

An Overview of Biopulping Research: Discovery and Engineering

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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, 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. We envision the process to be done in either a chip-pile or silo-based system for which several factors need to be considered: the degree of decontamination, a hospitable environment for the fungus, and the overall process economics. Currently, treatment of the chips with low-pressure steam is sufficient for decontamination and a simple, forced ventilation system maintains the proper temperature, humidity, and moisture conditions, 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. Larger, 40-ton trials were also successful, with energy savings and paper properties comparable with the laboratory scale. The overall economics of the process also look very favorable and can result in significant annual savings to the mill. Although the current research has focused on biopulping for mechanical pulping, it is also beneficial for sulfite chemical pulping and some applications to recycled fiber have been investigated.

1. 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

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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 overall conclusion of the Biopulping Consortium at the USDA-Forest Service, Forest Products Laboratory (FPL) in Madison, Wisconsin, U.S.A. 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.¹⁻⁴ In addition, the fungal pretreatment for mechanical pulping has less environmental impact than chemical pretreatments.⁵

2. 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. Fig. 1 is a conceptual overview of

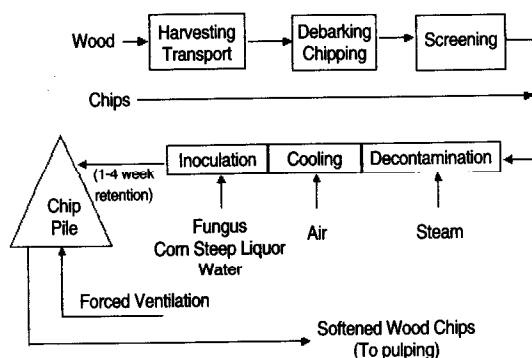


Fig. 1. Overview of the biopulping process showing how the biotreatment process fits into an existing mill's wood-handling system.

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.

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

3. Scale-up Equipment and Methods

Recent efforts have focused on bringing the successful laboratory-scale procedures up to the industrial level. Our laboratory process treats approximately 1.5 kg of chips (dry weight basis) at one time. Commercial processes need to treat about 200 to 2,000 tons or more per day of wood chips processed, representing a 105 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) to demon-

strate that chips can be decontaminated and inoculated on a continuous basis rather than a batch process, and (2) to 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. 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)}

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. Fig. 2 is an overview of the continuous process equipment used in 4- and 40-ton trials. Steam is injected into the first screw conveyer, which heats and decontaminates the chip surface. A surge bin 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 of the conveyor. From the screw conveyer, the chips fall into the pile or reactor for a 2-week incubation. In the first scale-up trial, 4 tons of spruce wood chips were inoculated

and incubated at a throughput of approximately 0.5 tons per hour. The first successful outdoor trial with the biopulping fungus *C. subvermispora* had 40 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 wide-ranging ambient conditions.

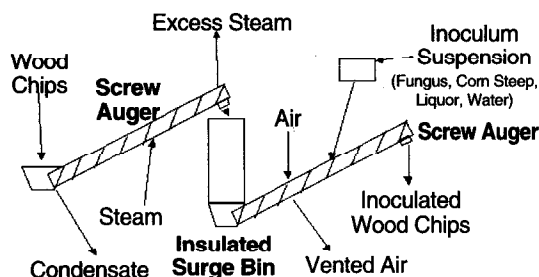


Fig. 2. Continuous treatment system to decontaminate and inoculate wood chips. Wood chips are steamed in the first screw conveyor before being placed into a surge bin. The second screw conveyor then picks up the chips, cools them, and applies the inoculum.

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 4- and 40-ton trials, Thermo-Mechanical Pulping (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 40-ton trial, the chips were refined in a commercial TMP mill, with a pressurized primary stage and an atmospheric secondary stage and with continuous feed between the two.

