MEETING BIOLOGICAL AND ENGINEERING CHALLENGES DURING SCALE-UP OF BIOPULPING

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ABSTRACT

Biopulping, defined as the treatment of ligoncellulosic materials with lignin-degrading fungi prior to pulping, is an environmentally friendly process that can increase mill throughput by 30%. The process reduces the electrical energy requirement by at least 30%. and also improves paper strength properties during mechanical pulping. Over a period of ten years, we established the economic feasibility of biopulping at a pilot scale after meeting both biological and engineering challenges. We identified a fungus, *Ceriporiopsis subvermispora* that performs biopulping very effectively on different types of wood and reduced its amount of inoculum to a Commercially attractive range. We also established that a brief atmospheric steaming decontaminates the wood chip surfaces, and allows the fungus to perform biopulping. Methods for decontaminating wood chip surfaces, cooling the chips after steaming, and inoculating them with the fungus on a continuous basis were developed. Methods were developed to maintain the optimum growth temperature and moisture in the chip pile so that the fungus could perform biopulping effectively and uniformly. An economic analysis was also performed which looks very attractive, and the process appears to fit well into a mill's woodyard operations.

INTRODUCTION

Mechanical pulping accounts for about 25% of the wood pulp production in the world today. This volme is expected to increase in the future as raw material resourses 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 electrical energy-intensive and produces paper with lower strength compared with the chemical pulping processes. Biopulping, which uses natural wood decay organisms, appears to have the potential to overcome these shortcomes. The fungal pretreatment is a natural process; therefore, no adverse environmental consequences are foreseen.

Past work on biopulping suggested the potential of using lignin-degrading fungi in pulping processes. However, researchers encountered difficulties in attempting to scale-up the process; details can be found in review articles and the literature cited therein (1,2).

The subsequent effort to research and develop biopulping at the USDA Forest Service, Forest Products Laboratory (FPL) has been a unique collaboration on the part of 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 rite commercial and economic feasibility of using fungal pretreatment prior to mechanical pulping to save energy and/or improve paper strength properties.

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 which none of them individually would have been willing to finance. However, in 1995, 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.

Consequently, 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. Biopulping has the potential to improve the pulping process, reducing the energy costs of these important customers and enhancing their competitiveness. The ECW therefore 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.

With their financial support, biopulping has now been scaled up to near industrial levels, and the overall conclusion is 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 (3,4). The process appears to be less polluting than chemi-mechanical processes, and the economics look very attractive (5,6); key challenges and the process economics 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. 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 fungi, and started optimizing variables for the best biopulping fungus. These variables included ventilation, nutrients, and wood species; details can be found in a previous publication (3). Some of the key variables that made biopulping process more economically attractive are discussed in the following section.

Fungus

In early experiments, several white-rot fungi were screened for their biomechanical pulping performance. The process involved the treatment of wood chips with the fungi in bioreactors on a bench scale at appropriate temperature and humidity, mechanical pulping of control and fungus-treated chips through a single-disk atmospheric refiner, preparation of paper and resting of the paper for physical properties. Details of electrical energy measurements, paper preparation, and testing methods have been described in a previous publication (3).

Based on energy savings and paper strength improvements, six fungi were initially selected: *Ceriporiopsis subvermispora, Phanerochaete chrysosporium, Phlebia tremellosa, Phlebia subserialis, Phlebia brevispora, Dichomitus squalens,* and *Poria medulla-panis.* Unfortunately, the most effective fungi with hardwood species were found to be relatively ineffective with softwood species. *C. subvermispora* was found to be effective on both hardwood and softwood species. A. U.S. patent was issued on the use of *C.* subvermispora for biomechanical pulping (7). A 2-week treatment of wood chips with *C. subvermispora* prior to mechanical pulping saves least 30% electrical energy, and enhances paper strength properties reproducibly.

Inoculum

The above results with *C. subvermispora* were obtained when 3 kg inoculum per ton of wood (dry weight basis) was used. This amount of inoculum was too high to be practical. So, we sought ways to reduce it. 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 (at a cost of approximately $0.55 per ton of wood, dry weight basis) reduced the amount of inoculum of *C. subvermispora* and other fungi to 5 g or less/ton of wood (dry weight basis) without sacrificing biopulping efficacy of each fungus. These results were obtained with both aspen (hardwood species) and loblolly pine (softwood species) chips. However, results with only aspen chips are presented in Table 1. This amount of inoculum is now well within a commercially attractive range.

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

		Savings or improvement over control (%)	
Fungus	CSL	Energy	Tear index
Ceriporiopsis subvermispora	-	0	0
	+	33	22
Phlebia brevispora	-	0	0
	+	38	19
Phlebia subserialis	-	0	0
	+	40	0
Phlebia tremellosa	-	0	0
	+	27	24
Hyphodontia setulosa	-	0	0
	+	36	16

[a] Chips steamed, cooled, and inoculated with 5 g inoculum/ton of wood (dry weight basis); ±0.5% unsterilized corn steep liquor (dry weight basis); 2-week incubation (8).

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 neatest 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 (9).

