INCORPORATING BIOPULPING TECHNOLOGY INTO WOOD YARD OPERATIONS

Gary M. Scott
Faculty of Paper Science and Engineering
State University of New York
One Forestry Drive
Syracuse, NY 13210

Masood Akhtar
Biopulping International, Inc.
P.O. Box 5463
Madison, WI 53705

Michael J. Lentz
Biopulping International, Inc.
P.O. Box 5463
Madison, WI 53705

Eric Horn
Biopulping International, Inc.
P.O. Box 5463
Madison, WI 53705

Ross E. Swaney
Department of Chemical Engineering
University of Wisconsin
1415 Engineering Drive
Madison, WI 53706

David F. Shipley
Energy Center of Wisconsin
565 Science Drive
Madison, WI 53711

ABSTRACT

Biopulping is the treatment of wood chips and other lignocellulosic materials with lignin-degrading fungi prior to pulping. Ten years of industry-sponsored research has demonstrated the technical feasibility of the technology for mechanical pulping at a laboratory scale. Two 50-ton outdoor chip pile trials recently conducted at the USDA Forest Service, Forest Products Laboratory (FPL) in Madison, Wisconsin have established the engineering and economical feasibility of the technology. After refining the control and the fungus-treated chips through a thermomechanical pulp (TMP) mill, the resulting pulps were made into papers on the pilot-scale paper machine at FPL. In addition to the 30% savings in electrical energy consumption during refining, improvements in the strength of the resulting paper were seen due to fungal pretreatment. Because of the stronger paper, we were able to substitute at least 5% kraft pulp in a blend of mechanical and kraft pulps. This recent work has clearly demonstrated that economic benefits can be achieved with biopulping technology through both the energy savings and substitution of the stronger biopulped TMP for more expensive kraft, while maintaining the paper quality.

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 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 lower strength compared with chemical pulping. Biopulping, which uses natural wood decay organisms, has the potential to overcome these problems. 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 [1-5].

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

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. In our scale up experiments that took biopulping from this lab scale to larger scales, certain implementations of each step were chosen. The chosen implementation allowed use to reach our two goals for this phase of the project: (1) To demonstrate that chips can be decontaminated and inoculated in a continuous process rather than as a batch process; and (2) To demonstrate that the process scaled as expected from an engineering standpoint. The following discusses the results obtained during the scaleup trials in relation to industrial processes.

In our reactor scale-up 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 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. Details on the configurations of these reactors and the chip piles have been published [1, 6].

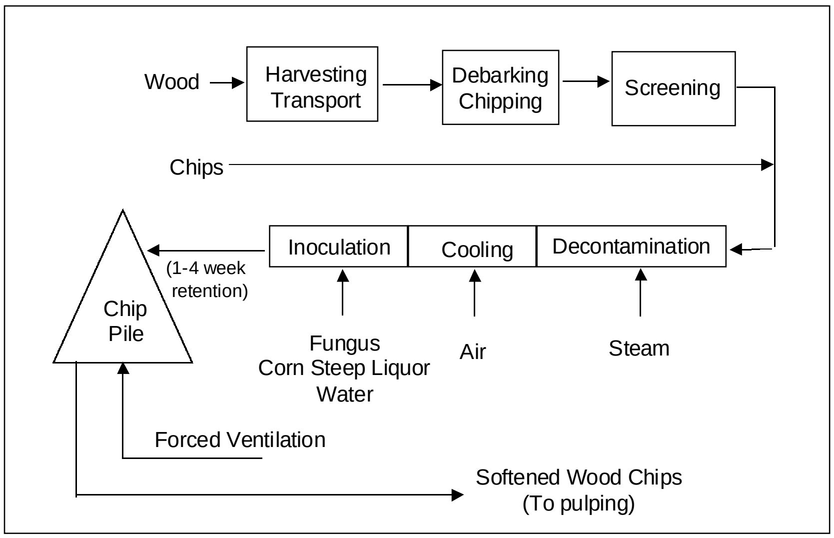

Figure 1. Overview of the biopulping process showing how the biotreatment process fits into an existing mill's wood-handling system.

