PEER REVIEWED

New technology for papermaking: commercializing biopulping*

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ABSTRACT

Biopulping is defined as the treatment of wood chips with lignin-degrading fungi prior to pulping. Fungal pretreatment prior to mechanical pulping reduces electrical energy requirements during refining or increases mill throughput, improves paper strength, reduces the pitch content, reduces cooking time for sulfite pulping, and reduces the environmental impact of pulping. Our recent work involved scaling up the biopulping process toward the industrial level, investigating both the engineering and economic feasibility of the technology. We envision the process to be done in either a chip-pile or silo-based system for which several factors need to be considered: the degree of decontamination, a hospitable environment for the fungus, and the overall process economics.

Currently, treatment of the chips with low-pressure steam is sufficient for decontamination. Furthermore, a simple, forced ventilation system can be used to maintain the proper temperature, humidity, and moisture content throughout the chip bed, thus promoting uniform growth of the fungus. The pilot-scale trial resulted in the successful treatment of 4 tons of wood chips (dry weight basis), with results comparable to those on a laboratory scale. For mechanical pulping, a 2-week treatment results in approximately 30% energy savings, which, considering the additional equipment and operating costs, results in an overall savings of US$ 10–20 per ton of pulp in a chip-pile system. Larger, 40-ton trials were also successful, with energy savings and paper properties comparable with the laboratory scale.

Application:

Biopulping technology produces stronger mechanical pulps together with energy savings, resulting in substantial economic savings.

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 with the chemical pulping processes. Biopulping, which uses natural wood decay organisms, appears to have the potential to overcome these problems. Fungi alter the lignin in the wood cell walls; this has the effect of "softening" the chips. This substantially reduces the electrical energy needed for mechanical pulping and leads to improvements in the paper strength properties. The fungal pretreatment is a natural process; therefore, no adverse environmental consequences are foreseen.

The concept of using fungal treatments in pulping processes, including refiner mechanical pulping, is based on removing or modifying the lignin in the wood. Early researchers in Sweden, Japan, and the United States *(1–8)* screened several lignin-degrading fungi for their lignin selectivity and performance during mechanical pulping. The results indicate that fungi that are selective for lignin degradation produce energy savings and paper strength improvements for mechanical pulping *(9)*.

The overall conclusion of the Biopulping Consortium at the USDA Forest Service, Forest Products Laboratory (FPL) was that biopulping works. Through the use of the proper lignin-degrading fungus, at least 30% electrical energy can be saved in mechanical pulping, and paper strength properties are improved. The process economics also look attractive *(9–12)*. In addition, the fungal pretreatment for mechanical pulping has less environmental impact than chemical pretreatments *(13)*. The use of the fungal pretreatment for sulfite pulping has also been investigated, with favorable results *(14, 15)*.

PROCESS OVERVIEW

Based on the results of previous work and discussions with mill personnel, we envision a fungal treatment system that fits into existing mill operations with minimal disturbance. **Figure 1** is a conceptual overview of the biotreatment process in relation to existing woodyard operations. Wood is harvested and transported to the mill site for debarking, chipping, and screening. Chips are decontaminated by steaming, maintaining a high temperature for a sufficient time to decontaminate the wood chip surfaces and then cooled so that the fungus can be applied. The chips are then placed in piles that can be ventilated to maintain the

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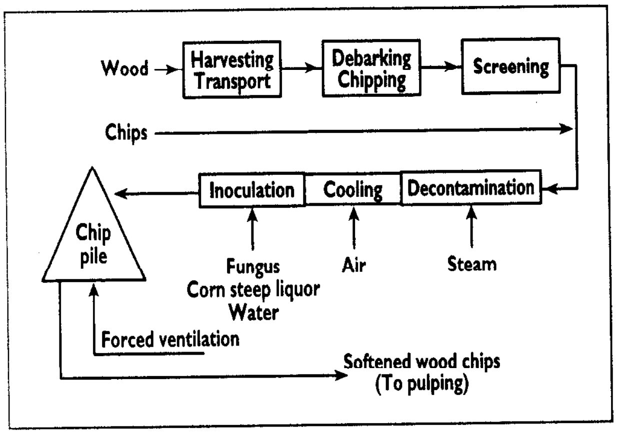
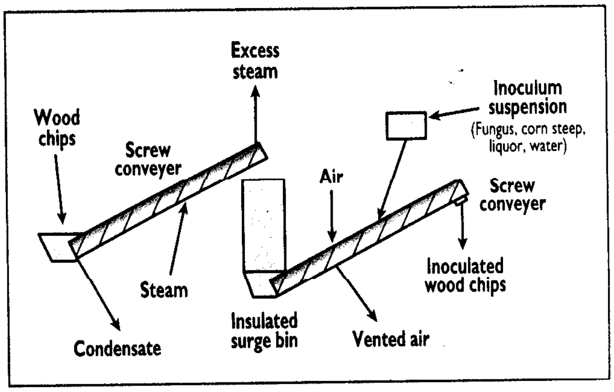


