

LCA Case Studies

Environmental Assessment of Enzyme Assisted Processing in Pulp and Paper Industry*

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Abstract

Background Aims and Scope. The pulp and paper (P&P) industry is traditionally known to be a large contributor to environmental pollution due its large consumptions of energy and chemicals. Enzymatic processing, however, offers potential opportunities for changing the industry towards more environmentally friendly and efficient operations compared to the conventional methods. The aims of the present study has been to investigate whether the enzyme technology is a more environmentally sound alternative than the conventional ways of producing paper. The study addresses five enzyme applications by quantitative means and discusses the environmental potential of a range of other enzyme applications by qualitative means.

Methods. LCA is used as analytical tool and modelling is facilitated in SimaPro software. Foreground LCA data are production/company specific and collected from P&P technology service providers, specific P&P companies and P&P researchers. The background data on energy systems, auxiliary chemicals, etc. are primarily taken from the ecoinvent database.

Results. The study shows that fossil energy consumption and potential environmental impacts (global warming, acidification, nutrient enrichment, photochemical smog formation) induced by enzyme production are low compared with the impacts that they save when applied in bleach boosting, refining, pitch control, deinking, and stickies control.

Discussion. The general explanation is that small amounts of enzyme provide the same function as large amounts of chemicals and that enzymatic processes generally require less fossil energy inputs than conventional processes. Data quality assessments and sensitivity analyses indicate that this observation is robust for all processes except deinking, although the results are subject to uncertainty and much variation.

Conclusions and Recommendations. The environmental improvements that can be achieved by application of enzymatic solutions in the P&P industry are promising. To get a greater penetration of enzymatic solutions in the market and to harvest the environmental advantages of biotechnological inventions, it is recommended that enzymatic solutions should be given more attention in, for instance, 'Best Available Technology' notes within the framework of the European Directive on Integrated Pollution Prevention and Control (IPPC).

Keywords: Bleach boosting; deinking; enzyme assisted processing; integrated pollution prevention and control (IPPC); LCA; paper; pitch; pulp; pulp and paper (P&P) industry; refining, stickies

Introduction

Traditionally, the industrial use of biotechnology was mainly confined to fermentation processes in the food and beverage industry and the pharmaceutical industry. Over the past decades, however, biotechnology – including enzymatic processes – has gained ground from chemical processes in manufacturing in a variety of industrial branches (Ullmann's 2003). Being based on biological raw materials and biological processes, biotechnology offers potential advantages over traditional chemical processes in terms of environmental impacts and resource consumption. These potentials have been widely discussed in a variety of studies, surveys and forecasts, one important commissioner being OECD.

In the mid 1990s, OECD reported on the role of biotechnology in its capability to prevent, detect and remediate existing pollution (OECD 1994). In a subsequent study (OECD 1998), the focus changed from the perspective of removing pollutants to the possibilities for reshaping industrial processes and thus preventing pollution at the source. In the latest study (OECD 2001), the focus finally shifted fully to the biotech opportunities for more sustainable products and processes.

Other players have contributed to the environmental characterisation of industrial biotechnology. EuropaBio (2003) presents an overview to demonstrate the environmental aspects of biotechnology. The American Biotechnology Industry Association (2004) builds on OECD (2001) and expands its findings, primarily in relation to the US industrial sector, offering cases on pulp and paper (P&P), textiles, plastic, chemicals, fuels and pharmaceuticals. A recent study BREW (2006) focuses on the numerous opportunities presented by white biotechnology for the manufacture of organic bulk chemicals.

According to these studies, one of the most promising fields of industrial biotechnology is enzymatic biotechnology, i.e.

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the application of enzymes in industrial processing. Enzymes are biological catalysts with an enormous capacity to accelerate biochemical reactions and enable processes that would otherwise not occur under given conditions (Berg et al. 2002). Enzymes are produced industrially and used in a wide variety of industries, and due to their high specificity and efficiency they are often superior to their conventional alternatives in terms of raw material and fossil energy consumption and in terms of yield and the quality of the final product (Ullmann's 2003). All studies seem to agree that enzymatic processing is environmentally preferable to conventional processing, but a common characteristic is that most are based on qualitative judgements.

One exception to this is a technology foresight study by Jørgensen et al. (2006). This study reports a quantitative screening of eleven enzyme applications, comparing the overall energy consumption of systems involving enzymatic processing versus systems involving conventional chemical processing and providing the same overall functionalities. Furthermore, a limited number of individual LCAs on enzyme applications have been reported in the literature, generally supporting the environmental friendliness of the enzymatic alternatives: phytase and xylanase applied in pig production (Nielsen and Wenzel 2007, Nielsen et al. 2007b); laccase applied in bleaching in the P&P industry (Fu et al. 2005); protease/lipase applied in leather-making (Nielsen 2006); lipase applied in production of skin care products (Thum and Oxenbøll 2006) and phospholipase applied in degumming of soybean oil (Maria et al. 2007). The picture of the quantitative environmental characteristics of enzymatic processing in industry presented in the literature up to now is thus pieced together by relatively few enzyme applications.