LARGE SCALE IMPLEMENTATION OF BIOPULPING

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 5- and 50-ton trials. Steam is injected into the first screw conveyer, which heats and decontaminates the chip surface. A surge bin, located between the two conveyers, acts as a buffer. From the bottom of the surge bin, a second screw conveyer removes the chips, which are subsequently cooled with filtered air. 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 a 2-week incubation. In the first scale-up trial, 5 tons of spruce wood chips were inoculated and incubated at a throughput of approximately 0.5 tons per hour. Our successful outdoor trials with the biopulping fungus *C. subvermispora* had nearly 50 tons of spruce treated at a throughput of about 2 tons per hour (dry weight basis) continuously for over 20 hours. During the 2 weeks, the chip pile was maintained within the temperature growth range for the fungus, despite the outdoor exposure to ambient conditions.

Decontamination

In our pilot scale trials, the screw conveyer used for steam decontamination was essentially open to the atmosphere. This design, while adequate for a pilot scale demonstration, let a great deal of steam escape uncondensed. Fortunately, as the scale of the project increases, construction of the equipment will probably become much easier due to the availability of stock process equipment. On the industrial scale, equipment is available in the required capacity ranges that will suit the purpose of this technology. For example, chip steaming and decontamination could be easily accomplished in a presteaming vessel similar to that used for Kamyr digesters [7]. In this device, a star valve feeds the chips to the vessel, where a slowly turning screw conveyor carries the chips through the vessel. Alternatively, a vertical, pressurized steaming bin with a downward flow of chips could also be used. Low-pressure steam can be used to heat the chips and drive off the air. Because the vessel is pressurized above atmospheric pressure, temperatures greater than 100^{o}C can be used for the decontamination of the wood chips; these are similar to the temperatures and pressures of autoclaving. Since excess steam cannot escape the sealed system, the contained unit will also significantly reduce steam requirements.

In our 5-ton pilot trial, additional steam was added to the surge bin to increase the decontamination time for the chips. The need for this additional steaming was empirically determined through an evaluation of the steamed chips for fungal growth. In the subsequent 50-ton outdoor trials, the larger screw conveyor eliminated the need for additional steaming in the surge bin. That is, the chips were suitably decontaminated after steaming in the screw conveyor. In fact, in the second 50-ton trial, the surge bin was used for additional cooling capacity by blowing air into the bottom of the surge bin.

With the higher steam temperatures that can be obtained in pressurized vessels, the surge bin will not be needed for decontamination. It must be kept in mind that good surface exposure of the chips to the steam is important to short-time decontamination. However, some surge capacity between the operations may still be desirable to isolate the effects of short-term shutdowns and process variations in the sequence. Also, the flexibility to use the surge bin for additional cooling or steaming can make the process more robust. Our pilot systems used a holdup time of between 5 and 20 minutes in the surge bin, which was sufficient to handle the variation in the chip flow as well as provide additional decontamination or cooling. The amount of surge capacity will depend on the decontamination needs, cooling needs, operational requirements, and space availability.

Cooling and Inoculation

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 from nearly 100^{o}C to ambient conditions within 20 seconds during which the chips traveled a distance of 2 m. Of course the effectiveness of air cooling depends on the temperature and humidity of the air being used. The ideal situation is to use as dry of air as possible to promote evaporative cooling. Since we used ambient air for our cooling, additional capacity was needed for cooling in the second trial due to the humid summer conditions. Blowing air through the surge bin countercurrent to the chip flow was very effective in increasing the cooling capacity of the system.

Ventilation may also be possible using belt conveyers, although this has not been tested on a laboratory or pilot scale. Special consideration needs to be given to the cleanliness of the air that is used in cooling, air conveying, and subsequent ventilation of the pile. After decontamination, the chips should not be exposed to possible contamination until inoculated and sent to the chip pile. This would require filtering of the cooling air to remove the contaminants. However, a very simple filtering system suffices for this purpose. The filters used in all the pilot-scale trials were inexpensive filters similar to those used in home furnaces. In the 4-ton trial, no contamination was seen near the bottom of the pile by the air inlet, indicating no significant contamination entered through the ventilation system. Likewise in the 50-ton trials, we observed no contaminantion that could be attributed directly to the air handling systems.

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 and then mixed in the screw conveyer. At the end of the screw conveyer, the chips were deposited into the pile. The screw conveyer provided sufficient mixing so that the inoculum was uniformly distributed over the chips. The use of belt conveyers has not been explored; therefore, we do not have information regarding the uniformity achieved by spraying inoculum on chips passing on a belt. However, the Cartapip(R) product has been successfully applied in this fashion [8].

