Biotechnology in the Pulp and Paper Industry
L. Viikari and R. Lantto (Editors)

Recent Developments in Biopulping Technology at Madison, WI

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Biopulping is defined as the treatment of wood or other lignocellulosics with a "natural" lignin-degrading fungus prior to pulping. Research consortia made up of the USDA Forest Service, Forest Products Laboratory (FPL) in Madison and the Universities of Wisconsin and Minnesota have evaluated biopulping from a small laboratory scale to a 50-ton semi-commercial scale over the past 12 years. The investigations were supported in part by 23 pulp and paper and related companies and the Energy Center of Wisconsin. The State University of New York, College of Environmental Science and Forestry has also joined as a partner in this research. The research established that biopulping substantially lowers the electrical energy required for mechanical pulping (or increases mill throughput), improves certain strength properties (reducing the need to augment with chemical pulps), and reduces environmental impact. Biopulping also reduces the pitch content of the pulp.

At a pilot scale, we have developed methods for decontamination of wood chips, cooling, and fungal inoculation sequentially in screw conveyers, and controlling temperature and moisture throughout the chip pile. Mill-scale refining of fungus-treated chips 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 and the strength improvements, the process economics looks very attractive. Several independent economic evaluations of biopulping have now been completed by both university and industry economists and engineers and are in agreement. Based on energy savings and reduction in kraft pulp in the final product, substantial savings can be realized. The additional benefits of increased throughput, and reduced pitch content and environmental impact improve the economic picture for this technology even further.

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 than chemical pulps. Kraft pulp is often added to mechanical pulps to impart strength, but it is much more expensive than mechanical pulps. These disadvantages limit the use of mechanical pulps in many grades of paper. Biomechanical pulping, defined as the treatment of lignocellulosic materials with a natural lignin-degrading fungus prior to mechanical pulping, has the potential to ameliorate some of these problems. The reader is referred to several much more comprehensive summaries of the research and development leading to the current status of biomechanical pulping (1-5). Citations to the original papers and patents can be traced through these summaries.

2. PILOT SCALE EQUIPMENT

Once the biological variables were optimized, we turned to engineering process development and scale-up, focusing mainly on chip pretreatment, incubation conditions, and economics. Commercial biopulping will involve treatment of about 200 to 2,000 tons of wood chips per day. The gap between laboratory scale and the much larger commercial scale was bridged through a series of experiments, culminating in two 50-ton trials. The scale-up studies demonstrated that: (a) chips can be decontaminated and inoculated on a continuous basis rather than a batch process as was done on the laboratory scale and (b) the process can be scaled as expected from an engineering standpoint.

A treatment system was built based on two screw conveyers that transported the chips and acted as treatment chambers (Fig. 1). Steam was injected into the first screw conveyer, which heated and decontaminated the wood chip surfaces. A surge bin was located between the two screw 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 filtered air blown into the second conveyer. In the second half of the second conveyer, the inoculum suspension was applied and mixed thoroughly with the chips through the tumbling action in the screw conveyer. From the screw conveyer, the chips fell into a pile for the 2-week incubation. Equipment of this design was used to treat 50 tons of spruce chips (dry weight basis) with *Ceriporiopsis subvermispora* at FPL at a throughput of 2 tons per hour (dry weight basis). During the subsequent 2-week incubation, the chip pile was ventilated with conditioned air to maintain the proper growth temperature (27-32°C) and chip moisture (50-60% on a wet weight basis) throughout the pile. Fig. 2 is a photo of one of the 50-ton trials with the equipment beside it.

