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# Biomechanical pulping: a mill-scale evaluation

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## Abstract

Mechanical pulping process is electrical energy intensive and results in low paper strength. Biomechanical pulping, defined as the fungal treatment of lignocellulosic materials prior to mechanical pulping, has shown at least 30% savings in electrical energy consumption, and significant improvements in paper strength properties compared to the control at a laboratory scale. In an effort to scale-up biomechanical pulping to an industrial level, 50 tons of spruce wood chips were inoculated with the best biopulping fungus in a continuous operation and stored in the form of an outdoor chip pile for 2 weeks. The pile was ventilated with conditioned air to maintain the optimum growth temperature and moisture throughout the pile. The control and fungus-treated chips were refined through a thermomechanical pulp mill (TMP) producing lightweight coated paper. The fungal pretreatment saved 33% electrical energy and improved paper strength properties significantly compared to the control. Since biofibers were stronger than the conventional TMP fibers, we were able to reduce the amount of bleached softwood kraft pulp by at least 5% in the final product. Fungal pretreatment reduced brightness, but brightness was restored to the level of bleached control with 60% more hydrogen peroxide. The economics of biomechanical pulping look attractive.

*Keywords:* Mechanical pulping; White-rot fungi; Papermaking; Thermomechanical pulping; Wood chips; Bleaching; Electrical energy

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## 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 less strength compared to the chemical pulping process. Kraft pulp is often added to mechanical pulp to impart strength, but it is more expensive than mechanical pulp. These disadvantages limit the use of mechanical pulps in many grades of paper. Therefore, Agenda 2020 (paper industry's vision for the future) proposes the development of new methods or technologies to overcome these problems. Biomechanical pulping has the potential to ameliorate some of these problems.

## 2. Background research

The use of white-rot fungi for the biological delignification of wood was perhaps first seriously considered by Lawson & Still [1] at the West Virginia Pulp and Paper Company (now Westvaco Corporation). These researchers published a survey of the literature (72 lignin-degrading fungi), which pointed to the dearth of knowledge about the fungal degradation of lignin. In the 1970s, Eriksson at the Swedish Forest Products Laboratory (STFI) launched a fairly comprehensive investigation which demonstrated that fungal pretreatment could result in significant energy savings and strength improvements for mechanical pulping [2–5]. That research also resulted in a US patent that described a “method for producing cellulose pulp” [6]. Although this research met with limited success — encountering difficulties in scale up — it provided valuable insights [7,8]; details can be found in several review articles and the literature cited therein [9–16].

The subsequent effort to research and develop biomechanical pulping at the USDA Forest Service, Forest Products Laboratory (FPL) has been a unique collaboration among a diverse group of government bodies, research institutions, and private companies. Beginning in April 1987, a consortium was formed, including the FPL, the Universities of Wisconsin and Minnesota, and up to 22 pulp and paper and related companies. The overall goal of the consortium research was to evaluate the commercial and economic feasibility of biomechanical pulping. Because the fungal pretreatment is a natural process, environmental impact is expected to be minimal.

The consortium benefited from the ability to draw on the considerable resources of a prominent federal laboratory and two eminent research universities, as well as the expertise represented by the private companies involved. Together the companies were able to support a large and risky research project which none of them individually would have been willing to finance. However, in 1995, the pulp and paper industry experienced a downturn and a number of the consortium members pulled out. Additional funding was needed to demonstrate biomechanical pulping on a large enough scale to show how it might work in a real pulp mill. Consequently, biomechanical pulping attracted the attention of another collaborative organization, the Energy Center of Wisconsin, which agreed to provide the funding needed to scale up biomechanical pulping towards industrial levels.

With their financial support, biomechanical pulping has now been scaled up to near industrial levels, and the overall conclusion is that biomechanical pulping works. Through the use of the proper lignin-degrading fungus, at least 30% electrical energy can be saved in mechanical pulping, paper strength properties are improved, and pitch content is reduced [9,10,12]. A summary of key challenges faced during research and development of biomechanical pulping are discussed in the following sections.