1. Overview of the biopulping process showing how the biotreatment process fits into an existing mill's wood-handling system



2. Continuous treatment system to decontaminate and inoculate wood chips. Wood chips are steamed in the first conveyer auger before being placed into a surge bin. The second screw conveyer then picks up the chips, cools them, and applies the inoculum.

proper temperature, humidity, and moisture content for fungal growth and subsequent biopulping. The retention time is 1-4 weeks.

Although Fig. 1 shows a basic concept for the process, several variations can be easily envisioned. For those mills that purchase chips rather than logs, the chips can be fed directly into the decontamination step from the trucks or other storage. The process of decontamination, cooling, and inoculation could be done in screw conveyers (described later) or on conveyer belts. If sufficient silo or other indoor capacity is available, the entire process could be enclosed, thus minimizing the adverse effect of the environmental factors on the process.

SCALEUP EQUIPMENT AND METHODS

Recent efforts have focused on bringing the successful laboratory-scale procedures up to the industrial level. 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 200-2000 tons/day of wood chips processed, representing a 10^5 increase in scale. This gap is currently being bridged through a series of experiments to bring the process scale to this level. The goals of these scaleup studies are twofold: (a) demonstrate that chips can be decontaminated and inoculated on a continuous basis rather than a batch process as is done on the laboratory scale and (b) demonstrate that the process scales as expected from an engineering standpoint.

In our reactor scaleup studies, we investigated two types of reactor systems: tubular reactors and chip piles. The tubular reactors have an advantage in obtaining the necessary engineering and kinetic data for scaling up the process. The one-dimensional nature of the system is easy to analyze and model. The reactor also allows for well-controlled airflow in the system, with airflow patterns that are well known. Heat loss from the system is easily controlled with exterior insulation, thus achieving conditions that would be experienced in the center of large chip piles. Details on the configurations of these reactors and the chip piles have been published *(9, 16)*.

On a large scale, decontamination and inoculation must be done on a continuous basis and not batchwise, as had been done in the laboratory trials. To achieve this, we built a treatment system based on two screw conveyers that transport the chips and act as treatment chambers. **Figure** 2 is an overview of the continuous process equipment used in 4- and 40-ton trials performed at FPL. Steam is injected into the first screw conveyer, which heats and decontaminates the chip surface. A surge bin is located between the two conveyers to act as a buffer. From the bottom of the surge bin, a second screw conveyer removes the chips, which are subsequently cooled with filtered air blown into the screw conveyer. In the second half of the second screw conveyer, the inoculum suspension containing fungus, unsterilized corn steep liquor, and water is applied and mixed with the chips through the tumbling action. From the screw conveyer, the chips fall into the pile or reactor for the 2-week incubation.

In the first scaleup trial, 4 tons of spruce wood chips were inoculated and incubated at a throughput of approximately 0.5 tons/h. The first successful outdoor trial with the biopulping fungus *C. subvermispora* had 40 tons of spruce treated at a throughput of about 2 tons/h (dry weight basis) continuously for more than 20 hours. During the 2 weeks, the chip pile was maintained within the temperature growth range for the

I. Energy savings and paper properties as a function of scale on spruce at 100 mL CSF

Trial	Refining method	Energy savings, %	TENSILE INDEX Control, N·m/g	TENSILE INDEX Treatment, N·m/g	TEAR INDEX Control, mN·m²/g	TEAR INDEX Treatment, mN·m²/g	BURST INDEX Control, kN/g	BURST INDEX Treatment, kN/g	BRIGHTNESS Control, %ISO	BRIGHTNESS Treatment, %ISO
1.5-kg	RMP	24	30.0	38.0	2.96	4.51	1.24	1.68	53.2	39.9
4-ton	RMP	26	34.0	38.7	3.29	4.40	1.46	1.77	58.2	40.4
40-ton (1996)	RMP[a]	38	34.6	37.8	3.37	4.54	1.36	1.66	54.5	39.4
40-ton (1997)	RMP[a]	30	37.5	40.9	4.62	4.94	1.69	1.89	56.1	40.9
40-ton (1996)	TMP[b]	31	44.6	47.5	9.14	8.33	2.31	2.25	53.1	31.0
40-ton (1997)	TMP[c]	30	36.0	41.4	5.94	6.14	1.96	2.25	56.5	40.9

[a] Performed at FPL using a 30-cm atmospheric refiner

[b] Performed at Andritz Sprout-Bauer using a 91-cm pressurized refiner (1st stage) and a 91-cm atmospheric refiner (subsequent stages)

[c] Performed at Consolidated Papers Inc. using a 107-cm pressurized refiner (1st stage) and a 114-cm atmospheric refiner (2nd stage)

fungus, despite the outdoor exposure to cold ambient conditions.