Wood chip decontamination

The above results with *C. subvermispora* were obtained when wood chips were sterilized by autoclaving prior to fungal inoculation. White-rot fungi in general are not able to outcompete the indigenous microorganisms in unsterilized wood chips which often are quite dirty. Even with the most aggressive white-rot fungi, maintaining reproducible results on a routine basis will require some decontamination. Recent experiments have shown that a brief atmospheric steaming of chips (as short as 15 seconds) can suppress natural microorganisms on the wood chip surfaces, and allow *C. subvermispora,* even in heavily contaminated chips, to perform biopulping effectively, uniformly, and economically. Thus, we established that complete sterilization of wood chips is not required for effective biopulping.

ENGINEERING CHALLENGES

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 above that a brief steaming of the chips allows *C. subvermispora* to colonize and be effective. 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, corn steep liquor, and additional water. Challenges involved in this step include metering the inoculum, corn steep liquor, and water 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.

The second engineering challenge was in 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 moisture content of the chips. The fungus has an optimum growth range for each of these variables. Furthermore, the fungus is no self-regulating in respect to any of these variables. 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 No biopulping action was noted in that region. The use of forced air was explored for controlling temperature and moisture throughout the pile. This required an understanding of the air flow through the chip pile, the heat generation of the fungus, the change in the chip structure because of the fungus, and the nutrient and oxygen requirements of the fungus, etc.

Scale-up equipment and methods

Our laboratory process nears approximately 1.5 kg of chips (dry weight basis) at one time. Commercial levels of the process need be about 200 to 2,000 torts or more per day of wood chip proccessed, 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 were two-fold: (a) demonstrate that chips could be decontaminated and inoculated on a continuous basis rather than a batch process as was done on the laboratory scale and (b) demonstrate that the process could be scaled as expected from an engineering standpoint.

To demonstrate the operation on a continuous basis, a treatment system was built that was based on two screw conveyers that transported the chips and acted as treatment chambers. 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, faltered 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 were 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-ton 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. During the subsequent mechanical pulping, significant energy savings and improvements in paper strength properties were noted (Table 2); variation among different regions of the pile was insignificant.

Table 2. Energy Savings and Improvements in Strength Properties From Biomechanical Pulping of Spruce Chips With *C. subvermispora* at Laboratory and Pilot Scales (2-Week Incubation)

Parameters[a]	Laboratory scale (1.5 kg o.d. basis)	Pilot scale (50-ton o.d. basis)
Energy	24	38
Burst index	35	22
Tear index	52	35
Tensile index	27	9

[a] Percent energy savings or strength improvements calculated on basis of untreated control values.

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.) (10). 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 the electrical energy during mechanical pulping. 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 per 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 of chips 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 (5,6). Also, near the edges of the piles, contamination with other microorganisms may increase competition and reduce the biopulping efficacy. However, results of our pilot scale trials showed that the surface penetration of the contaminants was only 10 to 30 cm into 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 (10). 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 (11). 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. Previous work has shown that short-time steaming with good surface exposure is effective for decontamination (5,6). 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 that was 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 corn steep liquor 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 (10).

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 (11). 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 from 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

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

Furnish blend advantages

The biopulping process results in paper that has 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 biomechartical 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 no additional waste streams are 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 analysis given here is based on a 600 ton/day thermomechanical pulp (TMP) mill throughput and considers the benefits from energy savings, the 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 over $26 per ton of pulp produed, 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 per ton of pulp 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. 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 per ton of pulp. This results in an annual savings of nearly $8 million, which is equivalent to a simple payback period of 9.5 months. At a 20% throughput increase, the savings are more than $50 per ton of pulp. Additional capital may be needed to completely debottleneck the process. However, the savings that result from the debottlenecking can still result in a payback period of about 1 year. Of course all these values depend on the value of the product, in this case TM pulp, which has ranged from less than $400 per ton to more than $800 per ton in the past 15 years (12-14). An average value of $55 per 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. At a 10% throughput increase, a 5% substitution results in an additional savings of over $13 per ton can be realized which is over $3 million per year.

This preliminary analysis is subject to appropriate qualification. 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, have not been 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.

INDUSTRIAL-SCALE PROCESS FLOWSHEET

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. 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 an appropriate 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 1 to 4 weeks prior to processing.

We have recorded the biopulping process in a professionally produced video. It is available to interested parties, and has been widely disseminated in the U.S. and abroad. In addition, a color brochure, a flyer, and numerous scientific papers are available.

CONCLUSIONS

After about 10 years of research, we established the commercial and economic feasibility of biopulping. At a pilot scale, we have developed methods for surface decontamination of wood chips cooling, fungal inoculation, and controlling temperature and moisture throughout the chip pile. Our pilot scale trial in which the decontamination of chips, subsequent cooling, and inoculation occurred sequentially in screw conveyers gave results similar to those obtained using the laboratory scale bioreactors. With this information, a complete process flowsheet 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 $50 per ton of pulp.

A large amount of effort has gone into this research during the past 10 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 non-profit organizations. Current research is focused on extending the use of fungal pretreatments for kraft pulping, non-woody plants, and understanting the mechanism of biopulping.

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