BIOPULPING: TECHNOLOGY LEARNED FROM NATURE THAT GIVES BACK TO NATURE

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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 sib-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, 50-ton trials were also successful, with energy savings and paper properties comparable with the laboratory scale.

An economic analysis of a 600 t/d thermomechanical pulp (TMP) mill indicates that based on energy savings alone, the process is economically feasible, resulting in overall savings of about $10 per ton of pulp. Increasing the mill throughput by 20% achieves additional savings of over $40 per ton of pulp. Replacement of TMP for Kraft pulp results in additional savings. For any particular mill, the savings realized will depend on that specific mill's conditions, utility costs, and current operations. The final conclusion is that biopulping is feasible from both engineering and economic standpoints.

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 dfficult 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.

The overall conclusion of the Biopulping Consortium at the USDA-Forest Service, Forest Products Laboratory (FPL) was that biopulping works. Through the use of the proper lignindegrading 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 pretreatment [5].

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. 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.

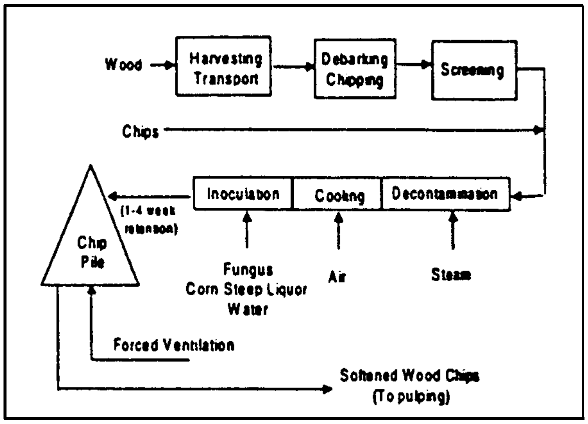

Figure 1. Overview of the biopulping process showing how the biotreatment process fits into an existing mill's wood-handling system.

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. The process of decontamination, cooling, and inoculation could be done in screw conveyers (described later) or on conveyer belts. If sufficient silo or other indoor capacity is available, the entire process could be enclosed, thus minimizing the adverse effect of the environment on the process.

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 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, 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. 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. Figure 2 is an overview of the continuous process equipment used in 4- and 50-ton trials. Steam is injected into the first screw conveyer, which heats and decontaminates the chip surface. A surge bin is located between the two conveyers to act as a buffer. From the bottom of the surge bin, a second screw conveyer removes the chips, which are subsequently cooled with filtered air. 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, 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 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.

In previous work [14], 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 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.

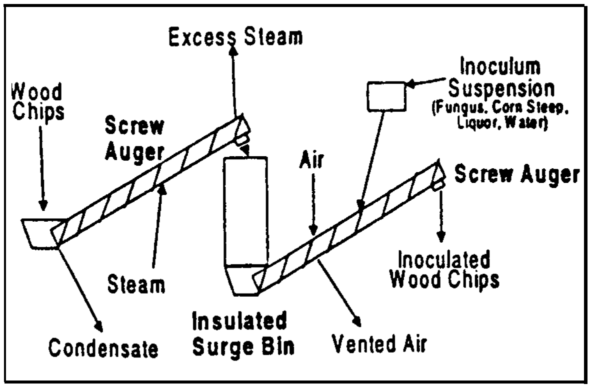

Figure 2. Continuous treatment system to decontaminate and inoculate wood chips. Wood chips are steamed in the first screw conveyor before being placed into a surge bin. The second screw conveyor then picks up th chips, cools them, and applies the inoculum.

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 for cooling 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 RPM (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°. 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 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 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 3 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.

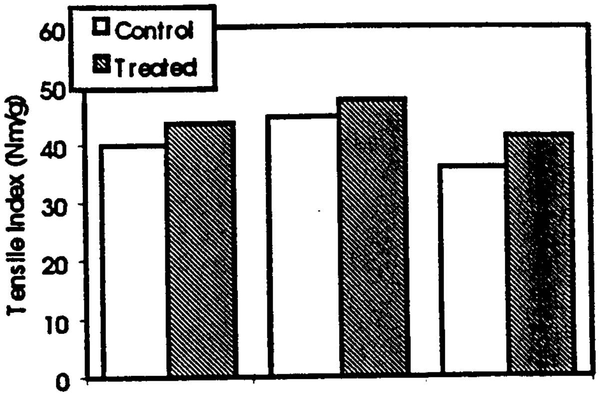

Figure 3. Tensile Index of pulp at different refining scales. All chips were treated in 50-ton outdoor piles.