## 3. Biological challenges

Many variables can affect biopulping. In our initial work, we simply made best guesses based on the literature, knowledge of fungal growth, and past experience. Investigations have sorted through the more than 30 variables associated with biopulping, including species and strains of fungi, inoculum form and amount, species of wood, wood chip size, environmental factors, effect of added nutrients, and need to sterilize the chips [9,10]. Some of the variables key to the economic viability of biopulping are summarized below.

### *3.1. Selection of a suitable fungus*

We identified a fungus, *Ceriporiopsis subvermispora*, that performs biopulping very effectively on both hardwood and softwood species. This fungus is a selective lignin degrader and was chosen after screening several hundred species of fungi and their strains.

### *3.2. Chip surface decontamination*

Wood chip surfaces normally are contaminated with cells and spores of many fungi and bacteria. These unwanted microorganisms can hamper biopulping fungus, making decontamination desirable. We discovered that a brief atmospheric steaming of chips (as short as 15 s) decontaminates the surfaces of wood chip and allows the biopulping fungus to outcompete unwanted microorganisms and perform biopulping effectively, uniformly, and economically. A recent article published in Tappi Journal [17] focuses on respiratory health problems associated with routine exposure of workers to the spores of miscellaneous fungi that inhabit wood chips in a normal wood yard operation. Some of these unwanted fungi also produce cellulolytic enzymes and thus would have an adverse effect on paper strength properties. Biopulping fungus is non-sporulating and is a selective lignin degrader, which would preclude such problems.

### 3.3. Inoculum

We reduced the required amount of inoculum from 3 kg to 5 g or less per ton of wood, which is well within a commercially attractive range. This was achieved by adding an inexpensive and commercially available nutrient source, unsterilized corn steep liquor, to the inoculum suspension [18]. This additive apparently 'kick-starts' the fungal growth, making it possible to use a much lower inoculum level. Since corn steep liquor is produced widely in the US, pulp and paper companies should be able to obtain a regular supply from the nearest location with minimal transportation cost.

## 4. Engineering and scale-up challenges

On a laboratory scale, steaming, cooling, and fungal inoculation were performed in a batchwise fashion. The real challenge was how to carry out these three steps continuously. As previously mentioned, a brief steaming of the chips allows *C. subvermispora* to colonize and become established on the chips. After steaming, the chips are near 100°C surface temperature. Thus, the chips need to be cooled sufficiently prior to fungal application. Complete cooling is not needed before the inoculum is added. However, the chips need to be within the temperature growth range of the fungus within a relatively short period after it is mixed with the chips. Hence, the cooling can probably take place in two stages: before inoculation and after the chips are placed into storage by using the ventilation system for additional cooling. The next step in the process is the inoculation of the wood chips with a suspension containing the fungus, corn steep liquor, and dilution water. Challenges involved in this step included metering the inoculum mixture to give the proper amount of fungus and obtain the correct moisture content for the chips. An additional challenge was the even distribution of the inoculum over the wood chips to promote uniform growth.

The second engineering challenge was maintaining the proper conditions in the chip pile to promote fungus growth. The key variables were the temperature and humidity of the air and the chip moisture content. The fungus has an optimum growth range for each of these variables. Furthermore, the fungus is not self-regulating in respect to any of them. For example, when biopulping was performed in a 1-ton chip pile without forced ventilation, the pile center reached about 42°C within 48 h after inoculation as a result of metabolic heat generated by the fungus. The fungus ceases to grow at this temperature, so we observed no biopulping action in that region of the pile. The use of forced air was explored for controlling temperature and moisture throughout the pile. This required an understanding of the air flow through the chip pile, the heat generation of the fungus, the changes in the chip structure caused by the fungus, and the nutrient and oxygen requirements of the fungus.