In previous work *(9-12)*, most of the energy savings and paper properties were evaluated through refiner mechanical pulping (RMP) in a 30-cm atmospheric laboratory refiner. For the 4- and 40-ton trials, thermomechanical pulping (TMP) was also done at FPL. In addition, samples were sent to two laboratories—Andritz Sprout-Bauer in Springfield, OH, and Herty Foundation in Savannah, GA—for independent configuration of our results. At Herty Foundation, primary refining was done in a 30-cm pressurized refiner. At Andritz Sprout-Bauer, a 91-cm pressurized refiner was used. The remaining two or three refining stages were done at atmospheric pressure. For the second large-scale trial, the chips were refined at an industrial TMP line, with a pressurized primary stage and an atmospheric secondary stage.

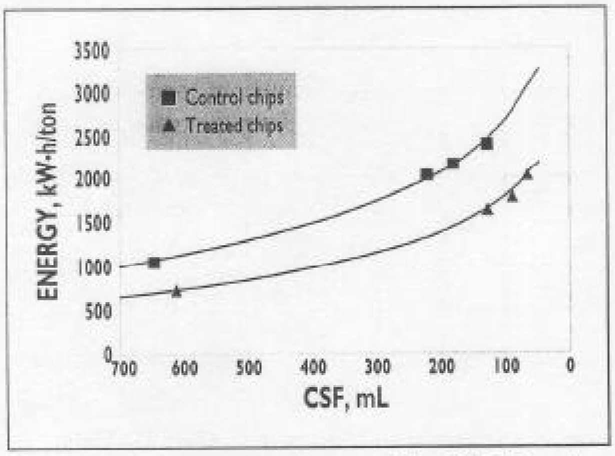
LARGE-SCALE EXPERIMENTAL RESULTS

From the many small-scale experiments, our key engineering findings included the degree of decontamination necessary for the fungus to grow, the cooling and inoculation of the chips, the heat generation in the pile, the compression of the chips during the incubation, and the airflow for cooling through the pile *(16)*. As we went up in scale, we expected to achieve the same results as far as energy savings and paper properties are concerned. **Table I** shows the energy savings obtained for RMP at three different scales for spruce treated with *C. subvermispora*. As the process scale increased from the bioreactors (1.5 kg) to the large trials, the energy savings for RMP (at 100 mL CSF) improved from 24% to more than 30% in our larger outdoor trials. The reason for this increased energy savings is not completely clear.

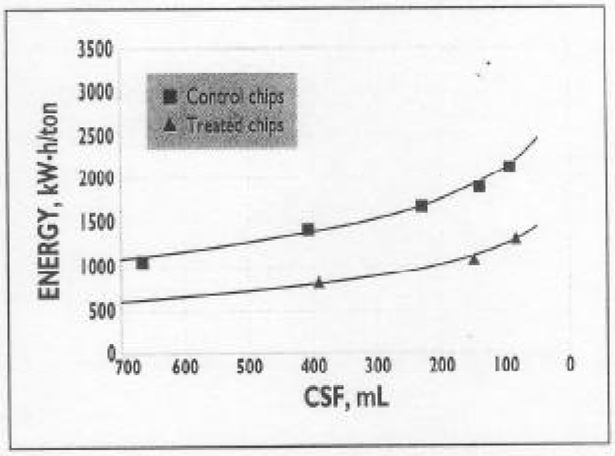
In addition to the scale, there were some differences between the trials. First, the 40-ton trials were held outdoors and were strongly affected by the ambient temperature, which ranged from -4°C to 16°C for the first trial and from 16°C to 32°C for the second. In contrast, the bioreactors were kept in a controlled environment at 27°C and did not experience temperature fluctuations. The indoor 4-ton trial was also enclosed and experienced little effect of the ambient temperature. The outdoor trial was exposed to the elements, including rain and wind, which could have had an effect on the growth of the biopulping fungus. Other operational differences between the smaller indoor trials and the outdoor trial may have also contributed to the differences.

