BIOPULPING: A NEW ENERGY-SAVING TECHNOLOGY FOR PAPERMAKING

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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 towards 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. These factors include 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 that, considering the additional equipment and operating costs, results in an overall savings of $9 to $20/ton of pulp in a chip-pile system The other benefits that biopulping confers improve the economics considerably A larger, 40-ton trial was also successful, with energy savings and paper properties comparable with the laboratory scale.

INTRODUCTION

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 material resources become more difficult to obtain. In mechanical pulping, the fibers are separated through mechanical action, essentially grinding the wood into pulp Mechanical pulping, with its high yield, is viewed as a way to extend these resources. However, mechanical pulping is energy intensive and produces 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 shortcomes. Fungi alter the lignin in the wood cell walls, which 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. Their results indicate that fungi, which are selective for lignin degradation, produce energy savings and paper strength improvements for mechanical pulping. Taken together, these studies suggested that biorefiner mechanical pulping merited a comprehensive investigation.

The subsequent effort to research and develop biopulping has been a unique collaboration on the part of a diverse group of government agencies, research institutions, and private companies. Beginning in April 1987, a consortium was formed, including the USDA Forest Products Laboratory (FPL), the Universities of Wisconsin and Minnesota, and several pulp and paper and related companies. The overall objective of the consortium research was to evaluate the technical and commercial feasibility of using fungal pretreatment prior to refiner mechanical pulping to save energy and/or improve pulp and paper properties. In addition, the consortium investigated the reduced environmental impact of biopulping compared with chemical pretreatments.[13] The use of fungal pretreatment for sulfite pulping was also investigated.[14, 15]

The consortium benefited from the ability to draw on the considerable resources of a large Federal laboratory and two eminent research universities, as well as the expertise scattered throughout the private companies involved. The companies were able to support a large research project that none of them individually would have been willing to finance. By 1995, the original research goals of the consortium had been largely achieved At the same time, however, the pulp and paper industry was experiencing a downturn, and a number of the consortium members pulled out, unable to continue funding the effort. Additional funding was needed to demonstrate biopulping on a large enough scale to show how it might work in a real pulp mill.

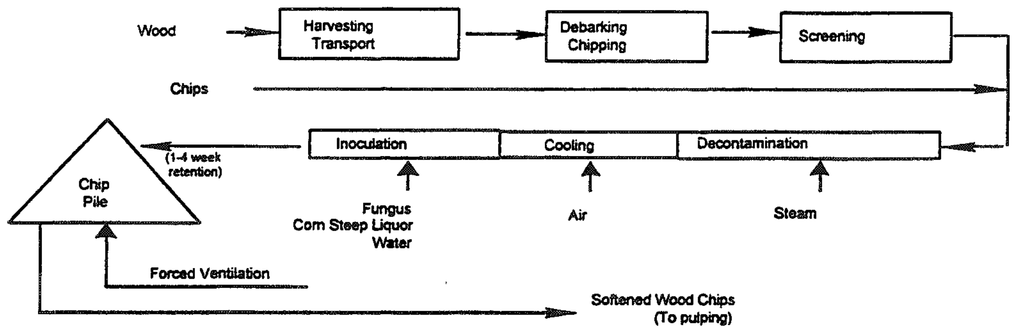
At this point, biopulping attracted the attention of another collaborative organization, the Energy Center of Wisconsin (ECW). Formed in the late 1980s by Wisconsin energy utilities, the Public Service Commission of Wisconsin, the University of Wisconsin, and public representatives, the ECW is dedicated to helping utility customers use energy efficiently. The pulp and paper industry uses more energy than any other Wisconsin industry and includes some of the utilities' largest customers. Biopulping has the potential to improve the pulping process, reducing the energy costs of these important customers and enhancing their competitiveness Therefore, the ECW agreed to provide the funding needed to scale up biopulping towards industrial levels. The biopulping effort now represents a broad convergence of interests, with government, researchers, the pulp and paper industry, and the energy community working towards a common goal.

