

Deinking with enzymes: a review

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RECYCLED FIBER HAS BECOME AN important source of raw material for the pulp and paper industry. Besides being a low-cost fiber source for paper and board manufacturing, it preserves forest resources, reduces environmental pollution, and conserves water and energy. The use of secondary fibers has increased greatly over the last two decades, made possible largely by developments in deinking processes. Worldwide consumption of secondary fibers in 1995 was 110 million tons, and secondary fibers accounted for 37% of overall fiber consumption. This is likely to increase to 55% by the year 2000 (1). Worldwide deinking capacity is expected to rise to 31 million tons by 2001, with particularly large expansions for newsprint, printing, and tissue grades (2).

A significant difficulty in dealing with secondary fiber is the removal of contaminants, particularly ink. The difficulty of ink removal depends primarily on the ink type, printing process, and fiber type. Some paper grades, such as newspapers printed with oil-based inks, can be deinked with relative ease by conventional deinking processes. Nonimpact-printed papers are more difficult to deink (3), and the quantity of such papers continues to grow as a proportion of the total volume of recovered paper. Similarly, the crosslinking colored inks used in offset lithography are also difficult to remove. Color printing via offset lithography is expanding in the United States at an annual rate of 25% (4), a trend that other

countries are likely to follow. Water-based flexographic newsprint grades of paper can cause problems in conventional flotation deinking.

Mixed office waste (MOW) is the most difficult raw material to deink. A large portion of these fibers are printed using photocopiers and laser printers that fuse the ink to the fibers, making ink removal difficult by conventional methods. MOW is a large, virtually untapped source of high quality fiber that could be used for fine papers and many other products if the deinking process could be improved.

Clearly, ink removal remains a major technical obstacle to greater use of recycled paper. Many of the conventional deinking processes require large quantities of chemicals, resulting in high wastewater treatment costs to meet environmental regulations. Deinking processes are also substantial sources of solid and liquid waste. Disposal is a problem, and deinking plants would benefit from more effective and less polluting processes. Enzymatic deinking seems to be a novel solution to these problems. This article presents an overview of recent developments in the application of enzymes for deinking.

ENZYMES USED IN DEINKING

The enzymes that are useful for deinking include lipases, esterases, pectinases, hemicellulases, cellulases, and ligninolytic enzymes. Many patents for the use of enzymes in deinking have been granted or applied for (5). Most of the published literature

RECYCLING

ABSTRACT

Biotechnological processes are receiving greater attention as industry seeks to reduce its impact on the environment. In the pulping arena, enzyme-based deinking shows promise as a means of reducing chemical use and wastewater treatment. Brightness response to enzyme treatment varies considerably, but it often rivals or surpasses brightnesses obtained with conventional deinking processes. Residual dirt count for enzymatically deinked pulps is also generally lower. Additional benefits include higher freeness and greater paper strength. Results for pulp yield are inconclusive. While the potential of enzyme-based deinking appears to be quite good, further research in a few areas is needed to fully exploit the same.

Application:

An overview of recent developments in the use of enzymes for deinking.

on deinking deals with cellulases and hemicellulases.

Deinking involves dislodging ink particles from fiber surfaces and then separating the dispersed ink from the fiber suspension by washing or flotation. Enzymatic approaches involve either attacking the ink or fiber surfaces. Lipases and esterases can degrade vegetable-oil based inks. Pectinases, hemicellulases, cellulases, and ligninolytic enzymes alter the fiber surface or bonds in the vicinity of the ink particles, thereby freeing ink for removal by washing or flotation.

Nine different possible mechanisms for enzyme deinking have been reported in recent studies by Welt and Dinus (5). Korean researchers pointed out that enzymes partially hydrolyze and depolymerize cellulose between fibers, freeing them from one another (6).

Type of printing	Enzyme	BRIGHTNESS, % ISO	
		Enzyme treatment	Control
Black-and-white letterpress	Cellulase + hemicellulase	58	53
Black-and-white flexo	Cellulase	55	51
Colored flexo	Cellulase	51	46

*Based on data from Prasad (12).