Striving to establish a more exhaustive picture, a joint research effort has been initiated by the Technical University of Denmark and the enzyme producer Novozymes A/S comprising a number of master's and doctoral studies, and a range of commercial projects. This paper builds on a master's thesis by Skals and Krabek (2006) with the aim of systematically approaching an entire industrial branch, namely the pulp and paper industry, to investigate the environmental opportunities of enzymatic processing by quantitative means where data are available and by qualitative means where data are absent or incomplete.

1 Methods

The study addresses several present and potential enzyme applications in the P&P industry. Five applications that have been implemented in full-scale production or are at a mature pilot-scale stage are subjected to quantitative life cycle assessments.

Environmental assessment is based on the method developed by Wenzel et al. (1997) although Eco-indicator 95 v. 2.03 impact assessment factors are used in the characterisation step. Modelling is performed in SimaPro 6.0.4

A range of other enzyme applications, mostly at a more experimental stage, are subjected to qualitative environmental judgements. Full LCAs compare conventional and enzymatic solutions providing the same function in the P&P industry

and modelling refers to the changes that occur when enzymatic solutions displace conventional solutions. A marginal and market-oriented approach is taken in the study, and coproduct issues are handled by system expansion (Wenzel 1998, Weidema et al. 1999, Ekvall and Weidema 2004).

2 Scope

Functional unit. Quantitative environmental assessments refer to one ton of pulp or one ton of paper depending on the application. P&P processes with and without enzymes have been adjusted to meet the same quality standards for the final product (brightness, strength, etc.) and the considered enzymatic and non-enzymatic processes are considered directly comparable.

Geographical, technological and temporal scope. The study addresses modern P&P production in Northern Europe. Capital investments required for implementation of the considered enzyme processes are generally small compared with the savings and there are no long-term technical or economical bindings to the enzymatic processes. Consequently, the time perspective of the assessment is now and the coming few years, and the study addresses the changes that would occur now and in the near future if pulp and paper producers switched from conventional to enzymatic technology.

Impact categories. Potential contributions to global warming, acidification, nutrient enrichment, photochemical smog formation and use of fossil energy resources are addressed in quantitative assessments. Stratospheric ozone degradation is disregarded because it is considered insignificant in the system under consideration. Toxicity is addressed by qualitative means because the available data base is considered too incomplete for quantitative estimations. Industrial production of enzymes is to a large extent based on agricultural inputs (Nielsen et al. 2007a) and benefits achieved from energy and chemical savings may happen at the expense of agricultural land. Use of agricultural land has therefore been included in the assessment in terms of m²-year at the direct supplier acknowledging that this is a simplification (Kløverpris et al. 2007) which ignores the ultimate effects of agriculture (impacts on biodiversity etc.). Water is not a significant issue in the considered applications and has not been given attention.

2.1 System description

The main processes in the P&P industry are shown in Fig. 1, with indication of present and potential points of enzyme addition. Applications that are subjected to full LCAs are explained in Table 1. Information about changes induced by enzyme application in each process is based on literature, enzyme product sheets, and dialogue with service providers and Scandinavian P&P factories.

(1) **Bleaching of kraft pulp.** Wood contains lignin, a substance that needs to be removed to make bright paper qualities. The enzyme xylanase degrades xylans and opens up the hemicellulose structure of the wood fibres. Used in the treatment of kraft pulp, this facilitates the washing out of lignin from the pulp and makes the pulp more susceptible to bleaching chemicals in subsequent bleaching steps. The technique is called 'bleach boosting' (Olsen 2004) and significantly