Biopulping has now been scaled up to near industrial levels, and the overall conclusion of the consortium effort 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 appears to be less polluting than chemi-mechanical processes, and the economics look favorable if the process can be performed in a chip-pile or silo-based system.[9–12] This paper describes the results obtained from the scaling up of this biopulping process towards the industrial level. Process economics are also discussed.

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 wood yard operations. Wood is harvested and transported to the mill site for debarking, chipping, and screening. At this point, the first change in the normal operation is made. Chips are decontaminated by steaming, maintaining a high temperature for a sufficient time to decontaminate the wood chip surface and allow the fungus to grow effectively. After decontamination, the chips are cooled sufficiently so that the fungus can be applied. The chips are then placed in piles that can be ventilated to maintain the proper temperature, humidity, and moisture content for fungal growth and subsequent biopulping. The retention time in the pile is 1 to 4 weeks.

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



Although Figure 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 environmental factors.

Several engineering challenges need to be answered to make biopulping commercially viable. Most challenges involve taking a successful laboratory procedure and redesigning it to be practical on a large scale. These challenges occur in two main areas: (1) preparing and inoculating the chips and (2) maintaining the proper growth conditions for the fungus during incubation.

On a laboratory-scale basis, each step in the process (Fig. 1) is done in a batchwise fashion. Recent work showed that a brief steaming of the chips allows *Ceriporiopsis subvermispora* to colonize and be effective. Although this steaming is not a complete sterilization of the wood chips, it is sufficient to allow the growth of the biopulping fungus. After steaming, the chips are near 100°C, at least at the surface. 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, nutrients, and additional water. Challenges involved in this step include metering the inoculum, nutrients, and water to give the proper amount of fungus and obtain the correct moisture content for the chips. An additional challenge is the even distribution of the inoculum over the wood chips to promote uniform treatment.

The second engineering challenge is in maintaining the proper conditions in the chip pile to promote fungus growth. The key variables here are the temperature and humidity of the air and the moisture content of the chips. The fungus has an optimum growth range for each of these variables. Furthermore, the fungus is not self-regulating with respect to any of these variables. The best method found so far to control temperature and moisture throughout the pile is forced air. Several variables need to be considered in this process. Depending on the configuration of the treatment equipment and the storage system, the relative importance of the variables will change.

SCALE-UP EQUIPMENT AND METHODS

Current 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 to 2,000 tons or more per 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 scale-up studies are two-fold: (1)

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 (2) demonstrate that the process scales as expected from an engineering standpoint.

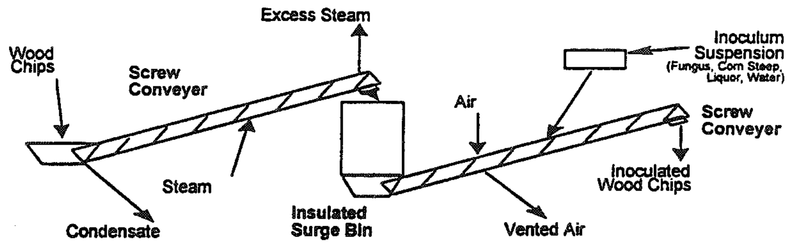
In our reactor scale-up studies, we investigated two types of reactor systems: tubular reactors and chip piles. Tubular reactors have an advantage in obtaining the necessary engineering and kinetic data for scaling up the process. The one-dimensional nature of the system is easy to analyze and model. The reactor also allows for well-controlled air flow in the system with air flow 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. Two sizes of tubular reactors were used in our scale-up studies Our small tubular reactor is a cylindrical PVC tube, 0.20 m in diameter and 1.0 m high. The bottom has a polyethylene grid perforated with 6-mm holes. Forced air is supplied to the bottom of the reactor beneath the grid. The reactor has a cover with an air outlet hole in it. Our larger silo reactor has a capacity of approximately 160 kg of chips on a dry basis. This reactor is 0.76 m in diameter, with an overall height of 2.0 m. A perforated plate at the bottom of the reactor supports the chips approximately 5 cm above the bottom of the reactor. Air is supplied to this void space at the bottom center of the reactor. The temperature is monitored at several locations in the reactors. Additional details on the configurations of these reactors have been published.[16]