I. Effect of enzymatic deinking on brightness improvement for ONP*

Enzyme	ENZYME DOSE/g pulp		Brightness, % ISO	Deinked pulp Residual ink area, %	Light-scattering coefficient, m ² /kg
	units (U)	mL			
Blank ^b	...	...	41	93	34.5
Control ^c	...	...	49	96	50.2
I ^d	0.2 ^h	0.033	52	77	70.5
II ^e	0.2 ^h	0.033	52	77	78.5
III ^f	100 ⁱ	0.500	53	65	75.8
IV ^g	19 ⁱ	0.033	54	79	69.9

^a Based on data from Prasad (13)

^b Reslashed pulp without enzyme treatment and no flotation

^c Reslashed pulp without enzyme treatment but with flotation

^d Enzyme preparation I contained 6 U/mL of carboxymethyl cellulase, 10 U/mL of xylanase, and 42 U/mL of filter paper activity.

^e Enzyme preparation II contained 6 U/mL of carboxymethyl cellulase, 6 U/mL of xylanase, and 1 U/mL of filter paper activity.

^f Enzyme preparation III contained 0.20 U/mL of carboxymethyl cellulase, 200 U/mL of xylanase, and 0.005 U/mL of filter paper activity.

^g Enzyme preparation IV contained 26 U/mL of carboxymethyl cellulase, 580 U/mL of xylanase, and 50 U/mL of filter paper activity.

^h Dosage based on carboxymethyl cellulose

ⁱ Dosage based on xylan

II. Effect of enzymatic deinking on optical properties of colored offset newsprint ^a

Ink particles are dislodged as the fibers separate during pulping. Researchers also believe that enzyme treatment weakens the bonds, probably by increasing fibrillation or removing surface layers of individual fibers (7). Woodward *et al.* (8) suggested that catalytic hydrolysis may not be essential, since enzymes can remove ink under nonoptimal conditions. Mere cellulase binding alone may be enough to disrupt the fiber surface to an extent sufficient to release ink during pulping. It is also reported that cellulases peel fibrils from fiber surfaces, thereby freeing ink particles for dispersal in suspension (7).

Enzymatic effects may be indirect, removing microfibrils and fines

and thereby improving freeness and facilitating washing or flotation (9). Fines content, however, is not always reduced during enzymatic deinking (10). Enzymatic treatment of nonimpact-printed paper has been reported to remove material from ink particles, thereby increasing particle hydrophobicity and facilitating separation during flotation (9). Mechanical action is supposed to be critical and a prerequisite to enzymatic activity (11), and some authors propose that it distorts cellulose chains at or near fiber surfaces, thereby increasing vulnerability to enzymatic attack. However, research conducted by Putz *et al.* (10) disputes the importance of mechanical action.

It is likely that a particular deinking system would involve more than one of these mechanisms. However, the relative importance of each mechanism would be dependent on fiber substrate, ink composition, and enzyme mixture.

DEVELOPMENTS IN ENZYME DEINKING

Several research groups have examined the application of enzymes in deinking different types of wastepapers. Low-pH cellulase and hemicellulase mixtures have been evaluated for deinking of letterpress and color offset-printed newsprint at pH 5.5 (12, 13). The highest brightness increase for letterpress paper was obtained with a hemicellulase preparation (xylanase), as shown in Table I. However, the lowest residual ink areas as measured via image analysis were achieved with a cellulase preparation, as seen in Table II. For colored offset papers (Table II), the best brightness was obtained with a mixture of cellulases and hemicellulases. These researchers also used similar enzymes to deink flexographic-printed newspaper (14, 15). Enzyme treatment and flotation removed the water-based ink with ease, resulting in brightness levels well above those obtained with conventional deinking (Table I).

When the hemicellulases from *Aspergillus niger* and cellulases from *Trichoderma viride* were evaluated for deinking, brightness increased with increasing enzyme dosage and reaction time (16). Soaking with enzyme before pulping was beneficial, but prolonged soaking reduced ink particle size, lowered flotation effectiveness, and reduced brightness. An optimal blend of cellulase and hemicellulase gave higher brightness gains than conventional deinking.

Regardless of ink type or printing process, enzyme treatment tends to reduce ink particle size. It has been reported that reduction in particle

size varied with pulping time in the presence of cellulases; overall reduction was greater than that noted in conventional deinking (6). Prasad *et al.* (12) and Rushing *et al.* (17) reported reductions in particle size from 16% to 37%, depending on ink type. So far, there is no credible explanation for this reduction in the size of ink particles.