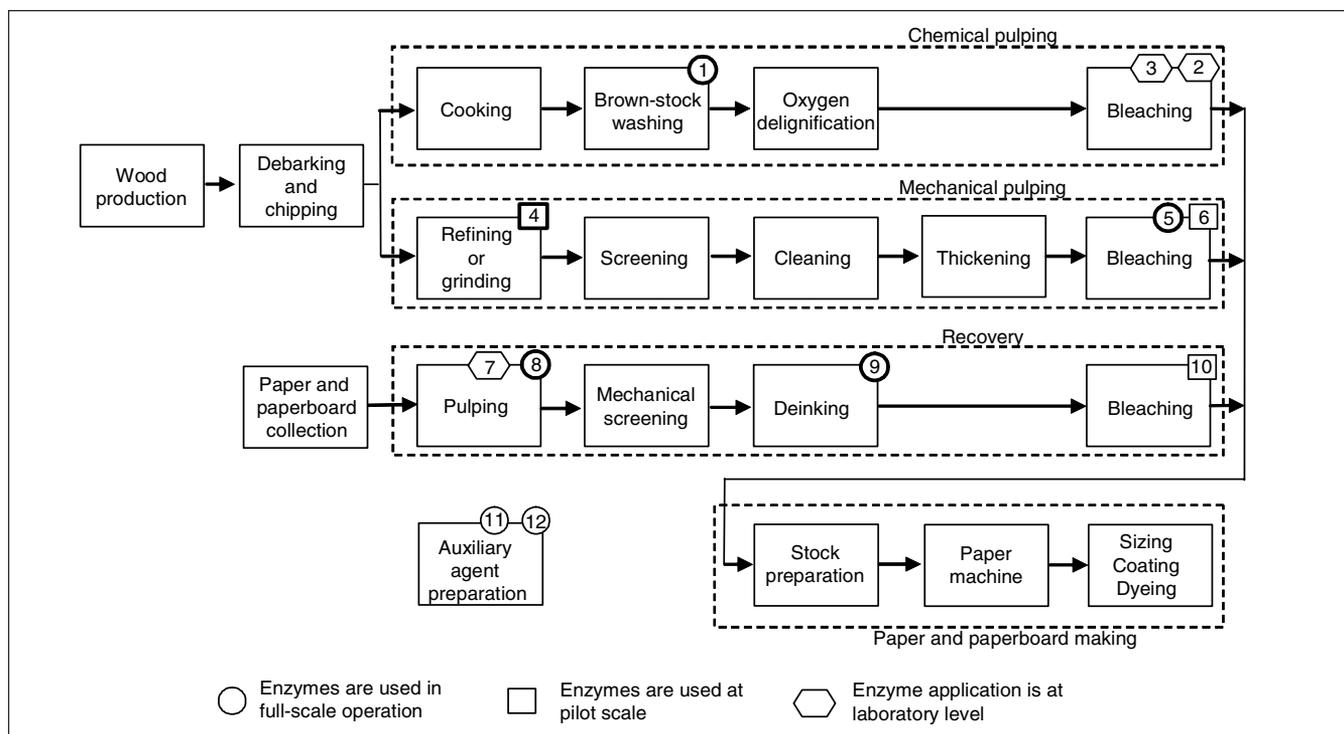


Fig. 1: Main processes in the pulp and paper industry with indication of present and potential points of enzyme application (to the authors' best knowledge). Enzyme applications highlighted in bold are subjected to full LCAs (see Table 1), while others are subjected to qualitative judgements (Table 5). Figures indicate where in the process the enzymes can be added

Table 1: Main characteristics of enzymes applied in various processes in the pulp and paper industry, and indication of changes in material and energy consumptions when enzymatic solutions replace conventional solutions. All quantities refer to air-dried tons (ADT). Quantities marked with + are added when enzymatic solutions replace conventional solutions (see left bar in Fig. 2), whereas quantities marked with minus are saved (right bar)

Process in P&P		Enzyme characteristics			Main changes induced by enzyme application			
#	Name	Trade name	Type	Function in PP	Compound	Unit	Quantity	Ref.
1	Bleach boosting of kraft pulp	Pulpzyme® HC	Xylanase	Saves bleaching chemicals by degrading xylans and enhancing lignin extraction	Pulpzyme HC NaOH (50%) ClO ₂	kg · t pulp ⁻¹ kg · t pulp ⁻¹ kg · t pulp ⁻¹	+0.75 -9.6 -3.7	1,2
4	Refining of TMP	Novozym® 476	Cellulase	Saves energy by softening cellulose fibres	Novozym 476 Steam (wood) ^a Electricity	kg · t pulp ⁻¹ kWh · t pulp ⁻¹ kWh · t pulp ⁻¹	+0.69 +150 -160	1,3,4
5	Pitch control of TMP	Resinase® HT	Lipase	Saves downtime and cleaning agents by hydrolysing pitch	Resinase HT Cleaning agent Talc Steam (wood) Electricity	kg · t paper ⁻¹ kg · t paper ⁻¹ kg · t paper ⁻¹ kWh · t paper ⁻¹ kWh · t paper ⁻¹	+0.3 -0.07 -3.5 -23 -11.4	1,5,6
8	Deinking	Novozym® 342	Cellulase	Saves conventional deinking chemicals by degrading cellulose and releasing ink	Novozym 342 ClO ₂ Alun NaOH (50%) NaHSO ₃ Urea H ₂ O ₂ (50%) Talc Retention aid	kg · t pulp ⁻¹ kg · t pulp ⁻¹	+0.55 +0.68 +0.65 -8.56 -2.6 -0.54 -3.7 -5.8 -1.1	1,7
9	Stickies control	Optimize®	Esterase	Saves chemicals and energy during downtime by hydrolysing PVAc	Optimize Solvent (unspec.) Talc Steam (fuel oil) Electricity	kg · t paper ⁻¹ kg · t paper ⁻¹ kg · t paper ⁻¹ kWh · t paper ⁻¹ kWh · t paper ⁻¹	+0.018 -0.025 -1.5 -20 -9.8	6,8,9

^a Heat from the refiner is used elsewhere in the factory and reduced heat output from the refiner as a result of enzyme application is compensated for by combusting wood chips.