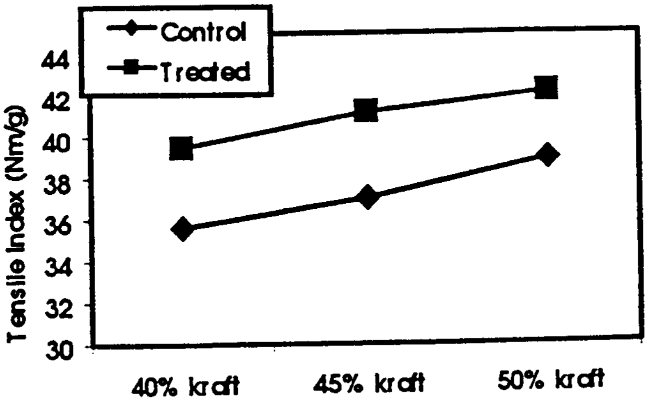

Figure 4. Tensile Index of TMP pulp blended with different levels of kraft pulp.

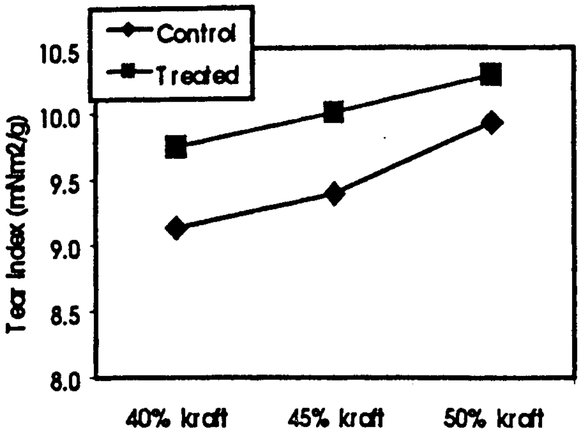

Figure 5. Tear Index of TMP pulps blended with different levels of softwood kraft.

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 confined our findings on a pilot paper machine. Strength properties improved even when blending the TMP and groundwood with 40 to 50% softwood kraft. Figure 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 Figure 5, a similar result can be seen for the tear index. Thus, biotreated pulp allows the substitution of less-expensive TMP for kraft

As has been the case throughout biopulping research, a darkening of the chips occurs, resulting in a loss of brightness in the paper (Figure 6), but bleaching will regain most of this lost brightness. Figure 6 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. 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.

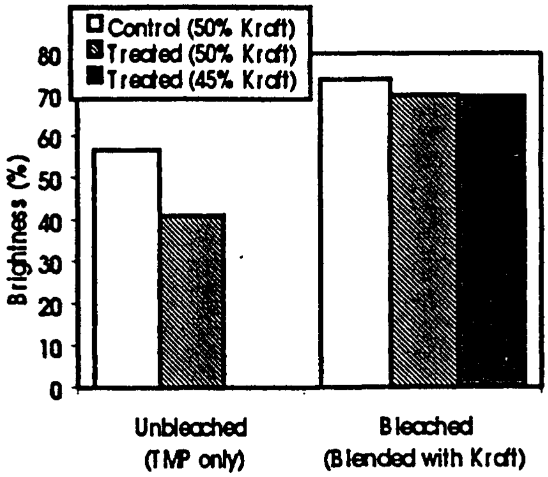

Figure 6. Brightness of unbleached and bleached and blended TMP pulps.

Process Economics

For this analysis, a 600 ton/day mill producing bleached TMP is considered. Table 1 summarizes the cost assumptions for the analysis. The reference [7] serves as the basis for some of these values. Of course, many of these parameters will be quite site specific and are subject to variability. The values of Kraft and TMP are market dependent and also highly volatile. For example, over the past 16 years, the price of Bleached Chemi-thermomechanical pulp (BCTMP) has ranged from $320 to $830 per ton, with the average (used in this analysis) being $550 per ton. Likewise the price of Kraft pulp has also fluctuated, with an average of $700 per ton being used in this study [8,9].