Kim *et al.* (6) have reported that newspaper pulps bleached after being deinked by enzymatic and conventional means had similar brightness values. In the case of conventional deinking, hydrogen peroxide is used in the pulping as well as the bleaching step, but in the case of enzymatic deinking, hydrogen peroxide is used only in the bleaching process. Enzymatically deinked pulps were thus easier to bleach and required half as much hydrogen peroxide.

In a similar study with letterpress-printed newspaper, enzymatically deinked pulps had lower initial brightness values than conventionally deinked pulps (17). However, subsequent bleaching with hydrogen peroxide produced similar brightness values, with peroxide usage lowest for the enzymatic process. Putz *et al.* (10) reported that brightness levels obtained after bleaching enzymatically deinked offset-printed newspaper pulp were slightly higher than for pulp produced by conventional deinking with the same quantity of hydrogen peroxide applied during pulping.

The benefits of neutral cellulase for deinking MOW was exploited by a French group (18). Using a neutral cellulase as a post-treatment to a standard alkaline chemical treatment, they reported additional brightness and greater ink removal. Baret *et al.* (19) evidently did not consider the use of neutral cellulase without any other chemical pretreatment. This other alternative was investigated by researchers at the USDA's Forest Products Laboratory

(FPL) (9). They reported enhanced deinking of wood-free, nonimpact-printed wastepapers with cellulases (9, 20, 21). Not surprisingly, the neutral cellulases showed a benefit over the acidic cellulases, even when the pH of the MOW furnish was adjusted to the initial pH region with sulfuric acid (9). The deinking response observed by the FPL group required a relatively small amount of enzyme to achieve the optimum ink removal responses, although the dose-response curve reported by this group is unusual and has not been satisfactorily explained to date. Their pilot plant results agreed with the laboratory results for two enzymes (20). With one of the enzymes, the ink removal efficiency was 94% in the pilot plant compared with 96% in laboratory trials. Recently, they have reported that in continuous processing of 2300 kg batches of 100% toner-printed office papers, cellulases greatly reduce the residual particle count while increasing brightness and freeness (22). Strength properties and fiber length were essentially unchanged. A vendor (Novo-Nordisk, Denmark) also performed several lab flotation runs using a neutral cellulase (Novozym 342) that they had developed for use in deinking copier paper (23). The response in terms of brightness improvement was similar to that seen by FPL investigators.

Treatment with a pure alkaline cellulase significantly improved brightness levels of photocopied and laser-printed papers relative to pulping in water without enzymes (24). A brightness improvement of four ISO

units was observed, as seen in **Table III**. Residual ink area (dirt count) was reduced by 94%. Enzyme treatment also affected fiber length distributions. Such results might be expected, since these papers typically contain bleached softwood chemical pulp, and cellulases are more likely to affect fiber distributions of chemical pulps. Enzyme-treated pulps showed a similar increase in freeness and in strength properties (breaking length and burst index) relative to control pulps, as seen in Table III.

Heise *et al.* (25) reported the results of three industrial-scale trial runs to evaluate enzymatic deinking of nonimpact-printed toners. Increased ink removal was achieved using a low level of a commercially available enzyme preparation in combination with a surfactant. The brightness of enzymatically deinked pulp was two points higher than that of the control pulp. The enzyme trials also displayed improved drainage and comparable strength when compared with the control. No significant differences in the quality and treatability of the process water were noted, although the effluents from these trials had lower oxygen demand and toxicity than the effluents from the control.

Enzymatic deinking of mixed wastepapers (laser/xerographic-printed and UV-coated papers) and old newspapers/old magazines (ONP/OMG) eliminated or substantially reduced the use of chemicals in the deinking process (26). The brightness of enzymatically deinked MOW papers containing 90% laser

Treatment	Brightness, % ISO	Dirt count, mm ² /m ²	Freeness, mL CSF	Breaking length, km	Tear index, mN·m ² /g	Burst index, kPa·m ² /g
Blank	82.1	4200	400	6.5	8.5	4.55
Control	84.2	1200	440	6.2	7.9	4.38
Enzyme	88.3	70	490	6.8	8.0	4.75

*Based on data from Prasad (24)