Both small and large chip piles were used to investigate the efficacy of biopulping under less-controlled conditions. Small chip piles typically consisted of approximately 30 kg (dry) of inoculated chips covered with 10 kg of uninoculated chips, resulting in a pile approximately 0.65 m high. We placed inoculated chips onto an insulated pad and monitored the internal temperature of the pile near the top of the pile. The chips were left in the piles for 2 to 3 weeks. The large chip piles contained from 160 to 320 kg of inoculated chips, and similar to the small chip piles, were covered with about 60 kg of uninoculated chips. The pile was about 1.1 to 1.4 m high and 2.5 m in diameter. The larger piles were built with the provision for ventilation from the center at the bottom of the pile. The temperature was monitored at various locations throughout the pile.

On a large scale, decontamination and inoculation must be done on a continuous basis and not batchwise as has been done in the laboratory trials. To demonstrate the operation on a continuous basis, a treatment system was built that is 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 the 4- and 40-ton trials performed at FPL. Steam is injected into the first screw conveyer, which heats and decontaminates the chips. A surge bin is located between the two conveyers to act as a buffer as well as to hold the chips for a sufficient time to decontaminate. From the bottom of the surge bin, a second screw conveyer removes the chips, which are 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 are applied and mixed thoroughly with the chips through the tumbling action in the screw conveyer. From the screw conveyer, the chips fall into the pile or reactor for the 2-week incubation. Continuous equipment of this design has been used in two trials at the FPL. In the first scale-up trial, 4 tons of spruce wood chips were inoculated and incubated at a throughput of approximately 0.5 tons/hour. The first successful outdoor trial with the biopulping fungus *C. subvermispora* had 40 tons of spruce treated at a throughput of 2 tons/hour (dry weight basis) continuously for nearly 24 hours. During the 2 weeks, the chip pile was maintained within the temperature growth range for the fungus, despite the outdoor exposure to very cold ambient conditions. The experimental results from these trials are discussed in detail in the following.

On a laboratory scale, most energy savings and paper properties were evaluated through Refiner Mechanical Pulping (RMP) in a 30-cm atmospheric laboratory refiner. RMP uses strictly mechanical energy in order to separate the fibers in the wood. These results have been published in many articles.[9–12] For the 4- and 40-ton trials, Thermo-Mechanical Pulping (TMP) was also done at FPL. TMP is typically done in equipment that can be pressurized with steam, thus increasing the temperature at which the refining is done. Increasing the temperature improves fiber properties, especially strength, of the resulting pulp. In

Figure 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.



addition, samples were sent to two laboratories—Andritz Sprout-Bauer in Springfield, Ohio, and Herty Foundation in Savannah, Georgia—for independent confirmation 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.

LARGE-SCALE EXPERIMENTAL RESULTS

From the many small-scale experiments using the reactors described previously, much of the engineering data needed to scale up the process was obtained. The key engineering findings include 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 air flow for cooling through the pile. These factors are discussed in detail in Scott et al. [16] Implications of these findings on the scaling up of the process are discussed here.