For TMP at the 40-ton scale (1996), energy savings were approximately 31% at 100 mL CSF, according to the refining trials done at Andritz Sprout-Bauer and Herty Foundation. This is consistent with previous TMP results at the bioreactor scale. **Figure 3** shows the refining energy as a function of the freeness for TMP. After the first fiberization step, the treated chips had a lower CSF with less energy input. With each subsequent refining pass, the energy needed for the treated pulp samples was significantly less than that needed for control. In fact, similar percentage energy savings were achieved at all levels of freeness. **Figure 4** shows a similar trend for RMP. This indicates that the refining energy savings can be achieved regardless of the final freeness level of the pulp.

For RMP, improvements in the strength properties as the scale increased were also maintained (Table I). The same tensile strength was achieved for the control at all process scales. At the laboratory scale (1.5 kg), treatment resulted in improvements up to 27%. At the larger scales, improvements were



3. *Energy savings for TMP as a function of the CSF of the pulp for the 40-ton trial. Note that energy savings are experienced at all levels of the refining so that regardless of the final freeness, approximately 30–35% energy savings are realized.*



4. *Energy savings for RMP as a function of the CSF of the pulp for the 40-ton trial. Note that energy savings are experienced at all levels of refining so that regardless of the final freeness, approximately 40–45% energy savings are realized. For this sample, energy savings at 100 mL CSF was 41%.*

10–15%. The TMP results at the largest scales showed a slight improvement in the tensile strength. Table I also shows the same information for the tear index of the resulting papers. In this case, the tear index improved by 35% at the two larger scales for RMP and by more than 50% at the laboratory scale. For TMP, there was a slight decrease in the tear strength at the 40-ton level. However, we found that the paper properties for TMP made from fungally treated wood were strongly dependent on the first-pass refining conditions that had not been optimized for the treated wood (unpublished results). Burst strength results showed a similar trend to those obtained for tear strength.

As has been the case throughout biopulping research, a darkening of the chips occurs, resulting in a loss of brightness in the paper (Table I), but bleaching will regain most of this lost brightness. However, additional optimization of the bleaching steps for biopulping still needs to be done. Also, other fungi, such as *Phlebia subserialis*, are being investigated. These fungi may not darken the wood as much as *C. subvermispora* while still saving energy and improving paper strength.

COMMERCIALIZATION ISSUES

All this work is leading to the large-scale treatment of wood chips with a lignin-degrading fungus. In a related development, large-scale treatment of wood chips with a fungus is being done with the Cartapip™ process, developed by Sandoz Chemicals Co. (now Clariant Corp.) *(17)*. The Cartapip process removes pitch and controls unwanted colored microorganisms that consume bleach chemicals. It differs from our biopulping process in that the Cartapip fungus does not attack lignin nor does it save electrical energy during biopulping. In addition, decontamination of the chips and ventilation of the piles are not practiced with Cartapip, although these steps would probably lead to better control of the process. The fact that the Cartapip process is commercial indicates that mills are able and willing to insert a biotechnological step into their existing operations.

Several issues need to be considered in making the final scaleup to the industrial levels, which can range from 200 to 2000 tons (dry) or more of chips being processed on a daily basis. The larger scale, with a 2-week treatment time, would require the routine storage of 28,000 tons of wood for a 2000-tons/day plant. Although some mills do store and manage inventories in these ranges, others may need to make significant changes in their yard operations to take advantage of this technology. Chip rotation has to be controlled with a first-in, first-out policy to maintain a consistent furnish to the pulp mill—as is usually the case.

Another concern is the variation in the fungal treatment in different parts of the piles. As temperatures in the pile vary, so does the efficacy of the biopulping process *(16)*. Also, near the edges of the piles, contamination with other microorganisms may increase competition and reduce the biopulping efficacy. In larger piles, where the surface-to-volume ratio is quite low, the other chips represent a small fraction of the pile. Furthermore, untreated chips in large industrial piles often warm to more than 50°C because of indigenous microbial growth, leading to variation of the chip quality throughout the pile, with the hotter center of the pile being more affected by this growth. Furthermore, some indigenous organisms degrade the cellulose in the wood, leading to pulp quality reductions and variation *(18)*. With biopulping, this suite of naturally occurring organisms is being replaced with a single, lignin-targeted fungus that is grown under controlled conditions. The single organism, together with the better control of chip-pile conditions, should lead to a number of quality improvements, including a reduction in the pitch content of the wood chips by *C. subvermispora.*

On an industrial scale, suitable equipment is available for this technology. For example, chip steaming and decontamination could easily be accomplished in a presteaming vessel similar to that used for Kamyr digesters *(18)* or in a vertical, pressurized steaming bin. Cooling and inoculation will likely take place at atmospheric pressure. Air conveying will naturally cool the chips during transport, thus requiring the inoculation to be done at the end of the conveying system and before being incubated. Mills using other conveying methods—such as belts or screw conveyers—will probably require the addition of some type of ventilation. In our pilot-scale work, the cooling and inoculation of the chips were done through ventilation in a screw conveyer. Pile ventilation strategies are given in the literature *(16)*.