III. Effect of enzyme treatment (pure alkaline cellulase) on MOW pulp quality*

copies, 3% colored paper, and 7% other papers was significantly greater than that for a MOW furnish deinked using the chemical method. Enzymatic deinking achieved a 94% lower dirt count (visible) as well as 82% lower total dirt count. The treatment of U.S. ONP pulp with a blended cellulase in a Korean newsprint mill also resulted in about a two point improvement in brightness (27). They also conducted a mill trial run to evaluate enzymatic deinking of white-ledger-grade paper pulp at one of the largest Korean tissue mills. The trial ran for several days, and the results showed a reduction of residual ink count. The total ink removal efficiency increased from 93.9% to 98.3% by using the blended cellulase deinking. Zeyer *et al.* (28) studied the performance of enzymes in deinking of ONP. Their results demonstrated that the arrangement of unit operations is of importance. No deactivation of enzymes by shear stress was observed. Statistical investigation of particles on handsheets demonstrated that many ink particles were likely still at their original location.

Novo researchers used monocomponent cellulases SP-476 and SP-613 to deink MOW (23). The response obtained using SP-476 was similar to that observed for the multicomponent cellulase preparation. Cellulase SP-613, on the other hand, demonstrated a dose response closer to what would be expected for a typical enzyme system. The concomitant increase of brightness and decrease in ink count helped confirm that the use of brightness as an assessment method could provide a rough measure of response in these systems. This study shows that the monocomponent portion of the multicomponent cellulase system plays a major role by enhancing deinking of the wood-free nonimpact-printed wastepapers.

Paper sizing and other additives can prevent or limit direct physical contact between enzyme and substrate. This inhibits the effectiveness of the enzymes, since contact is a prerequisite to activity. The implications of sizing effects have been studied by many researchers (11, 20, 28). The literature shows that paper sizing reduces enzymatic deinking efficiency and that the effect may vary with sizing agents. For nonimpact-printed papers, deinking efficiency was lowest for papers sized with rosin and alum (20). Such papers have the greatest resistance to wetting and the highest fiber hydrophobicity. Papers sized with alkyl succinic anhydride are less resistant to wetting but are almost as difficult to deink.

Alkaline lipases are claimed to facilitate the removal of oil based inks. Nakano (29) has reported that an alkaline lipase efficiently removed offset-printing inks. Enzymes that catalyze the removal of surface lignin may hold promise for deinking of newsprint that contains a proportion of lignin-rich mechanical pulp. This approach has been evaluated using white-rot fungi *Phanerochaete chrysosporium* and with lignin-degrading enzymes (30). Ink removal by a laccase preparation proved comparable with that of conventional chemical deinking. However, the enzyme-treated pulps showed higher brightness and were easier to bleach.

A novel deinking process that couples separation technology with cellulase treatment has been described by Woodward *et al.* (8). They reported that ink particles dislodged from newsprint, presumably by cellulase activity, readhered to smaller fibers originally present or created by enzymatic action. The smaller fibers and adhered ink were then separated from longer deinked fibers. The longer deinked fibers are usable without further treatment.

Since ink adhered to the shorter fibers, conventional washing or flotation would be unnecessary, and ink would not be released into the effluents. The reason for strong association between ink and short fibers could not be identified. The separation of such fibers is technically feasible (31).

Commercial use of enzymes for deinking has started recently in the United States (32). The Enzynk process developed at the University of Georgia by Eriksson's group is being commercialized. The process uses a mixture of enzymes in combination with surfactants and few other chemicals (33). The enzyme mixture is very much dependent upon the furnish used. This process is said to give higher brightness, lower dirt count, higher freeness, and less sludge compared with chemical deinking.

EFFECT OF ENZYME ON PULP AND PAPER PROPERTIES AND PULP YIELD

Enzyme-deinked pulp typically has higher brightness, greater freeness, and superior strength properties compared with chemically deinked pulp. Yang *et al.* (26) reported that the freeness of enzymatically deinked MOW pulp was 32% higher than that of control pulp. Heise *et al.* (25) and Prasad *et al.* (24) found that enzyme treatment significantly increased pulp freeness from 510 to 570 mL CSF and 440 to 490 mL CSF, respectively. Prasad *et al.* (13) observed that freeness increased in all the enzyme-treated samples compared with the control. The freeness increase varied from 50% for a cellulase-treated colored flexo-printed newsprint to 14% for black-and-white-printed newsprint treated with a hemicellulase preparation.