As we went up in scale, we expected to achieve the same results, as far as energy savings and paper properties are concerned. This would indicate that the process is being scaled correctly, and the same results at the laboratory scale are achievable at large scales. Figure 3 shows the energy savings obtained for RMP at three different scales for spruce treated with *C. subvermispora* These savings are compared with untreated chips of the same species and refined under similar operating conditions. As the process scale increased from the bioreactors (1.5 kg) to the large trials, the energy savings for RMP (at 100 Canadian Standard Freeness (CSF)) improved from 24% to 38% in the largest outdoor trial. CSF is a measure of the drainability of the pulp, with higher numbers indicating a faster draining pulp As a pulp is refined to develop the strength properties of the paper, the CSF decreases. The reason for this increased energy savings is not completely clear. In addition to the scale, there were some differences between the trials. First of all, the 40-ton trial was held outdoors and was strongly affected by the ambient temperature, which ranged from -4°C to 16°C. In contrast,, the bioreactors were kept in a controlled environment and did not experience temperature fluctuations. Being uninsulated, they maintained a constant 27°C. The indoor 4-ton trial was also enclosed and experienced little effect of the ambient temperature. In addition, 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 could have also contributed to the differences.

For TMP at the 40-ton scale, energy savings were approximately 31% at 100 CSF, according to the refining trials done at Andritz Sprout-Bauer. These savings are compared with untreated chips refined with the same equipment under similar operating conditions This is consistent with TMP results at the bioreactor scale for loblolly pine in which the TMP results were somewhat less than the RMP results. Figure 4 shows the refining energy as a function of the freeness. After each pass through the refiner, the cumulative refining energy and the CSF were recorded. The lines were fit to a two-parameter logarithmic function. 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 was significantly less than that needed for control. In fact, similar percentage energy savings were achieved at all levels of freeness. Figure 5 shows a similar effect for RMP. This indicates that the refining energy savings can be achieved regardless of the freeness level that the mill is pulping.

Figure 3. Energy savings compared with a control achieved for mechanical pulping of spruce using *C. subvermispora* and refining to 100 CSF. For RMP, best results were obtained at the largest scale. For the 4- and 40-ton trials, energy savings represent an average compared with several samples that were refined.

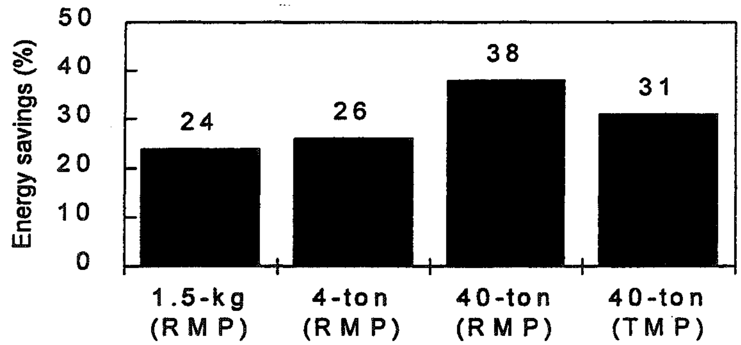


Figure 4. Energy savings for TMP as a function of the CSF of the pulp for the 40-ton trial. Note that energy savings are experienced at all levels of the refining so that regardless of the final freeness, approximately 30% to 35% energy savings are realized.

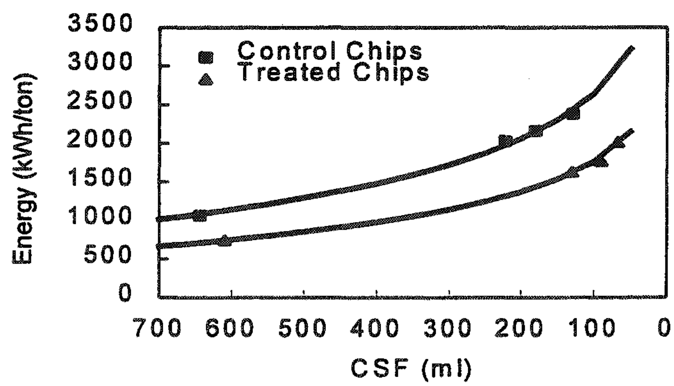
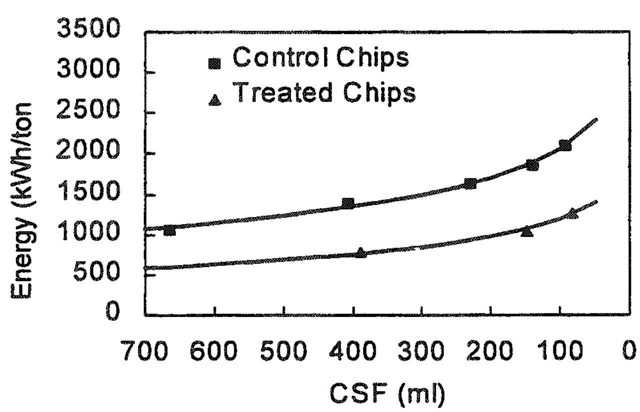