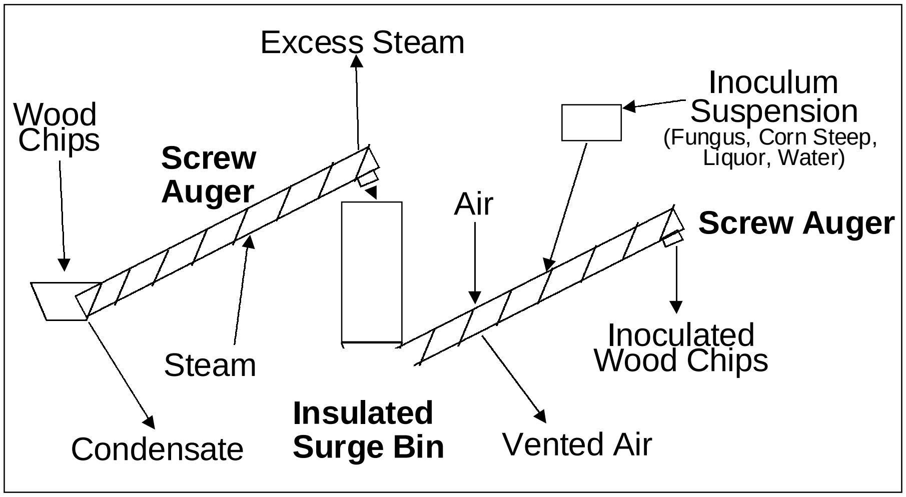

Figure 2. Continuous treatment system to decontaminate, cool, and inoculate wood chips. Wood chips are steamed in the first screw conveyor before being placed into a surge bin. The second screw conveyor then picks up the chips, cools them, and applies the inoculum.

Pile Storage and Ventilation

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. Although some mills do store and manage inventories in these ranges, others may need to make changes in their wood yard operations to take advantage of this technology. As is usually the case, chip rotation has to be controlled with a first-in, first-out policy to maintain a consistent furnish to the pulp mill.

Many mill chip yards are turning to radial-arm stackers and horseshoe-shaped piles in order to better control their chip inventory using a first-in, first-out strategy. The biopulping treatment would fit well into a design such as this because the cooling and the inoculation could take place on the radial arm, with the steaming taking place somewhere before this. With this type of operation, the handling of the chips is minimized after inoculation, thus reducing the possibility of contamination. Of course, the air to different zones of the pile would need to have individual controls for air flow rate.

Currently, it is estimated that losses of approximately 1% per month of wood occur in outside chip storage systems [7]. 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 can also be considered as an option for incorporating a biopulping operation into a mill. Enclosing the chip storage operation should significantly reduce blowing dust and other environmental concerns. Furthermore, better control of the environment for the growth of the fungus could be maintained throughout the year. Enclosing the chip storage would also allow the recovery of the heat produced by the fungus for use in onditioning 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 areas.

As seen in our laboratory reactors (Figure 3), the temperature (and hence the heat production) rapidly increases during the third or fourth day of incubation, going through a maximum and then slowly decreasing during the second week. Similar temperature profiles and heat production rates were seen in the larger, pilot-scale trials. 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 if the ambient conditions are either too hot or too cold. That is, if the chips being placed on the pile are too cool, the air which should be within the range of optimum growth temperature range for the fungus, can be used to warm the chips.

After the third or fourth day, the air flow is increased to a higher level to remove the additional heat from the pile. The inlet air should in the lower temperature 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. From experience, it will be known approximately what this air flow rate is, and the change can be made as soon as the increase in temperature is detected. More complex air handling strategies can also be 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 lengthly time delays between the control action and the change in temperature will need to be considered in setting up this system. It may also be possible to completely eliminate the air flow for the last few days of the trial, thus reducing the operational costs of the system [6].

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 [6]. 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 outer chips represent only a small fraction of the pile. Furthermore, untreated chips in large industrial piles often heat 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 also degrade the cellulose in the wood, leading to pulp quality reductions and variation [9]. With biopulping, this suite of naturally-occurring organisms is 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.