Currently, it is estimated that losses of approximately 1%/month of wood occur in outside chip storage systems *(18)*. This loss is mainly due to the blowing of fines, respiration of the living wood cells, and microorganism activity. The blowing of fines and sawdust as well as microorganism growth can also cause environmental difficulties in the vicinity of the chip piles. Thus, indoor storage should also be considered as an option for incorporating a biopulping operation into a mill. Enclosing the chip storage operation will significantly reduce blowing dust and other environmental concerns. Furthermore, better control of the environment for the growth of the fungus would be maintained throughout the year. Enclosing the chip storage would also allow the recovery of the heat produced by the fungus for use in conditioning the incoming air. The geometry of the enclosed storage would also tend to reduce the blower costs. These factors could result in substantial energy savings, especially during the winter months in northern climates.

ECONOMICS OF THE PROCESS

The economic benefits of biopulping, evaluated based on the process studies and engineering data, result from several effects. Energy reduction at the refiner was used as the primary criterion for the effectiveness of biopulping. For a 2-week process, the savings should be a minimum of 25% under the worst-case conditions of wood species and minimal process control, whereas up to nearly 40% can be achieved under some circumstances. In addition, mills that are currently throughput-limited as a result of refiner capacity may achieve total capacity increases as a result of biopulping. The improved strength of the biomechanical pulps would allow the required strength of the blend to be achieved with a lower percentage of the kraft pulp in those cases where the pulps are blended. Finally, only benign materials are used, and additional waste streams are not generated.

An economic analysis of the process yielded very favorable results. The analysis of a 200-tons/day TMP mill are summarized in the literature *(16)*. Under different scenarios and assumptions for utility costs, equipment needs, and operating costs, the net savings can range from US$ 10 to more than US$ 26 per ton of pulp produced, with an estimated capital investment of US$ 2.5 million. Mills that are refiner-limited can experience throughput increases of more than 30% from the reduction in refining energy by running the refiners to a constant total power load. Even a modest throughput increase of 10%, coupled with the energy savings of 30%, results in a payback in less than 1 year. This is equivalent to a savings of US$ 34/ton at a 15% rate of return on capital. Furthermore, many mills blend mechanical pulps and kraft pulps to achieve the desired optical and strength properties. Additional benefits of more than US$ 10/ton can be realized when the anticipated stronger biopulped TMP is partially substituted for kraft at a 5% rate. The additional advantages of biopulping, including the environmental benefits, have not been quantified in this paper. The results of a 600-tons/day analysis are given in a companion paper *(19)*.

CONCLUSIONS

Our engineering analysis indicates that the biopulping process is technologically feasible and economically beneficial. Previous work on a laboratory-scale basis has culminated in successful larger-scale trials. On the pilot scale, methods for the surface decontamination of wood chips, cooling, fungal inoculation, and controlling temperature and moisture content throughout the chip bed have been developed. Our 4- and 40-ton trials, in which the decontamination of chips, subsequent cooling, and inoculation occurred sequentially in screw conveyers, have given results similar to or better than those obtained in the laboratory. With this information, a complete process flow sheet has been established for the commercial operation of the process. Based on the electrical energy savings alone, the process appears to be economically feasible. The additional benefits—increased throughput and stronger paper—improve the economic picture for this technology and can increase the savings to more than US$ 50/ton.

Much effort has gone into this research during the past 9 years to bring this technology to commercialization. However, many questions remain unanswered. The most important basic question is the molecular mechanism of biopulping. An understanding of the mechanism will facilitate the optimization of the process for both mechanical and chemical pulping. Furthermore, most of the work has focused on the use of the biotreatment for mechanical pulping, and some work has been done for sulfite pulping. The use of biopulping as a pretreatment for the kraft process is still an open research issue. Finally, the use of this technology for other substrates—nonwoody plants, such as kenaf, straw, and corn stalks—will be investigated in the future. **TJ**

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