The capital costs for biopulping will vary according to the land and equipment that are currently available and the type of system installed. In addition to the treatment equipment needed for biopulping, these costs include land, 10 days of chip inventory, and the storage needed for the chips. Overall, we envision a silo or other enclosed storage system with a capacity based on the treatment time. The number of silos used and their configuration wood depend on the availability of the land and the layout of the mill and wood yard. Belt conveyors are probably the most likely candidate for moving the chips to and from the silos.

Additionally, the silos need to be ventilated in order to remove the heat produced by the fungus. The ventilation would be provided by a series of blowers and preconditioning systems with each silo serviced by several blowers. This allows a certain amount of redundancy in the design of the equipment. For greatest energy efficiency, especially in the northern climates, the air should be recovered from the top of the silos and the heat recovered.

Table 1. Cost assumptions for economic analysis

Assumptions	Value	Units
Utility &Raw Materials		
Electricity	0.05	\$/kWh
Steam	2.00	\$/10^6 Btu
Wood	60.00	\$/ton (o.d.)
Bleaching chemicals	60.00	\$/ton of pulp (o.d.)
Kraft pulp	700.00	\$/ton (o.d.)
TMP pulp	550.00	\$/ton (o.d.)
Biopulping		
Capital costs (for 600 ton/day of pulp)	5.7×10^6	\$
Operating costs	9.44	\$/ton of pulp (o.d.)
Process Operations		
Production days	350	days/year
Refining energy	2000	kWh/ton
TMP yield	95	%
Treatment yield	98	%
Additional bleaching	15	%
TMP Manufacturing		
Labor	15.00	\$/ton of pulp (o.d.)
Maintenance and operational supplies	30.00	\$/ton of pulp (o.d.)
Tax and insurance	8.00	\$/ton of pulp (o.d.)
Overhead	6.00	\$/ton of pulp (o.d.)

For such a system, the total capital costs are estimated to be \$5.7 million (Table 1). The additional operating costs for the treatment equipment ventilation blowers, chip handling, and inoculum is estimated to be \$9.44 per ton of pulp produced. This value is dependent on the costs of electricity and steam, also given in Table 1. The mill is assumed to operate 350 days/year, with a 95% yield through the refining process. Additional operating parameters, including costs for the TMP operation, are given in Table L

Economic Benefits Considered

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 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.

Process Dehottlenecking

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.

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.

Other Advantages

The biopulping process itself is benign environmentally. Only benign 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. Biopulping chip storage is carefully contained. 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,

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. Table 2 summarizes the three scenarios investigated in this paper. Each scenario assumes a base TMP production of 600 tons/day. In scenario #3, the TMP is blended with equal parts of Kraft pulp for a total production of 1200 tons/day. For all three scenarios, biopulping conferred an energy reduction at the refiner of 30%. For scenario #2, a 20% increase in throughput is realized. For scenario #3, a 10% throughput increase is achieved, with the additional TMP production reducing the amount of Kraft needed.

Table 3 shows the economic analysis for scenario # 1, where a 30% energy reduction is realized. Comparing the base case to scenario #1, the annual energy costs drop from $21.00 million to $14.70 million. After taking into account the additional costs for the wood and biopulping treatment, an annual savings of $2.14 million is achieved. This is a savings of $10.21 per ton of pulp produced. Under different scenarios and assumptions for utility costs, equipment needs, and operating costs, the net savings can range up to more than $26 per ton of pulp produced, with an estimated capital investment of $5.7 million. Simple rate of return can range from 25% to 95%, resulting in a payback of 1.0 to 3.9 years. Using typical values for the parameters of the analysis, a savings of $10.21 per ton of pulp can be expected after the cost of capital with a simple payback of 2.66 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 cart experience throughput increases of up to 30% from the reduction in refining energy by running the refiners to a constant total power load. Table 3 also shows the analysis when a throughput increase is achieved. In scenario #2, production increases by 20% to 720 tons/day. Comparing this to the base case, the annual energy costs went down from $21.00 million to $17.64 million, even with the increased production Due to the greater production, the other costs went up proportionally, but the total annual product value increased by over $23 million. The total additional profit achieved through biopulping is $13.82 million, which translates to over $50 per ton and a payback period of about 6 months.