Figure 5. Energy savings for RMP as a function of the CSF of the pulp for the 40-ton trial. Note that energy savings are experienced at all levels of refining so that regardless of the final freeness, approximately 40% to 45% energy savings are realized. For this sample, energy savings at 100 CSF was 41%.



For RMP, improvements in the strength properties as the scale increased were also maintained. Figure 6 shows the tensile index at each of the process scales. The tensile index is the strength of the paper in tension, normalized for the basis weight of the paper (weight per unit area) As shown, essentially the same tensile strength was achieved for the control at all process scales. In the laboratory scale (1.5 kg), treatment resulted in improvements up to 27%. At the larger scales, improvements were 10% to 15%. The TMP results at the largest scales showed a slight improvement in the tensile strength. Figure 7 shows the same information for the tear index of the resulting papers. The tear index is the amount of force needed to tear a sheet of paper, again normalized for the basis weight. In this case, the tear index improved by 35% in the two larger scales for RMP and more than 50% in the laboratory scale. For TMP, tear strength decreased slightly 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, the force needed to puncture a sheet of paper, showed a similar trend to that of 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. Brightness is especially important when making printing and writing grades of paper where white sheets are desired. This brightness loss can range from 5 to 15 points, but bleaching will regain most of this lost brightness. However, additional optimization of the bleaching steps for biopulping

Figure 6. Tensile strength of the resulting control and biotreated pulps compared at 100 CSF. For RMP, approximately the same results were obtained at all scales with an increase in the tensile index.

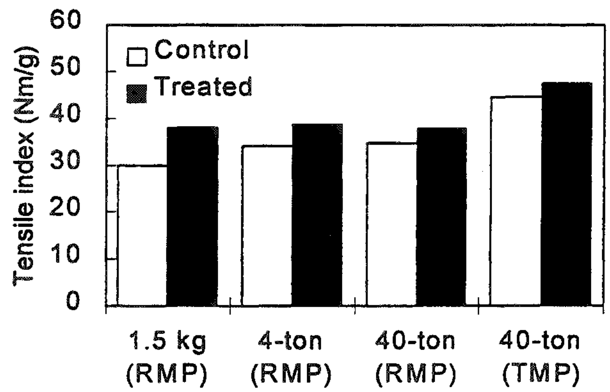
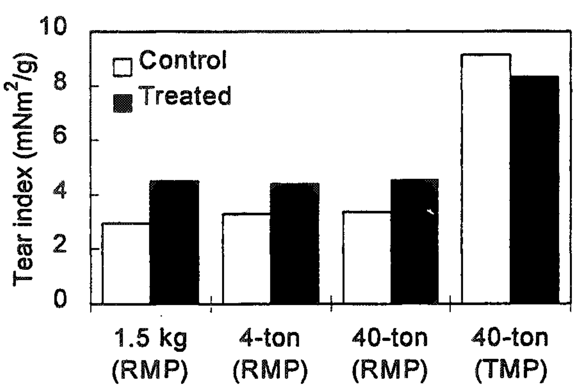


Figure 7. Tear strength of the resulting control and biotreated pulps compared at 100 CSF. For RMP, approximately the same improvements in tear index resulted at all process scales. A slight decrease in tear was seen in TMP, but thermomechanical pulping of biotreated wood has not been optimized.



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.