### *4.1. Scale-up equipment and methods*

Our laboratory process treats approximately 1.5 kg of chips (dry weight basis) at one time. Commercial levels of the process need to be about 200–2000 tons or more per day of wood chips processed, representing a $10^5$ increase in scale. This gap was bridged through a series of experiments. The scale-up studies were two-fold: (a) to demonstrate that chips can be decontaminated and inoculated on a continuous basis rather than a batch process; and (b) to demonstrate that the process can be scaled as expected from an engineering standpoint. The entire 50-ton trial has been repeated with similar results.

To demonstrate the operation on a continuous basis, a treatment system was built based on two screw conveyers that transported the chips and acted as treatment chambers. Steam was injected into the first screw conveyer, which heated and decontaminated the wood chip surfaces. A surge bin was located between the two 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 screw conveyer. In the second half of the second screw conveyer, the inoculum suspension containing fungus, unsterilized corn steep liquor, and water was applied and mixed thoroughly with the chips through the tumbling action in the screw conveyer. From the screw conveyer, the chips fell into the pile for the 2-week incubation. Continuous equipment of this design was used to treat 50 tons of spruce chips (dry weight basis) with *C. subvermispora* at FPL at a throughput of 2 tons per hour (dry weight basis) continuously for nearly 24 h. During the 2 weeks, the chip pile was ventilated with conditioned air to maintain the proper growth temperature (27–32°C) and moisture (50–60% on a wet weight basis) throughout the pile; details can be found in recent publications [19,20].

## 5. Mill-scale evaluation of fungus-treated chips

The control and fungus-treated chips were refined through a TMP mill producing lightweight coated paper. The fungal pretreatment saved 33% electrical energy (Fig. 1) and improved paper strength properties significantly compared to the control. 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 (Fig. 2).

Fungal pretreatment reduced brightness significantly, but brightness was restored to the level of bleached control with 60% more hydrogen peroxide in the bleached liquor. Data on strength and other physical properties of bleached handsheets are shown in Table 1. Our bleaching results were subsequently confirmed by Solvay Interox; their results are shown in Table 2. These results clearly demonstrate that the biofibers can be bleached to the level of bleached control. However, bleaching optimization needs to be performed for each wood species used.

## 6. 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

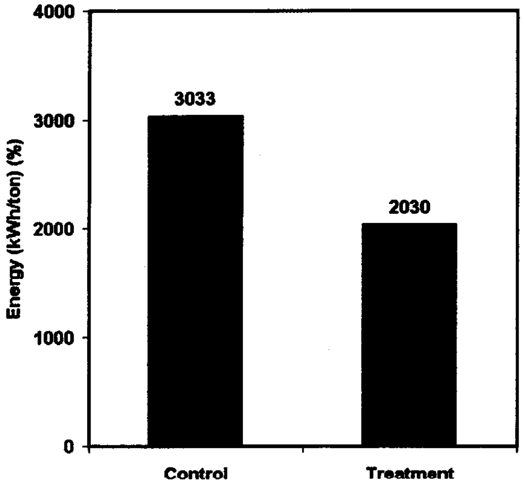

Fig. 1. Energy requirement for the control and the fungus-treated chips from the 50-ton trial during TMP process.