Figure 7 shows the savings as a function of the throughput increase. The savings are from the increase in the production using the same capital. The solid, lower line shows the savings as a function of the throughput increase. Even a modest throughput increase of 10%, coupled with the energy savings of 30%, results in a payback of less than 1 year. At a 20% throughput increase, the savings are more than $50 per ton of pulp. Even if additional capital expenditures are needed, throughput increases of 20% result in a payback of less than 1 year. These values depend on the value of the product, in this case TMP pulp, which has ranged from less than $400 per ton of pulp to more than $800 per ton of pulp in the past 15 years [8,9].

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. Table 4 summarizes the economic analysis for scenario #3 in which a mill is blending TMP with purchased Kraft. There is a 10% increase in the TMP production, which is used to replace Kraft in the product. The total energy costs drop from $21.00 million to $16.17 million; Kraft costs drop by almost $15 million per year. Overall, $11.13 million is saved per year, which is equivalent to $48.19 per ton of TMP produced. The payback period of this technology is slightly over 6 months for this scenario. Figure 7 also shows the effect of additional Kraft substitution on the savings for incorporating biopulping into the mill. The dotted line represents the total savings on a per ton basis that are realized when the additional TMP is used as a substitution for Kraft. A can be seen, for a 10% increase in production, an additional savings of $13 dollars is achieved through this substitution.

Commercialization Issues

All this work is leading to the large-scale treatment of wood chips with a lignindegrading 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.) [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 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

Table 2 Process capacities and biopulping effects for economic scenarios.

		Scenario		
	Units	#1	#2	#3
Base process capacity	(tons/day)	600	600	1200
TMP production	(tons/day)	600	600	600
Kraft pulp requirements	(tons/day)	0	0	600
Energy savings per unit weight	(%)	30	30	30
Production increase	(%)	0	20	10
TMP substitution for kraft	(%)	0	0	5

Table 3. Economic analysis for scenarios #1 and #2

	Units	Base	#l	#2
TMP production	(tons/day)	600	600	720
Biopulping capital costs	(10^6 $)	--	5.7	6.8
Manufacturing costs				
Energy	(10^6 $/year)	21.00	14.70	17.64
Wood	(10^6 $/year)	13.26	13.55	16.26
Bleaching chemicals	(10^6 $/year)	12.60	14.49	17.39
Biopulping treatment	(10^6 $/year)	--	1.98	2.38
Other costs	(10^6 $/year)	12.39	12.39	14.37
Total Costs	(10^6 $/year)	59.25	57.11	68.53
Product value	(10^6 $/year)	115.50	115.50	138.60
Marginal profit	(10^6 $/year)		2.14	13.82
Simple payback period	(years)		2.66	0.49
Savings	($/ton)		10.21	54.85

Table 4. Economic analysis for scenarios #3.

		Scenario	
	Units	Base	#3
Total production	(tons/day)	1200	1200
TMP production	(tons/day)	600	660
Kraft pulp requirements	(tons/day)	600	540
Biopulping capital costs	($10^6$$)	--	6.3
Manufacturing costs			
Energy	($10^6$$/year)	21.00	16.17
Wood	($10^6$$/year)	13.26	14.90
Bleaching chemicals	($10^6$$/year)	12.60	15.94
Biopulping treatment	($10^6$$/year)	--	2.18
Kraft Pulp	($10^6$$/year)	147.00	132.30
Other costs	($10^6$$/year)	12.39	13.63
Total costs	($10^6$$/year)	206.25	195.12
product value	($10^6$$/year)	262.50	262.50
Marginal profit	($10^6$$/year)		11.13
Simple payback period	(years)		0.56
Savings	($/ton)		48.19

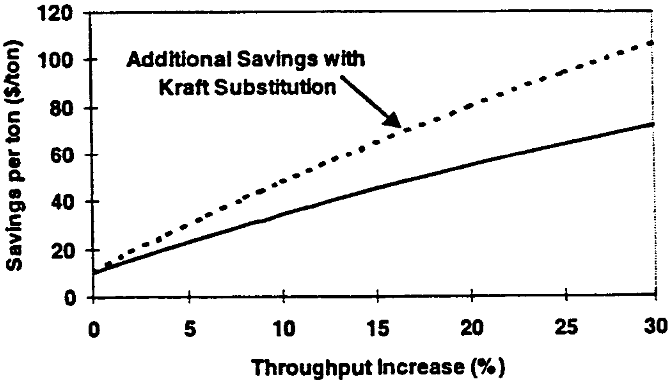

Figure 7. Effect of debottlenecking of the process through biopulping for a 600 ton/day TMP plant. The solid line shows the savings per ton as a function of the throughput increase. The dotted line demonstrates the additional savings that can be realized when the added TMP production is used as a replacement for Kraft pulp.