COMMERCIALLY VIABLE 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 commercially in the Cartapip™ process, developed by the 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 perform biopulping as defined here. Also, 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 successful 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 scale up to the industrial levels, which can range from 200 to 2,000 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 2,000 ton/day plant, which is a pile 160,000 m^3 in volume. To put the amount of chips in perspective, it would be a pile 100 m long, 40 m wide, and 40 m high. 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. As is the case with most new technology, incorporating it into new construction would be much easier than retrofitting it into an existing system. However, the first large-scale operation would probably be a retrofit. Chip rotation has to be controlled with a first-in, first-out policy to maintain a consistent furnish to the pulp mill. However, this would not be seen as a great difficulty for most mills because this strategy is currently used in inventory maintenance.

One 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. However, results of our 4-ton experiment showed that the surface penetration of the contaminants was only 10 to 30 cm into the pile. In the 4-ton experiment, this represents about 5% of the volume of the pile, In larger piles, where the surface-to-volume ratio is even lower, the percentage would be less. Furthermore, untreated chips in large industrial piles often heat to more than 50°C because of respiration and oxidation of the wood and extractives as well as bacterial and fungal metabolism. This natural growth in piles leads 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 also degrade the cellulose in the wood, leading to pulp quality reductions and variation.[17] With biopulping, this suite of naturally occurring organisms is being replaced with a single lignin-specific fungus that is grown under controlled conditions. The single organism, together with the better control of chip-pile conditions, should lead to quality improvements.

As the scale of the project increases, the construction of needed equipment will probably become much easier. On an industrial scale, equipment is available in the needed capacity ranges that will suit the purpose for this technology. For example, chip steaming and decontamination could be easily accomplished in a presteaming vessel similar to that used for Kamyr digesters.[18] Alternatively, a vertical, pressurized steaming bin with a downward flow of chips could also be used. Because the vessel is pressurized above atmospheric pressure, temperatures greater than 100°C can be used for the decontamination of the wood chips similar to the temperatures and pressures used for autoclaving. The contained unit will also significantly reduce the steam use because excess steam does not readily escape from the system. With the higher temperatures and pressures, the surge bin for decontamination time may or may not be needed. Previous work has shown that short-time steaming with good surface exposure is effective for decontamination.[16] The amount of surge capacity will depend on the decontamination needs, operational requirements, and space availability.

Cooling and inoculation will likely take place at atmospheric pressure. Mills that use air conveying to move the chips to the storage location are well suited for incorporation of this technology. The 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 placed into storage. Mills that depend on other conveying methods—such as belts or screw conveyers—will probably require the addition of some type of ventilation cooling to reduce the temperature of the chips. In our pilot-scale work, the cooling of the chips through ventilation in a screw conveyer used for the transport of the chips was very successful, reducing the temperature of the chips sufficiently within 20 seconds during which the chips traveled 2 m. Ventilation may also be possible using belt conveyers, although this has not been tested on a laboratory or pilot scale. In the pilot scale, the inoculation was done in the same screw conveyer that was used for cooling. Inoculum (together with the necessary nutrients and additional water) was applied to the chips, then mixed in the screw conveyer. The use of belt conveyers has not been explored; however, the Cartapip™ product has been successfully applied in this fashion.[17]

We have found that a two-step ventilation strategy is very effective in managing the temperature in the reactors. During the initial 3 days, during which little heat is being generated, a low air flow rate is used to maintain a positive pressure in the pile. If necessary, this initial air flow can also be used to maintain or adjust the temperature of the pile to the proper range. After the third or fourth day, the air flow is increased to a higher level to remove the generated heat from the pile. The inlet air temperature should be near the lower end of the active range of the fungus, and the rate of air flow just sufficient so that the maximum temperature of the chips is near the upper limit for the fungus. Through experience, this air flow rate can be determined, and the change can be made as soon as the increase in temperature is detected. More complex air handling strategies are also envisioned. For example, the rate of air flow could be controlled to achieve a certain temperature in a key location in the pile or to maintain the maximum temperature in the pile below a certain value. Of course, the lengthy time delays between the control action and the change in temperature need to be considered in setting up this system.