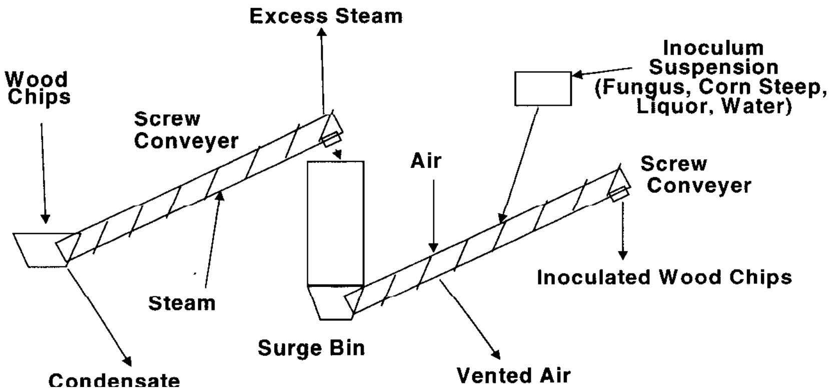

Figure 1. Overview of a continuous treatment process for decontaminating, cooling, and inoculating wood chips. The system is based on two screw conveyers with a surge bin between them.

Figure 2. Overview of a 50-ton trial held at the Forest Products Laboratory in Madison, Wisconsin. To the left of the pile are the aeration units, and to the right is the treatment apparatues.

3. EVALUATION OF FUNGUS-TREATED CHIPS IN PAPERMAKING

For many grades of paper, papermakers blend different pulps—mechanical and chemical, softwood and hardwood—to obtain the paper properties specific to that grade. In general, pulps such as softwood kraft are added to enhance the strength properties of the final sheet while mechanical pulps are added for their optical properties and lower costs. Since biopulping of the mechanical portion of the blend improves the strength properties of that fraction, significant economic savings can be realized since less of the more expensive chemical pulp can be used while still maintaining the sheet specifications.

The following detail two different case studies of blended pulps: One for lightweight coated paper and the other for a eucalyptus tissue paper. In each case, the kraft fraction was reduced resulting in significant annual savings.

3.1. Lightweight coated paper

Control and fungus-treated spruce chips (from one of the 50-ton trials) were refined through a commercial TMP mill producing lightweight coated paper (4,6). The fungal pretreatment saved 33% electrical energy (Fig. 3) and improved paper strength properties significantly compared to the control (Table 1). Yield loss for the biotreatment was approximately 2%. Since biomechanical pulp fibers were stronger than the conventional TMP fibers, we were able to reduce the amount of bleached softwood kraft pulp in the final product (7).

Table 1 shows that even with a 5% increase in the proportion of TMP in the blended pulp, the strength properties were still slightly improved over the control which consisted of a 50%/50% blend of TMP and softwood kraft. The optical properties (except for brightness) were also essentially the same. As has been noted many times with biopulping, there is a darkening of the biotreated pulp. However, as the table shows, this brightness can be recovered through an additional application of 1% hydrogen peroxide bleach on wood. This represents a 60% increase in the bleaching chemical used as compared with the control. Even with this additional bleaching, the process is economically feasible as will be discussed below.

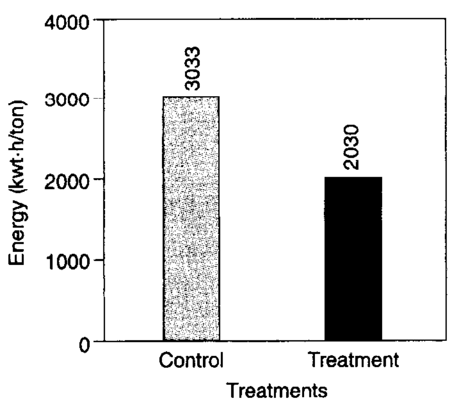

Figure 3. Energy requirements for the control and the fungus-treated chips from the 50-ton trial during thermomechanical pulping process to produce pulps at about 50 CSF.

Table 1. Strength and other physical properties comparison for blended pulp with spruce.

Parameters	Control (50%TMP + 50% kraft)	Treatment (55%TMP + 45% kraft)	
Burst index (kN/g)	2.29	2.39	
Tear index (mNm^2/kg)	9.92	10.0	
Tensile index (Nm/g)	38.9	41.2	
Brightness (%)	73.0	69.8[a]	73.0[b]
Opacity (%)	85.2	86.4	
Light scattering coefficient (m^2/kg)	46.2	47.7	
Drainage time (sec)	8.5	9.9	
Density (kg/m^3)	689	610	

[a]Same amount of hydrogen peroxide was applied in the control and treatment.
[b]Sixty percent more hydrogen peroxide was applied on the treatment. Strength and optical properties were not affected by the use of additional hydrogen peroxide (data not shown).