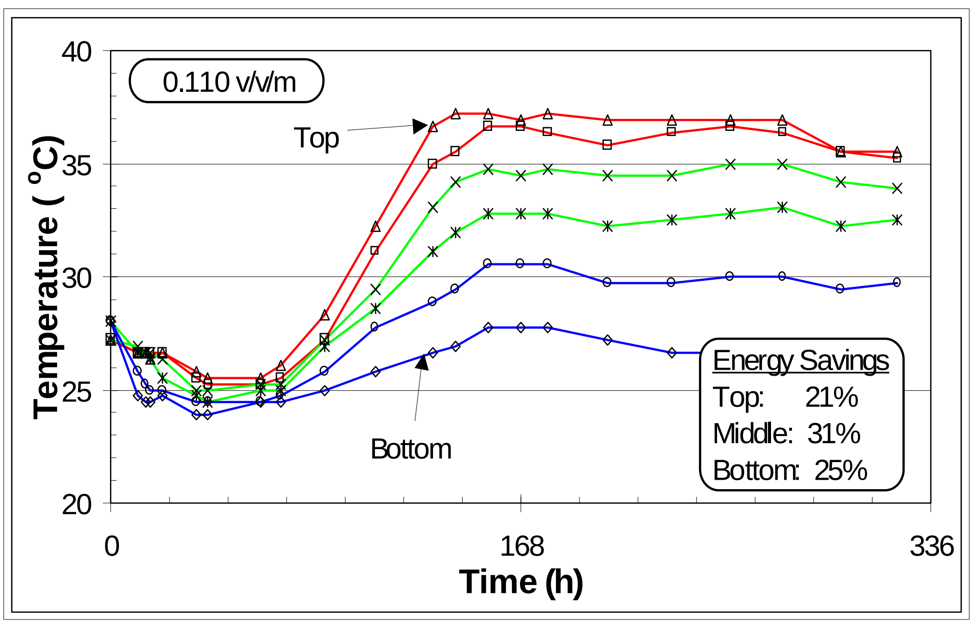

Figure 3. The temperature profiles in a tubular reactor as a function of time. The temperature quickly rises after the third day of incubation indicating a rapid increase in the heat production of the fungus.

Refining of Chips

In previous work [1-4], most of the energy savings and paper properties were evaluated through Refiner Mechanical Pulping (RMP) in a 30-cm atmospheric laboratory refiner. For the 5- and 50-ton trials, TMP was done at FPL. In 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. For the second 50-ton trial, the chips were refined in a commercial TMP mill, with a pressurized primary stage and an atmospheric secondary stage.

As we went up in scale, we achieved the same results as far as energy savings and paper properties are concerned. For RMP, 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 over 30% in our larger outdoor trials. In addition to the scale, there were some differences between the trials. First of all, the 50-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. On the other hand, the bioreactors were at a constant temperature of 27°C. The indoor 5-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 50-ton scale, energy savings were 31% at 100 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. 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 the control. Similar percentage energy savings were achieved at all levels of freeness. For the TMP at all process scales, we saw improvements in the strength properties. Figure 4 shows the tensile index as a function of the refining scale. For the treated chips, an improvement in the tensile index is seen at all refining scales.

Often, mills blend the TMP with groundwood and kraft pulp to produce paper with the desired characteristics. We performed such blending studies at the laboratory scale and confirmed our findings on a pilot paper machine. Strength properties improved even when blending the TMP and groundwood with 40 to 50% softwood kraft. Figure 5 shows the tensile index for control and treated pulps as a function of the amount of kraft pulp. The same tensile strength as the control with 50% kraft can be obtained with 10% less kraft (40%) when biotreated TMP is used. In Figure 6, a similar result can be seen for the tear index. Thus, biotreated pulp allows the substitution of less-expensive TMP for kraft pulp.

As has been the case throughout biopulping research, a darkening of the chips occurs, resulting in a loss of brightness in the paper (Figure 7), but bleaching will regain most of this lost brightness. Figure 7 also shows the resulting brightness of the paper after bleaching and blending with 50% kraft pulp. However, additional optimization of the bleaching steps for biopulping still needs to be done.

Figure 4. Tensile Index of pulps at different refining scales. All chips were treated in 50-ton outdoor piles.

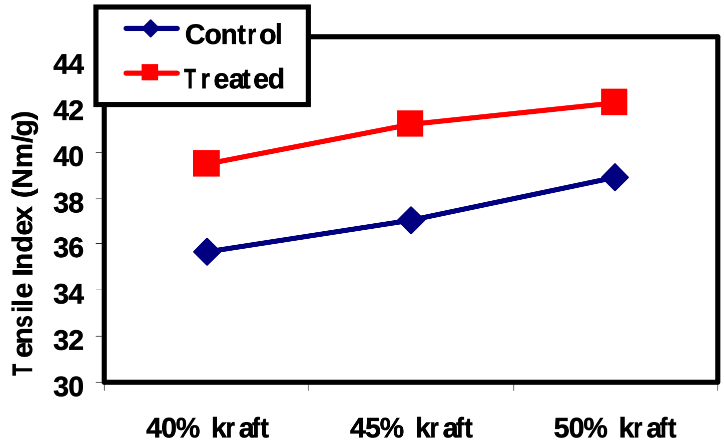

Figure 5. Tensile Index of TMP pulps blended with different levels of bleached softwood kraft pulp.