Currently, it is estimated that losses of approximately 1% per month of wood occur in outside chip storage systems.[18] This loss is mainly due to the blowing of fines, respiration of the wood, 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 the biopulping process have been evaluated based on the process studies and engineering data obtained to date and are a result of the following effects.

Refiner energy savings

As discussed previously, energy savings at the refiner were used as the primary criteria for the effectiveness of biopulping. Thus, this aspect of the savings has been well-quantified experimentally. 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, utility rates can vary substantially with the time of day or magnitude of the peak usage. In these circumstances, the cost benefits of refiner load reduction could be even greater.

Process debottlenecking

Reduction in the power requirement has an additional consequence that could be of great significance for some mills. Mills that are currently throughput-limited as a result of refiner capacity can assign substantial value to the debottlenecking effect that the fungal treatment will provide.

Furnish blend advantages

The biopulping process results in pulps that have improved strength properties. This is advantageous in situations where the product is a blend of mechanical pulps and expensive kraft pulps. The kraft component is used to impart strength and is more expensive than the mechanical pulps. 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. Of course, the exact blend in any application will need to be optimized to ensure that all product specifications are met. This aspect could also have a debottlenecking effect in mills that are kraft production limited, because the total blended pulp rates can be greater for a given production rate of the kraft pulp component.

Environmental advantages

The biopulping process itself is benign environmentally. Only benign materials are used, and additional waste streams are not generated. Biopulping chip storage is carefully contained. These features are in addition to the substantial amount of energy that is conserved by the process.

Economic scenarios

These advantages must be compared with the costs of implementing and operating the biopulping process. A preliminary assessment was conducted for a 2-week treatment and a flat-pile geometry operating in a northern climate. A southern climate scenario would show somewhat lower costs because of reductions in containment and air handling requirements. The results, based on a 200 ton/day throughput for the energy savings along is given in Scott et al.[16] The analysis given here is based on a 600 ton/day mill throughput and considers the benefits from process debottlenecking and the furnish blend advantages.

Under different scenarios and assumptions for utility costs, equipment needs, and operating costs, the net savings can be more than $26/ton of pulp produced, with an estimated capital investment of approximately $6 million. Using conservative values for the energy, operating, and other costs in this analysis, a savings of $10.21/ton can be expected after the cost of capital with a simple payback of 2.7 years.

It is important to remember that this considers only the economic benefit of energy savings. The additional advantages of debottlenecking are considerable. Mills that are refiner limited can experience throughput increases of up to 30% from the reduction in refining energy by running the refiners to a constant total power load. Figure 8 shows the effect on the savings as a function of the throughput increase. This analysis takes into account the additional operating and raw material costs that result from the increased throughput. The savings are from the increase in the production using the same capital. Even a modest throughput increase of 10%, coupled with the energy savings of 30%, results in savings of $35/ton of pulp. This results in an annual savings of nearly $8 million, which is equivalent to a simple payback of 9.5 months. At a 20% throughput increase, the savings are more than $50/ton. Additional capital may be needed to completely debottleneck the process. However, the savings that result from the debottlenecking can still result in a payback of about 1 year. Of course, all these values depend on the value of the product, in this case TMP pulp, which has ranged from less than $400/ton to more than $800/ton in the past 15 years.[19–21] An average value of $550/ton was used in this analysis.

Many mills blend mechanical pulps and kraft pulps to achieve the optical and strength properties desired. The biotreated pulp, being stronger, may require less kraft pulp to meet the product specifications. Figure 9 shows the effect of additional kraft substitution on the savings for incorporating biopulping into the mill. For this example, the mill is assumed to increase its TMP production and reduce its kraft needs by the same amount. The kraft is assumed to be purchased for $700/ton. The total pulp production (kraft and mechanical) is assumed to stay the same. As TMP is substituted for kraft, the savings increase, due to the difference in cost between the two furnishes. At a 10% throughput increase, a 5% substitution results in an additional savings of more than $13/ton can be realized, which is more than $3 million/year.