References: 1: Novozymes (2001–2003), 2: Mathur et al. (2005), 3: Stora Enso AB (production data and estimates), 4: Pere et al. (2000), 5: Hata et al. (1996), 6: Dalum Papir A/S (production estimates), 7: Dalum Papir A/S (production records), 8: Patrick (2004) and 9: Buckmann Laboratories International Inc. (experience from application)

reduces the need for bleaching chemicals. Use of enzymes in this way can limit emissions of adsorbable organic halides (AOX) from the bleaching process, and this has been a main driver in the implementation of enzymes (Fu et al. 2005).

(4) **Refining of thermo-mechanical pulp (TMP).** Refining is a mechanical process in which wood chips are separated into free fibres. The process uses a large amount of electricity. The enzyme cellulase acts on cellulose in the wood fibres and softens the wood chips so that the necessary refining time can be shortened and electricity saved (Pere et al. 2000).

(5) **Pitch control of TMP.** Pitch deposits are a common problem in paper-making from TMP pulp because they lower the quality of the paper and destabilise the operation of the paper machine. Problems can be limited by seasoning the logs and by adding talc. However, the enzyme lipase is able to degrade the pitch, and enzymatic pitch control has gained acceptance at mill scale due to large cost savings resulting from reduced downtime (Chen et al. 2001 and Hata et al. 1996).

(8) **Deinking.** Ink on waste paper must be removed to prepare the fibres for use in new products. Conventional deinking requires large amounts of chemicals such as NaOH, NaSO₃, H₂O₂, etc. Cellulase acts on the cellulose of the fibres and facilitates the loosening of the ink from the fibre. Application of cellulose in the deinking process reduces the need for chemicals in the deinking process (Tandon et al. 2005).

(9) **Stickies control.** Stickies are one of the major obstacles in the manufacture of quality paper using recycled fibre sources (Fitzhenry et al. 2000). Stickies are agglomerates of glues with fibre bundles and other non-fibre material. Polyvinyl-acetate (PVAc) is a major sticky source. If the stickies are not removed, they can cause holes and paper breaks, which is costly because it leads to poor paper quality and machine stops for cleaning. The conventional approach to removing stickies is a combination of mechanical and chemical cleaning. An alternative method is to use the enzyme esterase, which hydrolyses the PVAc and eliminates the problem. Saving of costly downtime of the paper machine has been a driver for esterase application in several mills (Patrick 2004).

3 Data Collection and Modelling

Data on enzymes are determined by modelling individual enzyme products in accordance with Nielsen et al. (2007a),

Table 2: Quality assessment of data on displaced chemicals and energy plus indication of significance in LCAs of enzymes applied in the considered P&P processes. Good indicates that data are considered satisfactory in terms of representativity, age and completeness. • Contribution from the substance is significant ◦ Contribution is insignificant

Comp./utility	Quality assessment	1	4	5	8	9
		Bleach boost.	Refining	Pitch contr.	Deinking	Stick. contr.
NaOH	Good	•	–	◦	•	–
ClO ₂	Uncertain	•	–	–	•	–
Talc	Uncertain	–	–	◦	◦	◦
Alun	Uncertain	–	–	–	◦	–
NaHSO ₃	Uncertain	–	–	–	•	–
Urea	Uncertain	–	–	–	•	–
H ₂ O ₂	Good	–	–	–	•	–
Retention aid	Uncertain	–	–	–	•	–
Electricity	Good	• ^a	•	•	• ^a	•
Steam	Good	–	•	•	–	•

^a Indirectly via electricity consumption for ClO₂

although the marginal source of electricity has been switched from natural gas to coal (Behnke 2006). Modelling of coal-based electricity: ecoinvent (2005).

Data on used and saved chemicals and energy are derived from ecoinvent (2005). NaHSO₃ has been simulated with Na₂SO₄. Talc has been simulated with mausil. Allocation related to NaOH production has been avoided by system expansion as described in the following: NaOH is a coproduct of the chlorine-alkali process (2NaCl + 2H₂O ⇌ 2NaOH + Cl₂ + H₂). Chlorine demand determines production, and a reduced demand for NaOH induced by enzyme application in the P&P industry does not therefore affect the chlorine-alkali process, but rather the process that is displaced by the additional NaOH on the market. NaOH and Na₂CO₃ provide the same function (neutralisation) in several industries, and a market survey suggests that production of 1.3 kg Na₂CO₃ can be avoided per kg NaOH saved in the P&P industry (see Wesnæs and Weidema 2006), which has been applied in modelling. Modelling of Na₂CO₃ is based on ecoinvent (2005), although 100% of impact has been allocated to Na₂CO₃ because the marginal coproduct of CaCl₂ is assumed to be wasted (Weidema 2003).

The dominant marginal source of electricity is assumed to be coal in Northern Europe (Stem 2002, Behnke 2006), and modelling of coal-based electricity refers to ecoinvent (2005).

The transportation of enzymes and chemicals from suppliers to pulp and paper factories is assumed to be insignificant within the considered geographical boundaries (see Fu et al. 2005) and has been ignored.

