Toward Commercialization of Biopulping

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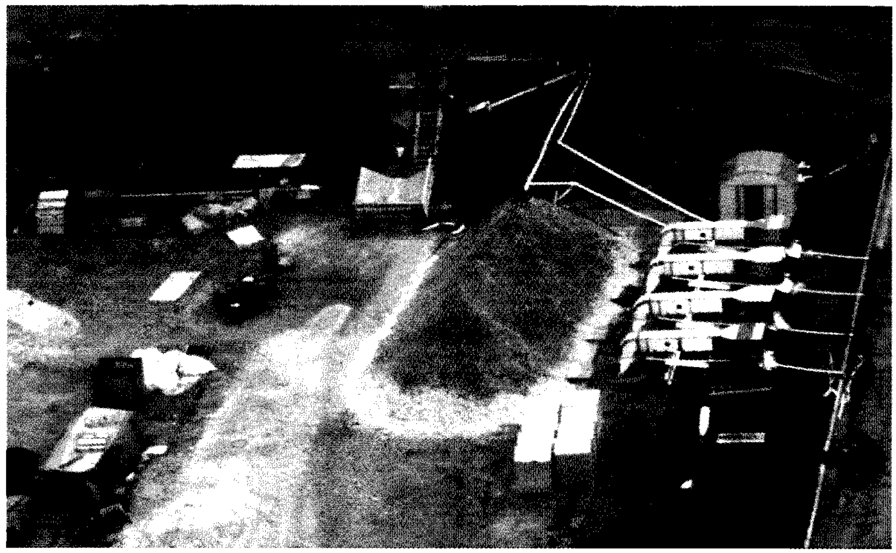

Overview of the 50-ton outdoor biopulping chip pile (4 meter high, 9 meter wide, 21 meter long).

Conventional Pulping Processes

The pulp and paper industry utilizes mechanical or chemical pulping methods, or a combination of the two to produce pulps of desired characteristics. Mechanical pulping accounts for about 25% of the wood pulp production in the world today. This volume is expected to increase in the future as raw materials become more difficult to obtain. Mechanical pulping, with its high yield, is viewed as a way to extend these resources. However, mechanical pulping is electrical energy-intensive and yields paper with less strength compared to the chemical pulping process. These disadvantages limit the use of mechanical pulps in many grades of paper. Chemical pulping accounts for about 75% of the wood pulp production in the world. This process produces paper with very high strength. However, the process has the disadvantages of being capital—and energy—intensive, giving low yields, producing troublesome waste products, and producing byproducts that are of relatively low value. Therefore, Agenda 2020 (paper industry's vision for the future) proposes the development of new methods or technologies to overcome these problems.

Biopulping

Biopulping, defined as the treatment of lignocellulosic materials with lignin-degrading fungi prior to pulping, has the potential to ameliorate some of these problems associated with conventional pulping. The fungi are natural wood decayers.

BIOMECHANICAL PULPING OF WOOD

Background Research. Early workers recognized the potential of using fungal pretreatments prior to mechanical pulping (biomechanical pulping) to save energy and/or improve paper strength, and conducted limited research which verified that potential. However, researchers encountered difficulties in attempting to scale up the process; details can be found in a recent publication[1]. The subsequent effort to research and develop biomechanical pulping at the USDA Forest Service, Forest Products Laboratory (FPL) has been a unique collaboration among a diverse group of government bodies, research institutions, and private companies. Beginning in April 1987, a consortium was formed, including the FPL, the Universities of Wisconsin and Minnesota, and several pulp and paper and related companies. The overall goal of the consortium research was to evaluate the commercial and economic feasibility of biomechanical pulping. Because, the fungal pretreatment is a natural process, environmental impact is expected to be minimal.

The consortium benefited from the ability to draw on the considerable resources of a prominent federal laboratory and two eminent research universities, as well as the expertise represented by the private companies involved. Together the companies were able to support a large and risky research project which none of them individually would have been willing to finance. However, in 1995, the pulp and paper industry experienced a downturn and a number of the consortium members pulled out. Additional funding was needed to demonstrate biomechanical pulping on a large enough scale to show how it might work in a real pulp mill. Consequently, biomechanical pulping attracted the attention of another collaborative organization, the Energy Center of Wisconsin, which agreed to provide the funding needed to scale up biomechanical pulping towards industrial levels.

With their financial support, biomechanical pulping has now been scaled up to near industrial levels, and the overall conclusion is that biomechanical pulping works. Through the use of the proper lignin-degrading fungus, at least 30% electrical energy can be saved in mechanical pulping, paper strength properties are improved, and pitch content is reduced. The economics look very attractive[4]. Four patents have been granted; five other applications are pending. A summary of key challenges faced during research and development of biomechanical pulping are discussed in the following sections.