The runnability of enzyme-deinked pulp on paper machines was also found to be better. It is mainly the enhanced drainage and

Trial	ENTERING DAF CLARIFIER			EXITING DAF CLARIFIER			REJECT STREAM	
	BOD ₅ , mg/L		Total COD, mg/L	BOD ₅ , mg/L		Total COD, mg/L	Dissolved BOD ₅ , mg/L	Total COD, mg/L
	Total	Dissolved		Total	Dissolved			
Control	441	234	1080	298	275	510	219	440
Enzyme runs								
1	327	168	1190	192	165	565	210	427
2	258	138	1455	115	123	415	180	346

*Industrial-scale enzyme deinking of nonimpact-printed toners; based on data from Heise *et al.* (25)

IV. Quality of water entering and exiting the dissolved-air flotation clarifier and in the reject stream*

wet web strength that contributes to enhanced runnability. Baret *et al.* (18) claimed to see a physical property enhancement even when applying as much as 4 L cellulase per ton of pulp. A hemicellulase preparation showed the largest strength increase with the least improvement in freeness.

Results in terms of yield are inconclusive. Some yield reduction appears to result from losses of fines and other small particles resulting from the action of the applied enzyme. More precise control over enzyme dosages and reaction time are expected to minimize such losses. Kim *et al.* (6) have reported that reducing sugars were released during enzymatic deinking of old newspaper, but yield losses were immaterial. Relatively short reaction times were thought to have restricted enzyme attack of fibrils on fiber surfaces. In another study with ONP, sugar release increased with enzyme dosage and reaction time (16). Yield was reduced by 5%, but freed sugars did not explain all the loss. Microfibrils freed from fibers by enzymatic activity were said to have been lost during flotation. Even then, yields from enzymatic deinking were higher than those obtained from conventional deinking.

EFFECT OF ENZYMES ON EFFLUENT CHARACTERISTICS

Enzymatic deinking produces a white water with a lower chemical

oxygen demand (COD) than that from a conventional alkaline deinking process, thus reducing the load on wastewater treatment systems (26). Wastewater effluent from enzymatic deinking was reported to be 20–30% lower COD than wastewater from chemical deinking processes (6). Additional environmental advantages may accrue by avoiding the use of high alkalinity in the pulping stage (9). Another report indicated that the COD load after enzyme treatment was 50% lower than for conventional deinking (10).

The following observations regarding effluent characteristics are based on the results of Heise *et al.* (25), who reported on the industrial-scale enzyme deinking of nonimpact-printed toners. Process water entering the clarifier from the enzyme runs contained lower total and dissolved biochemical oxygen demand (BOD) and higher COD than that of the comparable control, as seen in Table IV. However, the dissolved-air flotation (DAF) cell readily clarified the process water, and the water exiting the DAF contained lower BOD and COD than the clarified control water, also shown in Table IV. The best quality reprocessed water was achieved with enzyme run 2, which was also the best trial for ink removal. Enzyme run 2 also had the lowest BOD and COD in the reject effluent stream, as seen in Table IV. There was no detectable difference in the BOD rate study of different

samples from each trial. Toxicity of reject streams was also comparable. However, if the conventional chemical control were used for comparison, the enzyme runs would undoubtedly be less toxic than the conventional run, as observed previously on effluents collected from bench-scale experiments (9, 21).

In deinking of offset newsprint, the COD load in the white water from the pulp suspension after reaction was lowest, 5 kg/ton of deinked pulp, when no chemicals were added (10). With the total chemical reference formulation, a COD load of 22 kg/ton was generated because of the alkaline pulping environment. However, for the enzyme-treated pulp, the COD load depends on the amount of enzymes as well as on the enzyme type. On average, the following CODs were obtained (10): 11 kg/ton for 0.2% enzyme addition and 20 kg/ton for 1.0% enzyme addition. Compared with the common alkaline deinking procedure, the COD load of a treatment with 0.2% enzymes was 50% lower.

ADVANTAGES AND LIMITATIONS

Conventional deinking is a chemical-intensive process that requires extensive wastewater treatment, which is expensive and becoming highly regulated. Enzyme-based deinking offers a potential means for reducing chemical use in the deinking process and thus reducing the load on wastewater treatment systems.