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 [11]. 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 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 Kamyr digesters [12] 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-wale work the cooling and inoculation of the chips were done through ventilation in a screw conveys. 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 [11]. 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.

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 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.

Our economic analyses indicate that the biopulping process is technologically feasible and 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.

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.

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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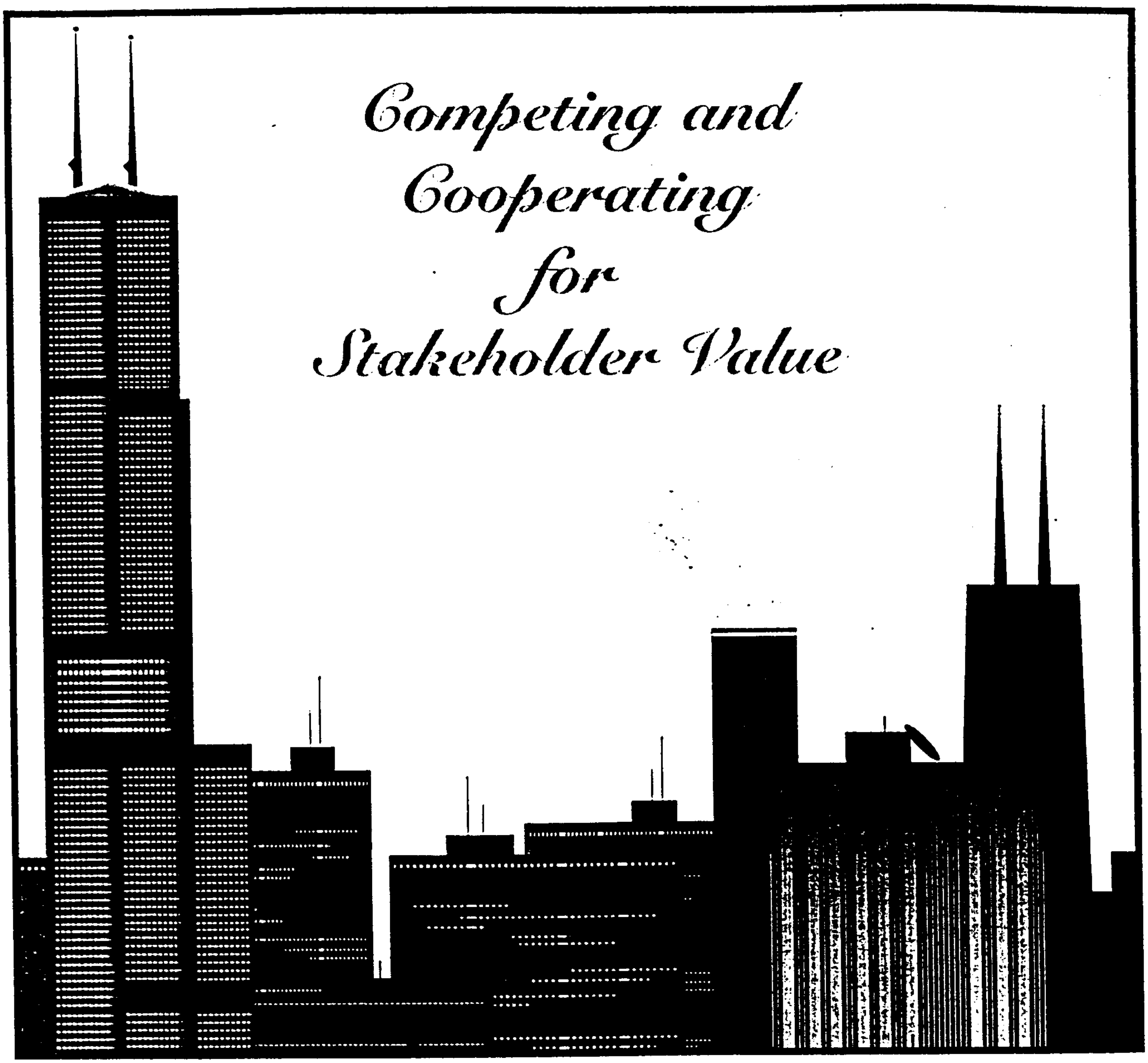

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