3.1 Data quality assessment

Enzyme production: Modelling is based on detailed and updated information on raw material and energy consumption as well as waste handling. Modelling includes at least 95% (W/W) of the ingredients applied in production, and data on significant inputs are updated and representative. The data quality is therefore considered to be good (Nielsen et al. 2007a).

Assessment of the quality of data on displaced chemicals and energy is based on evaluations provided in ecoinvent (2005) plus evaluation of age and representativity in the present context. The results are summarised in Table 2 to

gether with information about significance for the final outcome of the study.

Table 2 shows that the assessment of the impacts of displaced chemicals is based on good-quality data for refining, pitch control and deinking, whereas uncertain data play a significant role in bleach boosting and deinking.

4 Results and Discussion

The results of the quantitative environmental assessments of enzyme application in bleach boosting, refining, pitch control, deinking and stickies control are shown in Fig. 2.

Fig. 2 shows that fossil energy consumption and considered environmental impacts induced by enzyme production are generally small compared with saved impacts resulting from avoided production of conventional chemicals and energy. The general explanation is that small amounts of enzyme provide the same function as large amounts of chemicals and that enzymatic processes generally require less energy inputs. The contribution of enzymes to nutrient enrichment is generally relatively high compared with other impacts; the reason for this is that enzyme production largely relies on agricultural products (Nielsen et al. 2007a).