Mills can realize economic savings in several ways with the incorporation of biopulping into the process. The obvious one is the reduced electrical costs at the refiner. Savings can also be realized due to the increase in mill throughput as well as the savings due to the lower kraft pulp requirements. Although more difficult to quantify, the reduced pitch content of the pulp and the reduced environmental impact can also have economic benefits to the mill. Of course with the addition of biopulping to the process, there are some added costs. There is the additional cost of steam,power, and labor to operate the biopulping equipment as well as the cost of nutrients and inoculum. Additional bleaching chemicals may also be needed. Finally, there is a small amount of wood loss through the bioulping process, which needs to be accounted for.

Table 2 summarizes an example for a lightweight coated mill that produces 800 tons per day of paper that is a blend of kraft, TMP, and groundwood. The sheet is 50% softwood kraft, 27.5% TMP, and 22.5% groundwood. Table 3 summarizes the biotreatment operating costs. Additional electrical power is needed to operating the ventilation equipment and steam is used for the decontamination of the chips and for humidifying the ventilation air. A total cost of approximately US$15 is estimated. However, the 33% energy savings realized at the refiner result in a reduction in electrical costs of approximately US$40 per ton. Furthermore, as electrical energy costs increase, the savings become even more dramatic.

A complete economic analysis needs to take into account several other factors which are summarized in Table 4. As can be seen, while the biopulping process reduces the electrical energy requirements, there are increases in the wood, bleaching chemicals, and of course the biotreatment costs. However, there is still a net savings of approximately US$17 per ton of pulp for an annual savings of approximately US$1.3 million. Note that this analysis only takes into account the savings due to electrical energy savings. Other factors, such as increased mill throughput or kraft pulp reduction, would increase the savings. For lightweight coated paper, the increased TMP mill throughput and kraft pulp reduction could increase the annual savings to over US$11 million per year (7). Compared to the capital investment, these savings make the implementation of biopulping very attractive.

Table 2. Summary of economic assumptions for the economic analysis of an 800 ton/day lightweight coated paper mill.

Parameter	Value
Total production	800 ton/day
TMP production	220 ton/day
Kraft requirements @ US$650/ton	400 ton/day
Groundwood requirements @ US$233/ton	180 ton/day
Wood costs	US$80/ton
Production	350 days/year
TMP refiner energy	3033 kWh/ton
Electricity costs	US$0.04/kWh
TMP yield	95%
Treatment wood loss	2%
Additional bleaching chemicals	60%

Table 3. Biotreatment operating costs per ton of TMP pulp produced.

Operating parameter	Cost (US$/ton of pulp)
Steam	US$ 2.50
Electricity	US$ 6.16
Inoculum and nutrients	US$ 2.00
Labor, maintenance, taxes, overhead	US$ 4.10
TOTAL	US$14.76

Table 4. Comparison of conventional and biopulping TMP pulp manufacturing costs (US$/ton)

Cost	Conventional TMP	Biopulping TMP
Energy	121	81
Wood	84	86
Bleaching chemicals	10	16
Other costs	60	60
Biotreatment costs	-	15
TOTAL	275	258

3.2. Eucalyptus tissue paper

A tissue sheet is produced from a blend of 50% TMP and 50% hardwood bleached kraft. Again, as shown in Table 5, the biomechanical pulping of eucalyptus results in energy savings. While the savings in this case are not as dramatic as in the previous example, they are still significant. Furthermore, there is a very significant increase in the strength properties of the resulting pulp, with the tear and tensile indices more than doubling at a comparable freeness. The greatly improved strength properties of the biotreated TMP allow the kraft in the blended sheet to be reduced from 50% to 20% while still maintaining comparable properties (Table 6). While there is a decrease in the overall brightness, we expect that an increase in the bleaching chemicals used will recover this brightness loss as in the previous example.