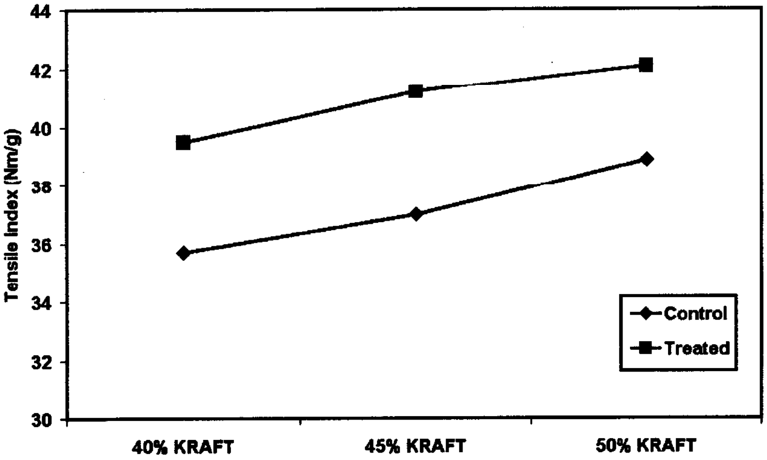

Fig. 2. Tensile index of TMP pulps from control and fungus-treated chips blended with different levels of kraft pulp.

Table 1
Strength and other physical properties comparison

| 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 (s) | 8.5 | 9.9 |
| Density (kg/m$^3$) | 689 | 610 |

[a] Same amount of hydrogen peroxide was applied on the control and the 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).

Table 2
Bleaching optimization for treated samples

| Hydrogen peroxide[a] (% more over the control) | Initial pH | Final pH | Brightness (%) |
|---|---|---|---|
| 0 | 11.2 | 7.8 | 70.0 |
| 30 | 11.1 | 8.0 | 71.8 |
| 60 | 11.1 | 8.3 | 73.8 |
| 90 | 11.2 | 8.2 | 75.3 |

[a] 113% consistency; 60°C; 60 min.

are piled and ventilated with filtered and humidified air for 1–4 weeks prior to processing (Fig. 3).

## 7. Process economics

The economics of biomechanical pulping look attractive. A preliminary economic evaluation has been performed for a 250 ton/day TMP mill [21]. The storage time was two weeks in a flat-pile geometry. Capital costs to incorporate biopulping technology into this paper mill are estimated to be about 6–$ 8 million (this preliminary analysis is subject to appropriate qualifications. The capital costs are subject to some variability, in particular the cost associated with integrating a new facility into an existing site. Much of the analysis will be quite site specific, depending on the operating conditions at a particular mill). Based on 33% energy savings and a 5% reduction in kraft in the final product, a savings of about $ 5 million each year can be realized. The cost of additional bleach chemicals was quantified and included in the analysis. The additional advantages of biopulping, such as environmental benefits and pitch reduction, have yet to be quantified.

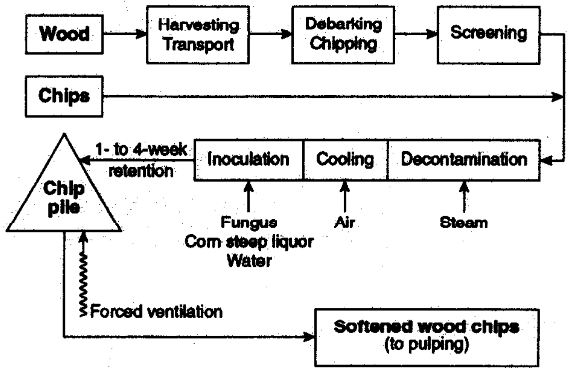

Fig. 3. Overview of the biopulping process showing how the biotreatment process fits into an existing mill's wood handling system.

## 8. Biopulping of loblolly pine chips at a laboratory-scale

In large scale trials, spruce wood chips were used. Recent studies with *C. subvermispora*-treated loblolly pine chips showed the potential of energy savings of up to 60% and significant improvements in paper strength properties compared to the control at a laboratory scale (Table 3). As expected, the fungal pretreatment reduced brightness; but brightness was restored to the level of bleached control with additional hydrogen peroxide (Table 3).