4. Large-Scale Experimental Results

From the many experiments, our key engineering findings included the degree of decontamination necessary for the fungus to grow, the cooling and inoculation of the chips, the heat generation in the pile, the compression of the chips during the incubation, and the air flow characteristics through the pile.⁶ 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 40-ton trials were held outdoors and were strongly affected by the ambient temperature, which ranged from -4°C to 16°C for the first trial and from 16°C to 32°C for the second. On the other hand, the bioreactors were at a constant temperature of 27°C. The indoor 4-ton trial was also enclosed and experienced little effect of the ambient temperature. The outdoor trial was exposed to the elements including rain and wind, which could have had an effect on the growth of the biopulping fungus. Other operational differences between the smaller indoor trials and the outdoor trial may have also contributed to the differences.

For TMP at the 40-ton scale, 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 stages of refining. For the TMP at all process scales, we saw improvements in the strength properties. Fig. 3 shows the tensile index as a function of the refining scale. Improvements are 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. Fig. 4 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 Fig. 5, a similar result can be seen

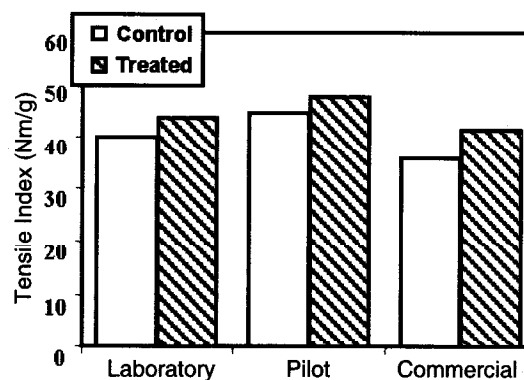


Fig. 3. Tensile Index of pulp at different refining scales. All chips were treated in 40-ton outdoor piles.

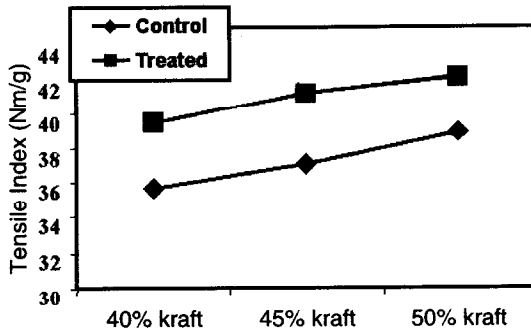


Fig. 4. Tensile Index of TMP pulp blended with different levels of kraft pulp. Note that the same tensile strength can be achieved with less kraft pulp in the furnish when bio-treated TMP is used.

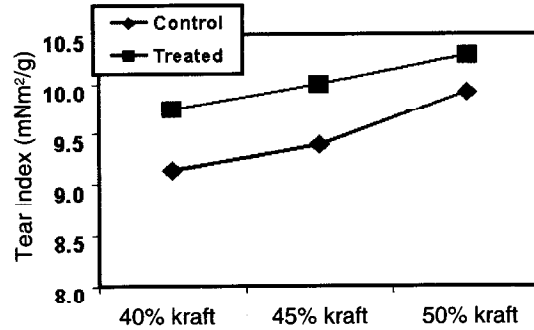


Fig. 5. Tear Index of TMP pulps blended with different levels of softwood kraft.

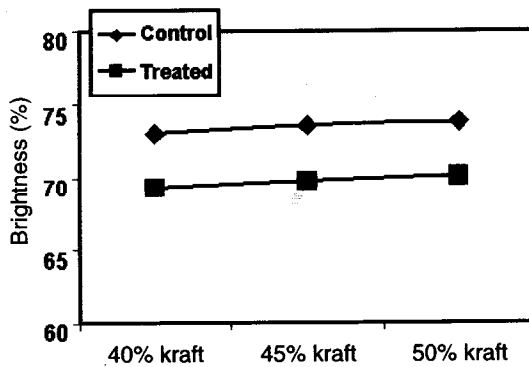


Fig. 6. Brightness of the resulting pulps after bleaching and blending with bleached softwood kraft.