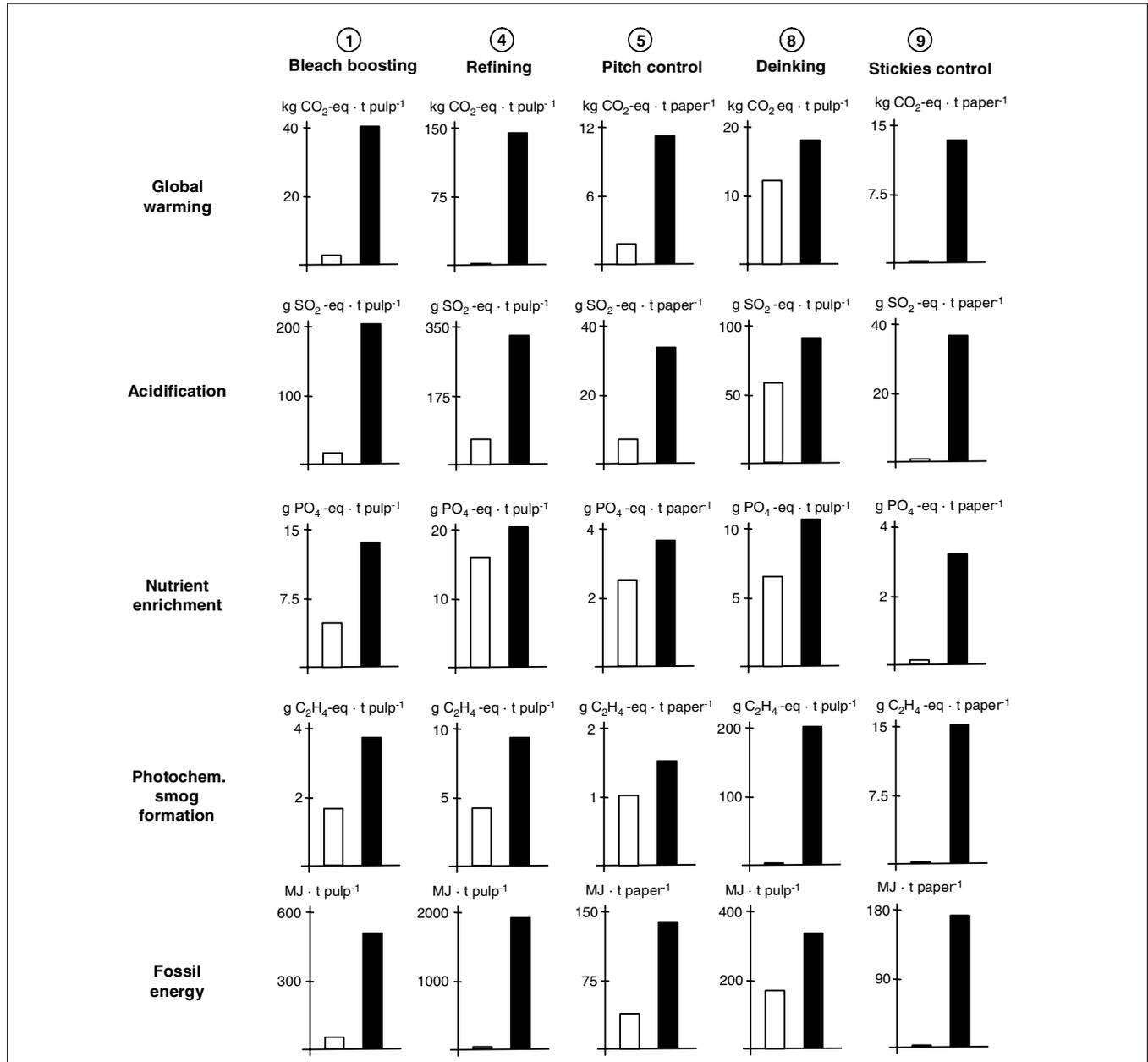


Fig. 2: Indication of induced (white bars) and saved (black bars) environmental impact potentials and fossil energy consumptions when enzymes are introduced in various processes in P&P production. Induced impacts and resource consumptions are due to enzyme production and production of additional auxiliary agents applied in the enzymatic process. Saved impacts and energy consumptions are due to chemical, heat and electricity savings. Different reference unit are applied for different processes in P&P production, and direct horizontal comparison of results should be avoided. Process numbers refer to Fig. 1. Pulp and paper quantities: ADT

Bleach boosting. Pulpzyme HC saves NaOH and ClO₂ in the bleaching process. A relatively large amount of electricity is used for producing ClO₂, and this explains about 90% of avoided energy consumption and contribution to global warming. Avoided contribution to acidification is to some extent also explained by avoided emissions of SO₂ during the production of sulphuric acid used in ClO₂ production. Pulpzyme HC is formulated in propylene glycol, and emission of volatile organic compounds (VOCs) during production explains a relatively high contribution to photochemical smog formation from enzyme production. Avoided contribution to toxicity from AOX resulting from reduced ClO₂ application is an important environmental advantage of enzymatic bleach boosting that has not been quantified here. Even though data on ClO₂ are considered rather uncertain (see Table 2), the observed advantage of enzyme application is considered clear because the influence of ClO₂ is limited and the saved impacts are well above induced impacts. Fu et al. (2005) found that the application of enzymes (laccase) in the bleaching process had a negative impact in terms of greenhouse gas emissions and contributions to summer smog compared with the conventional process. This outcome was explained by long-distance air transport of a mediator that is required for the laccase-based process. The present study addresses bleach boosting with xylanase enzyme (a completely different mechanism), which is independent of external mediator supplementation. This explains the different outcomes of the two studies and indicates that the xylanase-based bleach boosting process considered in this study is environmentally superior to the laccase-based process.

Refining. A small amount of Novozym 476 saves a considerable amount of electricity in the secondary refiner and in the reject refiner. Heat from the refiner is used elsewhere in the factory, and reduced heat output from the refiner is compensated for by combusting additional wood chips (which would otherwise be wasted). Combustion of wood chips does not add to fossil energy consumption and does not contribute to global warming, and this explains why the advantages of enzyme application are greater for these two impact categories than for acidification, nutrient enrichment and photochemical smog formation.

Pitch control. Environmental gains achieved by Resinase HT application in pitch control are primarily explained by fossil energy saving. Chemical savings are of minor importance. The application of propylene glycol as a formulation agent explains a relatively large contribution to photochemical smog formation from enzyme production, as explained for Pulpzyme HC above.

Deinking. The application of Novozym 342 together with small amounts of ClO₂ and alun in the deinking process saves a considerable amount of other chemicals (see Table 1). The environmental impacts induced by the enzyme and the additional chemicals (particularly ClO₂) are smaller than saved impacts resulting from chemical savings, and overall it seems that there is a net environmental advantage in enzyme application, even though the assessment is largely based on uncertain data on chemical inputs (see Table 2). A considerable amount of volatile organic compounds (VOCs) is emitted during production of the retention aid, and saving

of retention aid explains the large advantage of the enzymatic solution in terms of photochemical smog formation.

Stickies control. A very small amount of Optimyze can reduce the frequency of production stops as a result of stickies and thus save considerable amounts of electricity and steam consumed in stopping and starting production equipment. Environmental impacts induced by enzyme production are very small compared with the avoided impacts from steam and, particularly, electricity production, and this explains the large environmental advantage of enzyme application. Furthermore, solvent savings contribute to a reduced contribution to photochemical smog formation because less VOCs are emitted during production and use.

Land use. Industrial enzymes are to a large extent based on agricultural crops and the environmental achievements observed in Fig. 2 are at the expense of agricultural land because the savings are limited to fossil energy and inorganic chemicals (see Table 1). The CO₂ reduction efficiency of the considered enzyme applications is, however, high (Table 3) compared with direct biomass-to-energy technologies (2 ton CO₂·ha⁻¹·year⁻¹ (bio-diesel as alternative to conventional diesel) to 23 ton CO₂·ha⁻¹·year⁻¹ (energy crop as alternative to coal in electricity production), WTW 2006)), and the use of agricultural land is considered environmentally efficient in any of the considered cases.

5 Sensitivity Analyses

A large number of sensitivity analyses have been performed in order to assess the significance of applied assumptions and the robustness of the obtained results. The most important outcomes are summarised below.