Table 3

Freeness, energy requirement, strength and optical properties of handsheets made from unbleached pulps from control and fungus-treated loblolly pine chips[a]

| Parameters | Control | | |
|---|---|---|---|
| | Newsprint | Lightweight coated paper | Treatment |
| Freeness (ml) | 51 | 39 | 123 |
| Energy required (kwt.h/ton) | 4112 | 4527 | 1794 |
| Burst index (kN/g) | 0.97 | 1.44 | 1.40 |
| Tear index (mNm$^2$/kg) | 3.40 | 3.76 | 5.41 |
| Tensile index (Nm/g) | 20.3 | 26.2 | 26.3 |
| Brightness (%)[b] | 48.3 | 48.7 | 39.7 |
| Opacity (%) | 97.2 | 97.3 | 97.3 |

[a] *Ceriporiopsis subvermispora* (2-week incubation).

[b] Control samples required 1 and 3% hydrogen peroxide to reach 62% (newsprint) and 70% (lightweight coated paper) brightness, respectively, whereas the treated samples required 2 and 4% hydrogen peroxide to reach similar brightness levels, respectively.

## 9. Commercially viable issues

Several issues need to be considered in making the final scale-up to the industrial levels, which can range from 200 to 2000 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 2000 ton per day plant, which is a pile 160 000 $m^3$ in volume. To put the amount of chips in perspective, it would be a pile of chips 100 m long, 40 m wide, and 40 m high. Although some mills do store and manage inventories in these ranges, others may need to make significant changes in their yard operations to take advantage of this technology. As is the case with most new technology, incorporating it into new construction would be much easier than retrofitting it into an existing system. However, the first large-scale operation would probably be a retrofit. Chip rotation has to be controlled with a first-in, first-out policy to maintain a consistent furnish to the pulp mill. However, this would not be seen as a great difficulty for most mills because this strategy is currently used in inventory maintenance.

One concern is the variation in the fungal treatment in different parts of the piles. As temperatures in the pile vary, so does the efficacy of the biopulping process [19,20]. Also, contamination with other microorganisms may increase competition and reduce the biopulping efficacy near the edges of the piles. However, results of our pilot scale trials showed that the surface penetration of the contaminants was only 10–30 cm into the pile. In larger piles, where the surface-to-volume ratio is even lower, the percentage would be less. Furthermore, untreated chips in large industrial piles often heat to more than 50°C because of respiration and oxidation of the wood and extractives as well as bacterial and fungal metabolism. This natural growth in piles leads to variation of the chip quality throughout the pile, with the hotter center of the pile being more affected by this growth. Furthermore, some indigenous organisms also degrade the cellulose in the wood, leading to pulp quality reductions and variation [22]. With biopulping, this suite of naturally occurring organisms is being replaced with a single lignin-specific fungus that is grown under controlled conditions. The single organism, together with the better control of chip-pile conditions, should lead to quality improvements.

As the scale of the project increases, the construction of needed equipment will probably become much easier. On an industrial scale, equipment is available in the required capacity ranges that will suit the purpose for this technology. For example, chip steaming and decontamination could be easily accomplished in a presteaming vessel similar to that used for Kamyr digesters [23]. Alternatively, a vertical, pressurized steaming bin with a downward flow of chips could also be used. Because the vessel is pressurized above atmospheric pressure, temperatures greater than 100°C can be used for the decontamination of the wood chips similar to the temperatures and pressures used for autoclaving. The contained unit will also significantly reduce the steam use because excess steam does not readily escape from the system. Previous work has shown that short-time steaming with good surface exposure is effective for decontamination [19,20]. The amount of surge capacity will depend on the decontamination needs, operational requirements, and space availability.

Cooling and inoculation will likely take place at atmospheric pressure. Mills that use air conveying to move the chips to the storage location are well suited for incorporation of this technology. The air conveying will naturally cool the chips during transport, thus requiring the inoculation to be done at the end of the conveying system and before being placed into storage. Mills that depend on other conveying methods — such as belts or screw conveyers — will probably require the addition of some type of ventilation cooling to reduce the temperature of the chips. In our pilot-scale work, the cooling of the chips through ventilation in a screw conveyer that was used for the transport of the chips was very successful, reducing the temperature of the chips sufficiently within 20 s during which the chips traveled 2 m. Ventilation may also be possible using belt conveyers, although this has not been tested on a laboratory or pilot scale. In the pilot scale, the inoculation was done in the same screw conveyer that was used for cooling. Inoculum was applied to the chips, then mixed in the screw conveyer. The use of belt conveyers has not been explored; however, the Cartapip™ product has been successfully applied in this fashion [22].

