energy. This is equivalent to an annual savings of $2.1 million, which, compared to the estimated capital costs, results in a simple payback period of 2 to 3 years. Mills that are refiner-limited can experience increases of more than 30% from the reduction in energy by refining to a constant total power load. A 20% increase in throughput results in savings of about 55/ton pulp or $11.5 million annually. With this improvement. the payback period for this technology is approximately 6 months. Additionally, if 5% of the kraft pulp is substituted by biomechanical pulps in a blend, a savings of over $13/ton pulp might be realized. This preliminary analysis is subject to appropriate qualifications. The capital costs are subject to some variability, in particular the cost associated with integrating a new facility into an existing site. The addilional advantages of biopulping, such as environmental benefits and pitch reduction, were not quantified, but we did quantify the cost of additional bleach chemicals. Much of the analysis will be site specific, depending on the operating conditions at a particular mill.

Industrial-Scale Process Flowsheet

The fungal treatment process fits well into a mill's woodyard operation. Wood is debarked, chipped, and screened (normal mill operation). Chips are briefly steamed to reduce surface contaminants (natural chip microorganisms), cooled with forced air to the apropriate temperature, and inoculated with a water suspension of the biopulping fungus augmented with unsterilized corn steep liquor. The inoculated chips are piled and ventilated with filtered and humidified air for 2 weeks prior to processing.

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