Biological challenges. 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. Investigations have sorted through the more than 30 variables associated with biopulping, including species and strains of fungi, inoculum form and amount, species of wood, wood chip size, environmental factors, effect of added nutrients, and need to sterilize the chips. Some of the variables were key to the economic viability of biopulping; those are summarized in the following.

Selection of a suitable fungus. We identified a fungus, *Ceriporiopsis subvermispora*, that performs biopulping very effectively on both hardwood and softwood species. This fungus is a selective lignin degrader and was chosen after screening several hundred species of fungi and their strains. Several other species are also promising for biopulping.

Chip surface decontamination. Wood chip surfaces normally are contaminated with cells and spores of many fungi and bacteria. These unwanted microorganisms can hamper biopulping fungus, making decontamination desirable. We discovered that a brief atmospheric steaming of chips (as short as 15 seconds) decontaminates the surfaces of wood chip and allows the biopulping fungus to outcompete unwanted microorganisms and perform biopulping effectively, uniformly, and economically. A recent article published in Tappi Journal[2] focuses on respiratory health problems associated with routine exposure of workers to the spores of miscellaneous fungi that inhabit wood chips in a normal wood yard operation. Some of these unwanted fungi also produce cellulolytic enzymes and thus would have an adverse effect on paper strength properties. Biopulping fungus is non-sporulating and is a selective lignin degrader, which would preclude such problems.

Inoculum. We reduced the amount of inoculum from 3 kg to 5 g or less per ton of wood, which is well within a commercially attractive range. This was achieved by adding an inexpensive and commercially available nutrient source, unsterilized corn steep liquor, to the inoculum suspension. This additive apparently "kick-starts" the fungal growth, making it possible to use a much lower inoculum level. Since corn steep liquor is produced widely in the United States, pulp and paper companies should be able to obtain a regular supply from the nearest location with minimal transportation cost.

Engineering and scale-up challenges. The process as we now envision it is shown diagrammatically in **Figure 1**. On a laboratory scale, steaming, cooling, and fungal inoculation were performed in a batchwise fashion. The real challenge was how to carry out these three steps continuously. As mentioned, a brief steaming of the chips allows *C. subvermispora* to colonize and be effective. After steaming, the chips are near 100°C surface temperature. Thus, the chips need to be cooled sufficiently prior to fungal application. Complete cooling is not needed before the inoculum is added. However, the chips need to be within the temperature growth range of the fungus within a relatively short period after it is mixed with the chips. Hence, the cooling can probably take place in two stages: before inoculation and after the chips are placed into storage by using the ventilation system for additional cooling. The next step in the process is the inoculation of the wood chips with a suspension containing the fungus, corn steep liquor, and dilution water. Challenges involved in this step included metering the inoculum mixture to give the proper amount of fungus and obtain the correct moisture content for the chips. An additional challenge was the even distribution of the inoculum over the wood chips to promote uniform treatment.

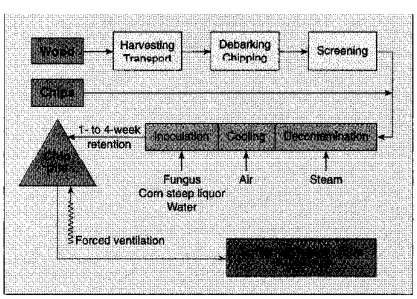

Figure 1. Overview of the biopulping process showing how the biotreatment process fits into an existing mill's wood handling system.

The second engineering challenge was maintaining the proper conditions in the chip pile to promote fungus growth. The key variables were the temperature and humidity of the air and the chip moisture content. The fungus has an optimum growth range for each of these variables. Furthermore, the fungus is not self-regulating in respect to any of them. For example, when biopulping was performed in a 1-ton chip pile without forced ventilation, the pile center reached about 42°C within 48 h after inoculation as a result of metabolic heat generated by the fungus. The fungus ceases to grow at this temperature, so we observed no biopulping action in that region of the pile. The use of forced air was explored for controlling temperature and moisture throughout the pile. This required an understanding of the airflow through the chip pile, the heat generation of the fungus, the changes in the chip structure because of the fungus, and the nutrient and oxygen requirements of the fungus.