Electricity consumption plays an important role in enzyme production (Nielsen et al. 2007a) and in all the applications under consideration (see Table 2). It is assumed in the base case that marginal electricity is based on coal, but it cannot be excluded that natural gas plays a role in the marginal mix or that natural gas will become the dominant marginal supplier in the future. All enzyme applications have therefore been assessed with natural gas as the marginal source of electricity. The results show that the environmental advantages of enzyme applications are reduced for bleach boosting, refining, pitch control and stickies control (because more electricity production is saved than induced in these

Table 3: Estimates of agricultural land use for producing enzymes for processing one of ton pulp or paper plus CO₂ saving efficiency in terms of avoided CO₂ emission in pulp and paper production per ha of agricultural land applied for enzyme production. Process numbers refer to Fig. 1

Process in P&P		Agricultural land use (m ² ·year)	CO ₂ -saving efficiency (ton CO ₂ ·ha ⁻¹ ·year ⁻¹)
#	Name		
1	Bleach boosting of kraft pulp	0.31	1200
4	Refining of TMP	0.54	2700
5	Pitch control of TMP	0.14	630
8	Deinking	0.22	290
9	Stickies control	0.013	11000

cases), whereas it is increased for deinking (because electricity production is mostly induced in this case). Overall, however, the considerable environmental advantage of enzymatic processes observed in the base case remains clear.

Steam supply in refining. It has been assumed in the base case that reduced output of heat from the refining process as a result of enzyme application is compensated for by increased steam production from wood chips. The extent of energy recovery from refining and the source of marginal heat supply can vary from factory to factory, and three sensitivity analyses have been carried out: 1) no energy recovery from refining and 2) compensatory heat based on a) natural gas and b) fuel oil (instead of wood chips). Use of natural gas/fuel oil instead of wood chips increases induced fossil energy consumption and contributions to global warming considerably, but this is from a very low level and enzyme application remains a clear environmental advantage. Heat recovery from the refining process reduces the advantage of enzyme application, and the elimination of steam recovery stresses the environmental advantage of enzyme application.

Steam supply in stickies control. It has been assumed that avoided steam is based on fuel oil, but other sources of heat could also be relevant. A sensitivity assessment of heat supply shows that the use of enzyme is a clear environmental advantage even if heat displacement is disregarded (avoided heat = 0), confirming that enzyme application is environmentally advantageous irrespective of the heat source.

Enzyme dosage depends on a range of conditions, and recommended dosages are always provided as quite broad ranges (Novozymes 2001–2003). The base case of the study has referred to the average of recommended dosages, and it has been assessed how results would change if the higher and lower end of the recommended dosages were applied. As one might imagine, reducing enzyme dosage increases the environmental advantage of enzyme application and vice versa. However, enzyme usage remains a clear environmental advantage also in all high-enzyme-dosage scenarios.

The **sequence of bleach boosting processes** varies from factory to factory, and the effects of enzyme application have been assessed in two additional bleach boosting scenarios with varying process sequence and identical brightness requirements. The effect on induced and saved environmental impact is considerable, but enzyme application remains a clear environmental advantage in any case.

NaOH is used in quite large quantities in bleach boosting and deinking. Dealing with coproducts in chlorine/NaOH production is a classic issue in LCA, and a sensitivity assessment in which allocation is based on mass (ecoinvent 2005) has been performed. The impact of mass-allocated NaOH is generally somewhat greater than the impact of NaOH modelled by system expansion (as in this study), and a change from 'system-expanded NaOH' to 'mass-allocated NaOH' stresses the environmental advantages of enzyme application in the bleach boosting and deinking processes.

Transport has been ignored because it is considered insignificant within the geographical framework under consider-

ation. Sensitivity assessments have justified that, even in cases where it is envisaged that enzymes are transported thousands of kilometres and displaced chemicals are only transported for instance one hundred kilometres (truck, ecoinvent 2005), the environmental advantage of enzyme application remains clear. The most sensitive environmental parameter is photochemical smog formation, and the most sensitive process is deinking because enzyme has a significant influence on chemical consumption in this process.

6 Qualitative Toxicity Assessment

Toxicity has not been included in the quantitative assessment because details of the emissions of relevant substances and the fate of these after emission in large parts of the system are not known. However, processes that are considered likely to contribute to toxicity have been assessed qualitatively, leading to the following judgements: For all applications except deinking, it is considered likely that enzyme application considerably reduces the contribution to toxicity because relatively small amounts of readily biodegradable and low-toxic enzyme products arising from the low-toxic biological production process and a range of low or non-toxic raw materials replace relatively large amounts of toxic chemicals (see Table 1) and save relatively large amounts of energy (see Fig. 2). Enzymatic deinking also saves considerable amounts of aggressive chemicals (NaOH, NaHSO₃ and H₂O₂), but since the process requires ClO₂ and alun in addition to the enzyme (see Table 1), toxicity cannot be assessed by the simple qualitative means above.