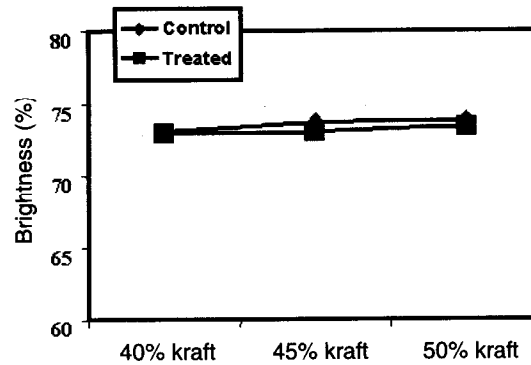


Fig. 7. Brightness of the resulting pulps after additional bleaching chemicals were used on the biotreated TMP.

for the tear index. Thus, biotreated pulp allows the substitution of the biotreated TMP for more expensive 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 (Fig. 6), but bleaching will regain most of this lost brightness. Fig. 6 also shows the resulting brightness of the paper after bleaching and blending with 50% kraft pulp. The use of 1% additional hydrogen peroxide (increasing the bleach application

from 2% to 3%) eliminates the brightness difference between the control and the treated chips (Fig. 7). Strength properties are further improved allowing for the displacement of kraft pulps in the blended furnishes. Fig. 8 shows the tensile index of the resulting pulp when treated with the additional bleaching chemicals. The tear index (Fig. 9) is likewise improved, allowing for 10% less kraft pulp in the blend. However, additional optimization of the bleaching steps for biopulping still needs to be done.

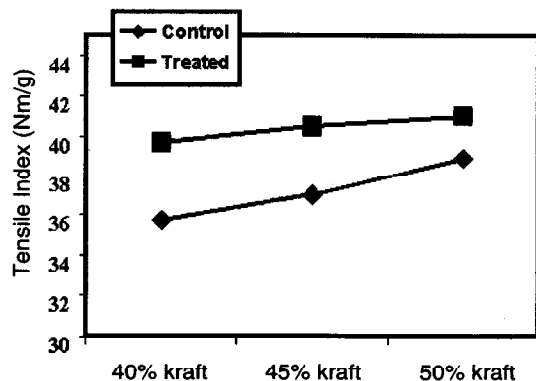


Fig. 8. Tensile index of blended pulps. The biotreated TMP has been bleached with additional bleaching chemicals.

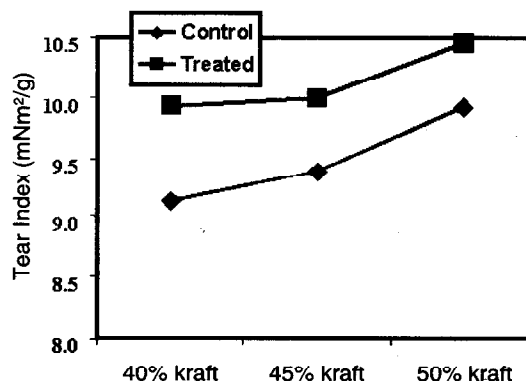


Fig. 9. Tear index of blended pulps. The biotreated TMP has been bleached with additional bleaching chemicals.

5. Commercialization Issues

All this work is leading to the large-scale treatment of wood chips with a lignin-degrading fungus. In a related development, large-scale treatment of wood chips with a fungus is being done with the Cartapip™ process developed by the Sandoz Chemicals Co. (now Clariant Corp.).⁷ 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 reduce electrical energy during biopulping. 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 commercial indicates that mills are able and willing to insert a biotechnological step into their existing operations.

Several issues need to be considered in making the final 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. Chip rotation has to be controlled with a first-in, first-out policy to maintain a consistent furnish to the pulp mill—as is usually the case.

Another concern is the variation in the fungal treatment in different parts of the piles. As temperatures in the pile vary, so does the efficacy of the biopulping process.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.⁸⁾ With biopulping, this suite of naturally-occurring organisms is 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 a number of quality improvements including a reduction in the pitch content of the wood chips by *C. subvermispora*.