We have found that a two-step pile ventilation strategy is very effective in managing the temperature in the reactors. During the initial 3 days, little heat is generated, so a low air flow rate can be used to maintain a positive pressure in the pile. If necessary, this initial air flow can also maintain or adjust the temperature of the pile to the proper range. After the third or fourth day, the air flow is increased to a higher level to remove the generated heat from the pile. The inlet air temperature should be near the lower end of the active range of the fungus, and the rate of air flow just sufficient so that the maximum temperature of the chips is near the upper limit for the fungus. Through experience, this air flow rate can be determined, and the change can be made as soon as the increase in temperature is detected. More complex air handling strategies are also envisioned. For example, the rate of air flow could be controlled to achieve a certain temperature in a key location in the pile or to maintain the maximum temperature in the pile below a certain value. Of course, the lengthy time delays between the control action and the change in temperature need to be considered in setting up this system.

Currently, it is estimated that losses of approximately 1% per month of wood occur in outside chip storage systems [23]. This loss is mainly due to the blowing of fines, respiration of the wood, and microorganism activity. The blowing of fines and sawdust as well as microorganism growth can also cause environmental difficulties in the vicinity of the chip piles. Thus, indoor storage should also be considered as an option for incorporating a biopulping operation into a mill. Enclosing the chip storage operation will significantly reduce blowing dust and other environmental concerns. Furthermore, better control of the environment for the growth of the fungus would be maintained throughout the year. Enclosing the chip storage would also allow the recovery of the heat produced by the fungus for use in conditioning the incoming air. The geometry of the enclosed storage would also tend to reduce the blower costs. These factors could result in substantial energy savings, especially during the winter months in northern climates.

No adverse effects of lignin-degrading fungi on humans have been reported in the literature. These fungi are natural wood decay fungi. However, we will be producing substantial amounts of fungus in a pile on a routine basis, and thus it should be tested. One of the chemical companies, which has agreed to produce and supply fungus to pulp and paper industry on a commercial scale, is currently engaged in this testing. Also, we do not expect any health or environmental hazards from the air emissions from the pile, but this has to be tested. Water runoff from the pile should also 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. Again, these are natural wood decay fungi; they are actually being used commercially to clean up chemically-contaminated soil.

## 10. Conclusions

After about 10 years of research, we 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 — increased throughput, and reduced pitch content and environmental impact — improve the economic picture for this technology even further. Current research is focused on extending the use of fungal pretreatments for kraft pulping, non-woody plants, and understanding the mechanism of biopulping.

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## References

[1] Lawson Jr LR, Still CN, Tappi J. The biological decomposition of lignin — literature survey, 1957;40(9):56A.

[2] Ander P, Eriksson K-E. Mekanisk massa fran forrotad flis-en inledande undersokning. Svensk Papperstid 1975;18:641.

[3] Eriksson K-E, Vallander L. Properties of pulps from thermomechanical pulping of chips pretreated with fungi. Svensk Papperstid 1982;85(6):R33.

[4] Johnsrud SC, Fernandez N, Lopez P, Guitierrez I, Saez A, Eriksson K-E. Properties of fungal pretreated high yield bagasse pulps. Nordic Pulp Paper Res J (Special Issue) 1987;2:47.

[5] Samuelsson L, Mjoberg PJ, Hartler N, Vallander L, Eriksson K-E. Influence of fungal treatment on the strength as a function of energy relationship in mechanical pulping. Svensk Papperstid 1980;8:221.

[6] Eriksson K-E, Ander P, Henningsson B, Nilsson T, Goodell B. 1976; US Patent 3 962 033.