Scale-up equipment and methods. Our laboratory process treats approximately 1.5 kg of chips (dry weight basis) at one time. Commercial levels of the process need to be about 200 to 2,000 tons or more per day of wood chips processed, representing a 10^5 increase in scale. This gap was bridged through a series of experiments. The scale-up studies were two-fold: (a) to demonstrate that chips can be decontaminated and inoculated on a continuous basis rather than a batch process as was done on the laboratory scale and (b) to demonstrate that the process can be scaled as expected from an engineering standpoint. The entire 50-ton trial has been repeated with similar results.

To demonstrate the operation on a continuous basis, a treatment system was built based on two screw conveyers that transported the chips and acted as treatment chambers (**Cover**). Steam was injected into the first screw conveyer, which heated and decontaminated the wood chip surfaces. A surge bin was located between the two conveyers to act as a buffer. From the bottom of the surge bin, a second screw conveyer removed the chips, which were subsequently cooled with blown, filtered air into the screw conveyer. In the second half of the second screw conveyer, the inoculum suspension containing fungus, unsterilized corn steep liquor, and water was applied and mixed thoroughly with the chips through the tumbling action in the screw conveyer. From the screw conveyer, the chips fell into the pile for the 2-week incubation. Continuous equipment of this design was used to treat 50 tons of spruce chips (dry weight basis) with *C. subvermispora* at FPL at a throughput of 2 tons per hour (dry weight basis) continuously for nearly 24 hours. During the 2 weeks, the chip pile was ventilated with conditioned air to maintain the proper growth temperature (27-32°C) and moisture (50-60% on a wet weight basis) throughout the pile; details can be found in a recent publication[3].

Mill-Scale Evaluation Of Fungus-Treated Chips

The control and fungus-treated chips were refined through a thermomechanical pulp (TMP) mill producing lightweight coated paper. The fungal pretreatment saved 33% electrical energy (**Figure 2**) and improved paper strength properties significantly compared to the control.

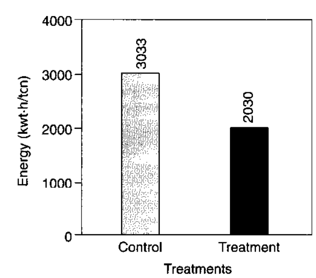

Figure 2. Energy requirement for the control and the fungus-treated chips from the 50-ton trial during thermomechanical pulping process to produce pulps at about 50 CSF.

Since biomechanical pulp fibers were stronger than the conventional TMP fibers, we were able to reduce the amount of bleached softwood kraft pulp in the final product (**Figure 3**). Fungal pretreatment reduced brightness significantly, but brightness was restored to the level of bleached control with 60% more hydrogen peroxide in the bleached liquor. The success of these trials has convinced a number of mills to look into the potential of this technology for their mills. As a consequence, some mills in the United States and in Europe asked us to evaluate the efficacy of *C. subvermispora* on their wood chips at a laboratory scale. With each wood species tested, at least 30% energy savings and significant strength improvements were realized.

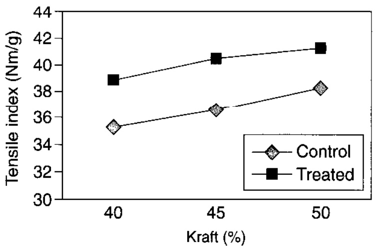

Figure 3. Tensile index of thermomechanical pulps from control and fungus-treated chips blended with different levels of kraft pulp.

Based on these promising results, some of the mills have expressed interest in conducting larger scale trials at their sites.

Industrial-Scale Process Flowsheet

The fungal treatment process can fit well into a mill's woodyard operations. Wood is debarked, chipped, and screened according to normal mill operation. The chips are then briefly steamed to eliminate natural chip microorganisms, cooled with forced air, and inoculated with the biopulping fungus. The inoculated chips are piled and ventilated with filtered and humidified air for 1-4 weeks prior to processing (**Figure 1**).

Process Economics

The economics of biomechanical pulping look attractive. A preliminary economic evaluation was performed. Based on 30% energy savings and a 5% reduction in kraft in the final product, a simple rate of return of about 62% each year can be realized; details can be found in a recent article[4]. The cost of additional bleach chemicals was quantified and included in the analysis. The additional advantages of biopulping, such as environmental benefits and pitch reduction, have yet to be quantified.

BIOCHEMICAL PULPING OF WOOD

Unlike biomechanical pulping, in-depth information on biochemical pulping (fungal pretreatments prior to chemical pulping) is not available. However, published information indicates the potential of fungal pretreatments for sulfite pulping, dissolving pulp production, organosolvent pulping, and kraft pulping; details can be found in a recent publication[1]. A summary of our research status on bio-kraft pulping is given below.