Conventional methods are relatively ineffective in deinking MOW, which presents technical and economic challenges to the paper recycler. MOW contains a wide variety of fibers and contaminants as well as toners and other nonimpact polymeric inks from laser-printing processes, which are the most difficult to deal with. Toners and laser-printing inks do not disperse readily during a conventional repulping process and are not readily removed during flotation or washing. Conventional deinking uses surfactants to float toners away from fibers, high temperatures to make toner surfaces form aggregates, and vigorous high-intensity dispersion for size reduction. Most of the deinking chemicals and high-energy dispersion steps are expensive. Microbial enzymes have been shown to enhance the release of toners from office wastepapers.

The size distribution and the shape of the ink removed can be effectively controlled using the enzymatic process to maximize the efficiency of the flotation process, which relies heavily on particle size. This can be accomplished by selectively varying enzyme composition, its dose and residence time, as well as variation of other additives and pH in the system to effectively dislodge the normally large, flat, and rigid ink particles into much finer and non-platelet forms. Enzymes may also retard redeposition of ink particles onto the fibers.

The most promising implication of high deinking efficiency from enzyme-enhanced deinking is that the dewatering and dispersion steps—as well as subsequent refloitation and washing—may not be essential. This should save capital expenses in construction of deinking plants while also reducing consumption of electrical energy for dewatering and dispersion.

The requirement of bleach chemicals is usually lower for enzymatic

deinking than for conventional chemical deinking. Reduced chemical use would result in lower waste-treatment costs while reducing the impact on the environment. Lower bleaching costs and less pollution can also be anticipated, since enzymatically deinked pulps have proved to be easier to bleach and require less chemicals than pulps deinked by conventional methods.

Enzymatically deinked pulp also displays improved drainage, superior physical properties, higher brightness, and lower residual ink compared with chemically deinked recycled pulps. Improved drainage results in faster machine speed, which yields significant savings in energy and thus overall cost. In addition, the use of recycled fiber reduces the need for virgin pulp. This results in great savings on the energy required for pulping, bleaching, refining, etc., which will also eventually reduce pollution problems.

Introducing enzymatic deinking technology in a mill-scale operation will necessitate extensive customization of the enzyme formulation and process variables to achieve optimal effectiveness. After extensive experience with U.S. mill-based trials (26), it is clear that the specific enzyme formulations will vary widely based on furnish, process water, equipment configuration, and the desired specifications of the deinked pulp. Moreover, an enzyme-based deinking process will naturally lead to a new chemical balance throughout the mill's entire water system. If enzymatic deinking is to be effectively introduced into the pulp and paper industry, the costs and risks of conversion must be minimized.

FUTURE PROSPECTS

It is clear that enzymes can facilitate deinking, but optimal process conditions have not yet been established. The areas needing further investigation include:

- Interaction of enzyme and fiber surfaces
- Synergistic effect between various enzyme components
- Effect of fillers, sizing agents, additives, ion strength, cationic species, and pH
- Effect of ink composition and printing process
- Methods to evaluate ink redeposition and factors affecting redeposition
- Point of enzyme application, consistency, and effects of shear forces.

Useful enzymes for deinking are now available in larger quantities and at lower cost than in the past. Production of specific enzymes in quantities sufficient for commercial use involves costly purification. However, increased usage and advances in fermentation and purification technology are expected to lower production costs. Alternatively, genetic engineering techniques can be used to identify the gene for a specific enzyme and transfer it to another organism, e.g., *Escherichia coli*, that normally does not produce the enzyme. Transfer and expression of cellulase genes have also been accomplished, and several vendors are now producing individual cellulases. The future may also see development of biomimetic catalysis. The compounds involved are simpler and have lower molecular weights than enzymes but maintain function and specificity. Such synthetic catalysts would be more stable in commercial deinking environments, thereby permitting wider application. **TJ**