On an industrial scale, suitable equipment is available for this technology. For example, chip steaming and decontamination could be easily accomplished in a presteaming vessel similar to that used for Kamyrdigesters⁹⁾ or in a vertical, pressurized steaming bin. Cooling and inoculation will likely take place at atmospheric pressure. Air conveying will naturally cool the chips during transport, thus requiring the inoculation to be done at the end of the conveying system and before being incubated. Mills using other conveying methods-such as belts or screw conveyers-may require the addition of some type of ventilation. In our pilot-scale work, the cooling and inoculation of the chips were done through ventilation in a screw conveyer. Pile ventilation strategies are given in.⁶⁾

Currently, it is estimated that losses of approximately 1% per month of wood occur in outside chip storage systems.⁸⁾ This loss is mainly due to the blowing of fines, respiration of the living wood cells, and microorganism activity. The blowing of fines and sawdust as well as microorganism growth can also cause environmental difficulties in the vicinity of the chip piles. Thus, indoor storage should also be considered as an option for incorporating a biopulping operation into a mill. Enclosing the chip storage operation will significantly reduce blowing dust and other environmental concerns. Furthermore, better control of the environment for the growth of the fungus would be maintained throughout the year. Enclosing

the chip storage would also allow the recovery of the heat produced by the fungus for use in conditioning the incoming air. The geometry of the enclosed storage would also tend to reduce the blower costs. These factors could result in substantial energy savings, especially during the winter months in northern climates. Mills that do not have sufficient space for the biopulping operation at their mill site could consider setting up a satellite chipping and treatment operation. In this way, chips could be treated prior to shipment to the pulp mill at a site that is convenient to the harvesting operations.

6. Process Economics

In order to be feasible, the biopulping technology must also be feasible economically. A complete analysis of a 600 ton/day TMP mill is given in¹⁰⁾ and those results are summarized here. 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.

6.1 Refiner Energy Savings

The energy savings at the refiner were used as the primary criterion 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.

6.2 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. Of course, even though the refiner is the rate-limiting step, additional capital may be needed to fully realize the throughput increases allowed by biopulping.

6.3 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 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 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.

6.4 Other Advantages

The biopulping process itself is environmentally benign. Only benign, natural materials are used, and no additional waste streams are generated. Furthermore, the two-week treatment with *C. subvermispora* significantly reduces the amount of pitch in

the wood chips. These features are in addition to the substantial amount of energy that is conserved by the process. Other economic benefits could be realized including the lower operating costs from an automatic system compared to a manual (bulldozer) system, better inventory control, and enclosed piles being less susceptible to environmental factors such as winter, rain, and wind.

6.5 Economic Benefits

The economic analyses using these considerations indicate that the biopulping process is economically beneficial. Under the assumptions in our analysis, savings of about \$10 per ton of pulp were obtained when the energy savings alone was considered (Fig. 7). Even greater benefits can be realized when the other benefits of biopulping—such as increased throughput and substitution for Kraft—are also considered. Throughput increases of 10% brings the savings over \$30 per ton and 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 of approximately \$13 per ton of pulp produced (Fig. 10). From this analysis, biopulping can produce substantial economic savings for TMP producers. 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 analysis. Finally, much of this analysis is site-specific, depending on the operating conditions at the particular mill considering incorporating biopulping into its operations.

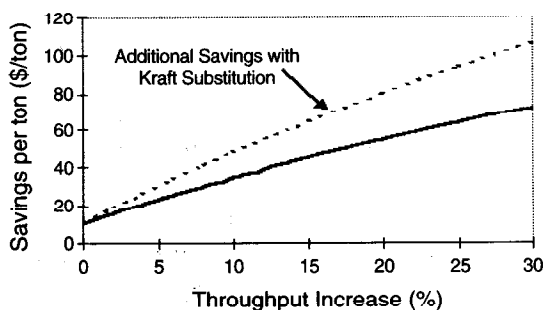


Fig. 10. Summary of the economics of biopulping for a 600 ton/day TMP plant. The solid line shows the savings per ton as a function of the throughput increase. A 0% throughput increase represents the savings from the energy reduction along. The dotted line demonstrates the additional savings that can be realized when the added TMP production is used as a replacement for Kraft pulp.

7. Conclusions

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

picture for this.

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 and research is continuing on this topic. Finally, the use of this technology for other substrates-nonwoody plants such as kenaf, straw, and corn stalks as well as recycled furnishes-is also being investigated.

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