Our electron microscope studies[1] indicate that fungal pretreatment causes swelling and loosening of cell walls structures, which increases the porosity of wood chips. Subsequent studies with uranyl acetate staining and ultrastructural observations have provided additional evidence that changes in cell wall porosity occur early in the colonization process by lignin-degrading fungi[5]. Also, these fungi remove or modify lignin in wood cell walls that might more easily be removed during kraft pulping. We therefore hypothesized that these fungus-induced physico-chemical changes in cell walls will improve chemical penetration and subsequently aid the kraft pulping processes. If so, this will reduce chemical load, cooking temperature, cooking time, emissions, and effluent load during pulping.

A study done in collaboration with Pramod Bajpai and Pratima Bajpai of Thapar Research Group, India, on bio-kraft pulping of eucalyptus chips demonstrated some of the benefits of fungal pretreatment. For example, the fungal pretreatment reduced the cooking time from 90 to 30 min without affecting the quality of the final product (**Table 1**). This means that kraft pulp mills could increase throughput and thus get more pulp production from the existing capital investment. In contrast, control chips cooked for 30 min. were only partially cooked, which resulted in a very high shive content. We are now evaluating several lignin-degrading fungi on North American wood species, after preliminary results suggested that biomechanical and biochemical pulping might involve different lignin-degrading fungi.

Parameters	Control (cooking time 90 min.)	Treated pulp (cooking time 30 min.)
Pulp yield (%)	46	46
Brightness (%)	88.6	90.5
Burst index (kN/g)	4.6	4.8
Tear index (mNm^2/g)	7.8	8.0
Tensile index (Nm/g)	68.9	70.5
Breaking length (m)	7026	7193

[a]17% active alkali, 23% sulfidity. Ramp time, 90 min.

Table 1. Bio-kraft pulping of eucalyptus chips with Ceriporiopsis subvermispora (2-week treatment)[a]

BIOPULPING OF NONWOODY PLANTS

The preservation of forests and increasing environmental awareness have focused research on exploration of agro-based resources for papermaking[6]. A rapid increase in the use of such resources for value-added products is already occurring in developing countries; with growing environmental and other pressures in the United States, these resources will become increasingly important. Currently the use of agricultural plants for pulp and paper in the United States is almost negligible, although several hundred millions of tons are apparently available[6]. Research done in other laboratories and ours has shown that the fungal pretreatment is very effective on kenaf for both mechanical and chemical pulping processes[1].

We determined the efficacy of the best biopulping fungus, *C. subvermispora*, on different non-woody plant materials utilizing different pulping methods. Six different materials were investigated: kenaf, bagasse, corn stalk, wheat straw, rice straw, and flax. Of these, kenaf seems to be the most promising fibrous material. Our results with mechanical pulping of whole kenaf indicated that the fungal pretreatment saved 36% electrical energy and improved paper strength properties significantly compared to the control (**Table 2**). During kraft pulping, the fungal pretreatment had a profound positive effect on the resulting brightness; for both whole and bast kenaf biokraft pulps, brightness ranged from 86%-88% compared to 78% to 81% for similarly bleached controls. The mechanical properties of bast kenaf biofibers were close to those of softwood kraft pulp and far superior to those of hardwood kraft pulp[7]. Current research is focused on process optimization, engineering/scale-up, and process economics.

Parameters	Control	Treatment
Freeness (ml)	170	180
Energy requirement (wt.h/kg o.d. material)	2344	1501
Energy savings (% over the control)	-	36
Burst index (kN/g)	0.65	1.10
Tear index (mNm^2/g)	2.85	3.89
Tensile index (Nm/g)	15.3	23.5
TEA index (j/g)	0.16	0.26

[a]Whole kenaf fibers were refined through a 300-mm-diameter single disk atmospheric refiner.

Table 2. Biochemical pulping of whole kenaf with Ceriporiopsis subvermispora (2-week treatment)[a]

Technology Transfer Activities

A professional video on the biopulping process is available, as are a color brochure and numerous scientific papers. The technology has been exclusively licensed to Biopulping International, Inc., a Wisconsin-based company that has taken the lead in commercializing biopulping technology and supporting further research at FPL and the State University of New York through a cooperative agreement. The principles of this company are promoting this technology worldwide and have developed an extensive technology package which includes the patent licensing arrangements, supply of fungal inoculum, design and supply of appropriate equipment, and most important, technical knowledge. For further information on biopulping, please contact Masood Akhtar at: Phone: 608-231-9484; Fax: 608-231-9543; email: makhtar@facstaff.wisc.edu ■

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