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LITERATURE CITED

1. Dash, B. and Patel, M., *IPPTA* 9(1): 61(1997).
2. Uutela, E., *Paper Technol.* 32(10): 44(1991).
3. Vidotti, R. M., Johnson, D. A., and Thompson, E. V., *TAPPI 1992 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 643.
4. Urushibata, H., Japanese pat. 59-9299 (1984).
5. Welt, T. and Dinus, R. J., *Progr. Paper Recycling* 4(2): 36(1995).
6. Kim, T.-J., Ow, S., and Eom, T. J., *TAPPI 1991 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, Book 2, p. 1023.
7. Eom, T. J. and Ow, S. S. K., German pat. 3,934,772 (1990).
8. Woodward, J., Stephan, L. M., Koran, L. J., et al., *Bio/Technol.* 12: 905(1994).
9. Jeffries, T. W., Klungness, J. H., Sykes, M. S., et al., *Tappi J.* 77(4): 173(1994).
10. Putz, H.-J., Renner, K., Gottsching, L., et al., *TAPPI 1994 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 877.
11. Zeyer, C., Joyce, T. W., Heitmann, J. A., et al., *Tappi J.* 77(10): 169(1994).
12. Prasad, D. Y., Heitmann, J. A., and Joyce, T. W., *Progr. Paper Recycling* 1(3): 21(1992).
13. Prasad, D. Y., Heitmann, J. A., and Joyce, T. W., *Nordic Pulp Paper Res. J.* 8(2): 284(1993).
14. Heitmann, J. A., Joyce, T. W., and Prasad, D. Y., *Proceedings of Fifth International Conference on Biotechnology in the Pulp and Paper Industry* (M. Kuwahara and M. Shimada, Eds.), Uni Publishers, Tokyo, 1992, p. 175.
15. Prasad, D. Y., Heitmann, J. A., and Joyce, T. W., *Papiripar* 36(4): 122(1992).
16. Paik, K. H. and Park, J. Y., *Korea Tappi* 25(3): 42(1993).
17. Rushing, W., Joyce, T. W., and Heitmann, J. A., *Proceedings of Seventh International Symposium On Wood and Pulping Chemistry*, China TAPI, Beijing, 1993, p. 233.
18. Baret, J. L., Leclerc, M., and Lamort, J. P., "Enzymatic deinking process," *Intl. Appl. PCT DK91/00090* (1991).
19. Baret, J. L., Leclerc, M., and Lamort, J. P., U.S. pat. 5,364,501 (1994).
20. Rutledge-Cropsey, K., Jeffries, T., Klungness, J. H., et al., *TAPPI 1994 Recycling Symposium Proceedings*, TAPPI PRESS, Atlanta, p. 103.
21. Sykes, M., Klungness, J., Abubakr, S., et al., *TAPPI 1995 Recycling Symposium Proceedings*, TAPPI PRESS, Atlanta, p. 61.
22. Jeffries, T. W., Sykes, M. S., Cropsey, K. R., et al., *Proceedings of Sixth International Conference on Biotechnology in the Pulp and Paper Industry*, ÖZEP, Vienna, 1995, p. 141.
23. Franks, N. E. and Munk, N., *TAPPI 1995 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 343.
24. Prasad, D. Y., *Appita* 46(4): 289(1993).
25. Heise, O. U., Unwin, J. P., Klungness, J. H., et al., *TAPPI J.* 79(3): 207(1996).
26. Yang, J. L., Ma, J., and Eriksson, K.-E. L., *Proceedings of Sixth International Conference on Biotechnology in the Pulp and Paper Industry*, ÖZEP, Vienna, 1995, p. 157.
27. Ow, S. K., Park, J.-M., and Han, S.-H., *Proceedings of Sixth International Conference on Biotechnology in the Pulp and Paper Industry*, ÖZEP, Vienna, 1995, p. 163.
28. Zeyer, C., Heitmann, J. A., Joyce, T. W., et al., *Proceedings of Sixth International Conference on Biotechnology in the Pulp and Paper Industry*, ÖZEP, Vienna, 1995, p. 169.
29. Nakano, J., *Korea Tappi* 25(1): 85(1993).
30. Call, H. P. and Strittmatter, G., *Papier* 46(10A): V32(1992).
31. Floccia, L., *TAPPI 1988 International Pulp Bleaching Conference Proceedings*, TAPPI PRESS, Atlanta, p. 181.
32. Eriksson, K.-E. L., Commercialization of Enzykn process, personal communication, 1997.
33. Eriksson, K.-E. L. and Adolphson, R. B., *TAPPI J.* 80(6): 80(1997).