Table 7 summarizes the economic assumptions for this particular mill producing a sheet that is a 50%/50% blend of eucalyptus TMP and hardwood kraft. Compared to the previous example, the electrical and wood costs are lower and the biotreatment energy savings are only 17%. Because of the lower energy savings, the process does not look economical based on energy savings along (Table 8). The electrical energy savings amount to only US$6 per ton, while the treatment costs are US$11 per ton. However, the much greater strength of the biotreated TMP pulp allows the amount of kraft to be reduced from 50% to 20% (Table 5). In essence, the biotreatment allows the substitution of kraft pulp at US$620 per ton with the biotreated TMP at US$195 per ton. The resulting savings is over US$11 million per year (Table 9). Although not considered in this analysis, additional bleaching (at a cost of US$10 per ton) would only reduce the annual savings to US$10.7 million per year.

Table 5. Energy savings and physical properties for the biomechanical pulping of eucalyptus.

Parameter	Control	Treatment
Freeness (ml)	402	390
Energy requirements (kWh/ton)	1005	833
Energy savings	-	17%
Burst index (kN/g)	0.20	0.34
Tear index (mNm^2/g)	1.03	2.93
Tensile index (Nm/g)	5.16	11.35

Table 6. Strength and other physical properties comparison for blended pulp with eucalyptus

Parameters	Control (50%TMP + 50% kraft)	Treatment (80%TMP + 20% kraft)
Burst index (kN/g)	0.35	0.38
Tear index (mNm^2/kg)	1.69	2.92
Tensile index (Nm/g)	9.40	11.26
Brightness (%)	79.8	74.5
Opacity (%)	88.5	88.8
Drainage time (sec)	5	5
Density (kg/m^3)	310	307

Table 7. Summary of economic assumptions for the economic analysis of a 260 ton/day eucalyptus mill.

Parameter	Value
Total production	260 ton/day
TMP production	130 ton/day
Kraft requirements @ US$620/ton	130 ton/day
Wood costs	US$20/ton
Production	350 days/year
TMP refiner energy	1400 kWh/ton
Electricity costs	US$0.025/kWh
TMP yield	95%
Treatment wood loss	2%

Table 8. Comparison of conventional and biopulping TMP pulp manufacturing costs for eucalyptus paper mill (US$/ton)

Cost	Conventional TMP	Biopulping TMP
Energy	35	29
Wood	21	21
Other costs	134	134
Biotreatment costs	-	11
TOTAL	190	195

Table 9. Costs and annual savings realized through decreased use of kraft pulp with biotreated eucalyptus TMP (US$ millions)

Pulp	Conventional (50% TMP + 50% Kraft)	Biopulping (80% TMP + 20% Kraft)
TMP	8.65	14.20
Kraft	28.21	11.28
TOTAL	36.86	25.48
SAVINGS		11.38

3.3. Capital cost

The savings detailed in the previous two examples must be compared to the capital costs involved in installing a biopulping system. The costs for a 208 ton/day treatment facility are given in Table10. This size of plant is needed to produce the 80% TMP requirements for the second example given above. From Tables 8 and 9, we can see that a US$12.4 million investment results in an estimated annual savings of US$11.4 million dollars. This represents an simple annual rate of return of 91.4%. Thus, the economics of biopulping for this scenario are extremely favorable.

Table 10. Capital costs of a 208 ton/day biopulping treatment facility.

Plant Component	Cost Estimate (US$1000's)
Sitework	188
Chip supply and return	1,360
Chip treatment and storage	4,176
Chip ventilation	1,474
Auxiliaries	1,572
Power distribution	329
Spares, commissioning, startup	650
Project management, design, engineering, contingency	2,693
Total Installed Cost	12,442

4. INDUSTRIAL-SCALE PROCESS FLOWSHEET

The fungal treatment process can fit well into a mill's woodyard operations. Wood is debarked, chipped, and screened according to normal mill operation. The chips are then briefly steamed to eliminate natural chip microorganisms, cooled with forced air, and inoculated with the biopulping fungus. The inoculated chips are piled and ventilated with filtered and humidified air for 1-4 weeks prior to processing (Fig. 4).