7 Conclusions

The present study shows that fossil energy consumption and potential contribution to global warming, acidification, nutrient enrichment and photochemical smog formation induced by enzyme production are low compared with the impacts that they save when applied in bleach boosting, refining, pitch control, deinking and stickies control. Qualitative assessments indicate that toxicity induced by enzyme application is low compared with saved toxicity as well, but this has not been documented. Enzymes are to a large extent produced from agricultural products and fossil energy savings and environmental improvements are at the expense of land use. The considered enzyme applications are, however, efficient in terms of CO₂ avoidance per ha of agricultural land applied compared with direct biomass-to-energy technologies and agricultural land use is environmentally efficient in any of the considered cases. Data quality assessments and sensitivity analyses indicate that the above observation are robust for all processes except deinking, although it is acknowledged that the results are subject to much variation and uncertainty. The assessment of enzyme application in the deinking process relies on uncertain data and the results are considered less robust.

9 Recommendations and Perspectives

The relative environmental improvement potential of the five enzyme applications with respect to global warming is esti-

Table 4: Estimates of relative improvement potential in terms of avoided contribution to global warming from using enzymes in various processes in pulp and paper industry. Contributions to global warming from reference products: ecoinvent (2005). Quantities of pulp and paper: ADT. Process numbers refer to Fig. 1

Process in P&P		Avoided contribution to global warming	Reference product	Relative improvement potential
#	Name			
1	Bleach boosting of kraft pulp	37 kg CO ₂ -eq · ton pulp ⁻¹	One ton conventionally bleached pulp (inc. wood production etc.)	7%
4	Refining of TMP	145 kg CO ₂ -eq · ton pulp ⁻¹	One ton TMP (inc. wood prod. etc.)	22%
5	Pitch control of TMP	8.7 kg CO ₂ -eq · ton paper ⁻¹	One ton paper from 100% TMP (inc. wood prod. etc.)	0.7%
8	Deinking	6.4 kg CO ₂ -eq · ton pulp ⁻¹	One ton recycled paper (inc. paper collection and sorting)	0.4%
9	Stickies control	13 kg CO ₂ -eq · ton paper ⁻¹	One ton recycled paper (inc. paper collection and sorting)	0.8%

Table 5: Enzyme applications subjected to qualitative environmental assessments. Process numbers refer to Fig. 1

Process in pulp and paper industry		Enzyme characteristics		
#	Name	Type	Function in P&P	Ref.
2	Peroxide removal	Catalase	Increases lifetime of production equipment by preventing corrosion (removal of H ₂ O ₂)	1
3	Fibre modification	Laccase, Cellulase	Increases strength of the paper	2,3
6	Anionic trash control	Pectinase	Saves retention aids and energy for drainage by degrading pectin	4
7	Starch removal	Amylase	Saves deinking chemicals by improving deinking efficiency	5
10	Drainage improvement	Cellulase, Hemicellulase	Saves energy for drainage by improvement of secondary fibres' fibril structure	6
11	Starch preparation	Amylase	Preparation of starch for coating by starch modification	7
12	Slime control	Protease	Reduces biocide consumption by degrading bacteria's link to surfaces of fibres	8,9

References: 1: Tong et al. (1999), 2: Lund and Felby (2001), 3: Kenealy and Jeffries (2003), 4: Ricard et al. (2004), 5: Pedersen et al. (2003), 6: unpublished note (Novozymes A/S), 7: Kearney (2003), 8: Haute (1999), 9: Simons et al. (2003)

mated in Table 4. Estimates are based on literature data on pulp and paper production (ecoinvent 2005) and results on global warming in Fig. 2. The results should only be seen as quite rough indications (particularly for refining) because impacts of pulp and paper production and effects of using enzymes depend on raw material basis, mill set-up etc. and are subject to variation. Table 4 indicates large relative environmental improvement potentials of enzyme use in bleaching and refining of pulp and moderate relative improvement potentials in deinking and pitch/stickies control. The explanation is to some extent that reference products are different.

Enzymes can be used in a broad range of processes in the P&P industry, and several are still under development, as indicated in Fig. 1. Table 5 provides an overview of the enzyme functions that have not been included in the quantitative environmental assessments in this study.

Table 5 shows that there is a considerable potential for further implementation of enzymes in the P&P industry and that many applications have a potential for environmental improvement because they save production equipment, raw materials, chemicals and/or fossil energy.

The penetration of enzymatic processes in the P&P industry is still limited. The main drivers for the acceptance are

usually problems with compliance with governmental regulations and downtime of pulp and paper machines that cannot be resolved with conventional methods. The main barriers for acceptance of enzymatic processes in the P&P industry are that too few are playing a role in the promotion of new technology, service providers being the most important.

To achieve greater penetration of enzymatic solutions in the market and to harvest the environmental advantages of biotechnological inventions, it is important to create more awareness of the potential of enzyme technology in the P&P industry, for instance by integrating enzymatic production methods in the relevant Best Available Technology (BAT) notes within the framework of the European Directive on Integrated Pollution Prevention and Control (IPPC) as experience of full-scale production increases.

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