[7] Eriksson K-E. Biotechnology in the pulp and paper Industry. Wood Sci Technol 1990;24:79.

[8] Eriksson K-E, Johnsrud SC, Vallander L. Degradation of lignin and lignin model compounds by various mutants of the white-rot fungus *Sporotrichum pulverulentum*. Arch Microbiol 1983;135:161.

[9] Akhtar M, Blanchette RA, Kirk TK. Advances in Biochemical Engineering/Biotechnology, vol. 57. Berlin: Springer–Verlag, 1997:127.

[10] Akhtar M, Blanchette RA, Myers GC, Kirk TK. An overview of biomechanical pulping research. In: Young RA, Akhtar M, editors. Environmentally Friendly Technologies for the Pulp and Paper Industry. New York: John Wiley & Sons, Inc, 1997.

[11] Akhtar M, Scott GC, Lentz MJ, Horn EG, Swaney RE, Kirk TK, Shipley DF. Meeting biological and engineering challenges during scale-up of biopulping. Biological Sciences Symposium. Atlanta, GA: Tappi Press, 1997. p. 35.

[12] Akhtar M, Scott G, Lentz MJ, Swaney RE, Kirk TK. Overview of biomechanical and biochemical pulping research. In: Eriksson K-E, Cavaco-Paulo A, editors. Enzyme Applications in Fiber Processing, American Chemical Society Symposium Series 687, Washington, DC, 1998:15–26.

[13] Kirk TK, Burgess RR, Koning Jr JW. Frontiers in industrial mycology. In: Leatham GF, editor. Proceedings of Industrial Mycology Symposium, June 25–26, 1990, Madison, WI, chapter 7. New York: Routledge, Chapman & Hall, 1992. p. 99.

[14] Kirk TK, Koning Jr JW, Burgess RR, Akhtar M, et al. Biopulping: a glimpse of the future? Res. Rep. FPL-RP-523, US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin, 1993, p. 74.

[15] Kirk TK, Akhtar M, Blanchette RA. Biopulping: seven years of consortia research. 1994 TAPPI Biological Sciences Symposium. Atlanta, GA: Tappi Press, 1994, p. 57.

[16] Messner K, Srebotnik E. Biopulping: an overview of developments in an environmetally safe paper-making technology. FEMS Microbiol Rev 1994;13:351.

[17] Diehl SV, Tappi J. Respiratory health problems associated with worker exposure to fungi on wood and wood chips, 1998;81:115.

[18] Akhtar M, Lentz MJ, Blanchette RA, Kirk TK, Tappi J. Corn steep liquor lowers the amount of inoculum for biopulping 1997;80(6):161.

[19] Scott GM, Akhtar M, Lentz MJ, Swaney RE. Engineering, scale-up, and economic aspects of fungal pretreatments of wood chips. In: Young RA, Akhtar M, editors. Environmentally Friendly Technologies for the Pulp and Paper Industry. New York: John Wiley & Sons, 1997.

[20] Scott GM, Akhtar M, Lentz MJ, Kirk TK, Swaney RE, Tappi J. New technology for papermaking: commercializing biopulping 1998;81:220.

[21] Scott GM, Swaney RE, Tappi J. New technology for papermaking: biopulping economics 1998;81:153.

[22] Farrell RL, Blanchette RA, Brush TS, Gysin B, et al. Cartapip™: a biopulping product for control of pitch and resin acid problems in pulp mills. In: Kuwahara M, Shimada M, editors. Biotechnology in Pulp and Paper Industry. Tokyo, Japan: UNI Publishers Co Ltd, 1992:27.

[23] Parham RA. Wood defects. In: Kocurek MJ, Stevens CFB, editors. Pulp and Paper Manufacture. Properties of fibrous raw materials and their preparation for pulping. Atlanta, GA: Joint Textbook Committee of the Pulp Industry, 1983:1.