5. COMMERCIAL VIABILITY ISSUES

Several issues need to be considered in making the final scale-up to the industrial levels. A larger scale operation with a 2-week treatment time would require the routine storage of 14,000 tons of wood for a 1,000 ton per day plant, which is a pile 160,000 m^3 in volume. To put that amount of chips in perspective, it would be a pile of chips 100 m long, 40 m wide, and 20 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. However, the first large-scale operation will 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.

As the scale of the project increases, the construction of needed equipment will probably become much easier, and will improve greatly with time and experience. However, industrial scale equipment is already available in the required capacity ranges that will suit the purposes of this technology for its initial utilization.

Indoor storage should also be considered as an option for incorporating a biopulping operation into a mill. Enclosing the chip storage/treatment operation will significantly reduce blowing dust, contamination by unwanted microorganisms, 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.

No adverse effects of lignin-degrading fungi on humans have been reported in the literature. These fungi are natural wood decayers. However, a biopulping operation would entail producing substantial amounts of fungus in a pile on a routine basis. For that reason, *C. subvermispora* was tested by professionals for toxicity, allergenicity, etc. It was concluded that the fungus is safe for use on a commercial scale. One of the paper companies in the U.S. has hired a professional company to look into the effects of the technology on the environment. The company is currently analyzing VOC's given off during biopulping and comparing them with those from a standard chip pile storage. Runoff water from the pile during mill-scale trials will be tested by professionals. We did not see any leachates coming out of our 50-ton pile, perhaps because of forced aeration used in the trial. It is notable that closely related fungi are actually being used commercially to clean up chemically-contaminated soils.

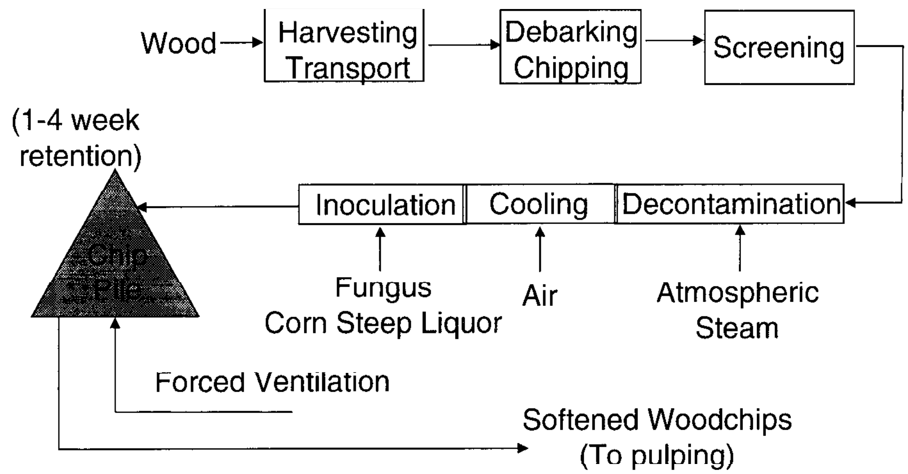

Figure 4. Overview of the biopulping process showing how the biotreatment process fits into an existing mill's wood handling system.

6. CONCLUSIONS

After 12 years of research, we have established the commercial and economic feasibility of biomechanical pulping. At a pilot scale, we have developed methods for decontamination of wood chips, cooling, and fungal inoculation sequentially in screw conveyers, and controlling temperature and moisture throughout the chip pile. Mill-scale refining of fungus-treated chips from this trial 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 and the strength improvements, the process appears to be economically feasible. The additional benefits of increased throughput, and reduced pitch content and environmental impact improve the economic picture for this technology even further. (Based on the promising results and attractive economics, pulp mills from the U. S., Brazil, Europe and India have made commitments to conduct large-scale trials at their sites.)

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