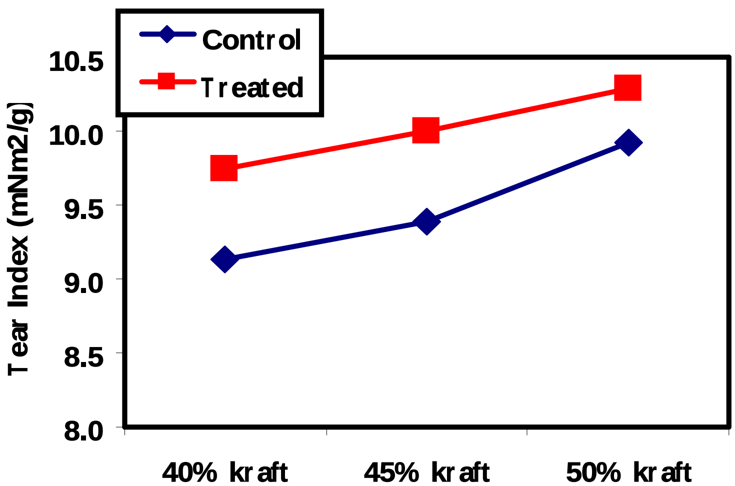

Figure 6. Tear Index of TMP pulps blended with different levels of bleached softwood kraft pulp.

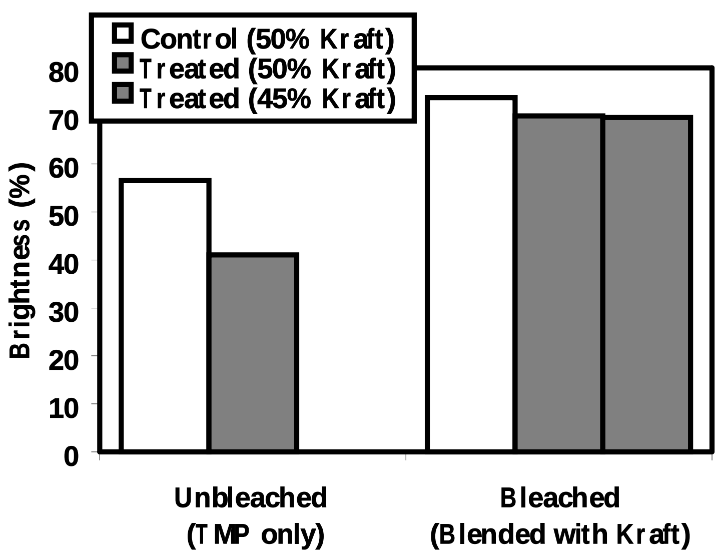

Figure 7. Brightness of unbleached and bleached and blended TMP pulps.

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. Additionally, mills that are currently throughput-limited as a result of refiner capacity may achieve total capacity increases due to 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 no additional waste streams are generated.

An economic analysis of the process yielded very favorable results. The analysis of a 200 ton/day TMP mill are summarized here [6]. Under different scenarios and assumptions for utility costs, equipment needs, and operating costs, the net savings can range from $10 to more than $26 per ton of pulp produced, with an estimated capital investment of $2.5 million. Mills that are refiner-limited can experience throughput increases of over 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 $34 per ton at a 15% rate of return on capital. Furthermore, many mills blend mechanical pulps and kraft pulps to achieve the optical and strength properties desired. Additional benefits of over $10 per ton can be realized when the anticipated stronger biopulped TMP is partially substituted for kraft at a 5% rate. The results of a 600 ton/day analysis have also been published [10].

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 and pitch reduction, 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.

CONCLUSIONS

Our engineering analysis indicates that the biopulping process is technologically feasible. 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 5- and 50-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 flowsheet has been established for the commercial operation of the process. Different options for implementing these steps have been discussed.

Our economic analysis indicates that the biopulping process is also economically beneficial. Under the assumptions detailed here, savings of about $10 per ton of pulp were obtained. Even greater benefits can be realized when the other benefits of biopulping--such as increased throughput and substitution for Kraft--are considered. Throughput increases brought the simple payback period of the process to less than one year. Substituting this increased production for Kraft pulp in blended products results in additional savings. From this analysis, biopulping can produce substantial economic savings for TMP producers.

A large amount of effort has gone into this research during the past 10 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.

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