Figure 8. Effect of debottlenecking of the process through biopulping for a 600 ton/day TMP plant. Net savings per ton is plotted against the throughput increase. At a 10% throughput increase, annual savings are nearly $8 million, with a simple payback of 9.5 months.

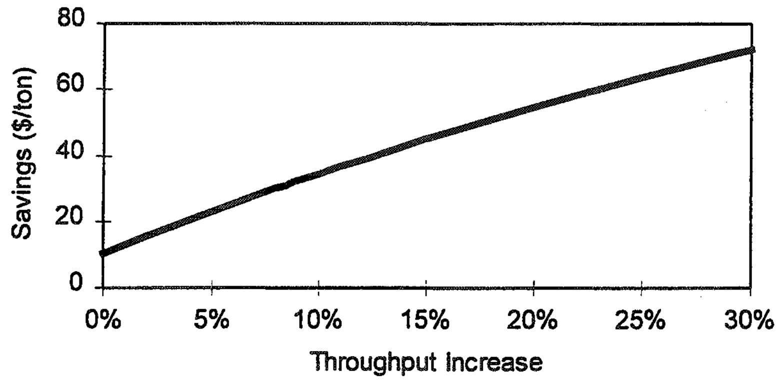
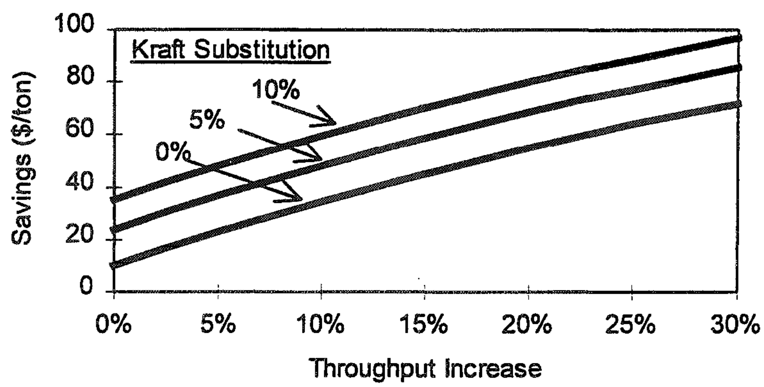


Figure 9. Effect of substituting TMP for kraft pulp in a blended furnish on the economics of the process. A 5% substitution of TMP for kraft saves an additional $13/ton or more than $3 million annually. Increasing the substitution to 10% saves an additional $11/ton.



This preliminary analysis is subject to appropriate qualifications. The capital costs are subject to some variability, in particular the costs associated with integrating the new facility into an existing site. The additional advantages of biopulping, including the environmental benefits, were not quantified in this paper. Finally, much of this analysis is site specific, depending on the operating conditions at the particular mill considering incorporating biopulping into its operations.

CONCLUSIONS

Our engineering and economic analyses indicate 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, gave results similar or better than those obtained in the laboratory. With this information, a complete process flowsheet was 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 $50/ton.

A large amount of effort has gone into this research during the past 9 years to bring this technology to commercialization. The success of this research is due to the strong collaborative effort of the Federal government, universities, industry, and nonprofit organizations However, many questions remain. The most important basic question is the mechanism of biopulping. An understanding of the mechanism of biopulping would 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.

ACKNOWLEDGMENTS

We thank Jean Livingston for editing the final manuscript. Many others played an important role in this research including Eric Horn and Rick Bergman, the staff of the Engineering Mechanics Laboratory, the staff of the Research Facilities Engineering, and the staff of the Pilot Plant. This work was financially supported by the Biopulping Consortium, the Energy Center of Wisconsin, the Wisconsin Alumni Research Foundation, and the University of Wisconsin University–Industry Relations Board.

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