BIOTECHNOLOGY IN THE PULP AND PAPER INDUSTRY:

8TH ICBPPI MEETING

Edited by

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8th ICBPPI Meeting

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Preface

Biocatalysts have significant potential for improving traditional pulp and paper manufacturing processes, achieving environmental benefits and introducing unique properties to the fibre raw materials. The general goals of pulp and paper industry today are to increase the cost efficiency, to develop environmentally benign processes and to improve the product quality. Fibre raw materials can be modified by enzymes or micro-organisms to improve chemical or mechanical process steps in pulp and paper manufacture. The challenge for commercial success is to identify superior enzymes and microorganisms and develop their applications. Advances in molecular genetics have already enabled the production and application of several new enzymes in industrial scale. In some applications, however, the identified enzymes represent products of the first generation, which may not act optimally under the harsh industrial conditions. The catalytic activity and stability of potential enzymes can further be improved by new powerful methods, such as directed evolution. During the last years the number of new applications of enzymes in pulp and paper manufacture has grown steadily, and several have reached or are approaching commercial use. These include enzyme-aided bleaching with xylanases, direct delignification with oxidative enzymes, energy saving refining with cellulases, pitch reduction with lipases, freeness enhancement with cellulases and hemicellulases as well as enzymatic slime control of the paper machine. In addition to enzymes, microbial treatments are potential for increasing pulping efficiency, reduction of pitch problems and enhancing process water reuse. This book is based on the written versions of selected papers presented at the 8th International Conference on Biotechnology in the Pulp and Paper Industry, held in Helsinki in June 2001. The conference gathered 300 participants from 31 countries. It fulfilled well its commission as a forum for scientists and technologists to meet, share their views and discuss the future lines of biotechnical research. About 200 participants represented universities and other public research organisations, the rest coming from enzyme companies and pulp and paper industry. European Union was powerfully presented. Experts from 12 member countries participated in the conference.

We wish to acknowledge the European Union, 5th Framework Programme, Quality of Life and Management of Living Resources, the European COST Organisation, the Academy of Finland, the TAPPI, as well as the Finnish Forest Industries Association for their financial support. In addition, we wish to thank AB Enzymes Finland, Genencor, Hercules, Iogen and Novozymes for sponsoring the conference. We also want to thank all the writers for their excellent contribution and members of the International Programme Committee for planning and acting as reviewers of publications of this book.

We hope that you enjoy this book.

Espoo, 15.12.2001

Liisa Viikari

Raija Lantto

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Trends in pulp and paper biotechnology

L. Viikari

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During the last decade new techniques and innovations in biotechnology have been overwhelming. Not only have the new developments in molecular biology made the production of new bulk enzymes economically feasible and enabled the design of improved enzymes, but also allowed us to understand the genetic background of biosynthetic and metabolic routes more thoroughly. The new methods include genomics, proteomics, metabolomics and bioinformatics. In the light of these developments, pulp and paper area should represent a huge market potential for engineering raw materials and biocatalysts. The key questions are, how the new techniques could be applied in the pulp and paper sector, and what the new breakthroughs will be.

This book is based on selected papers presented in the 8th International Conference on Biotechnology in the Pulp and Paper Industry. Within the last two decades, this triannual conference has become the major forum for reviewing latest achievements in the field. The need for an international forum was originally recognized by the European Liaison Committee for Pulp and Paper (EUCEPA) in 1980, and the first conference was held in 1981 in Canada. During the last decade, each of these meetings has attracted about 250-300 participants from all over the world. This series of meetings covers both basic and applied sciences in a rather specified area. The basic science of lignocellulose enzymology and plant genetics is covered also in many other meetings, whereas the application of biotechnology in process and product development is uniquely reviewed in the ICBPPI meetings.

The needs of the industry to find biotechnical solutions have obviously changed. Today, the general goals of pulp and paper industry are to increase the cost efficiency, to develop environmentally benign processes and to improve the product quality. Biotechnical methods can help to reach these goals, but seldom solve problems alone. The chlorine issue was hot in the late 1980s, raising the search for environmentally benign bleaching technologies. This was obviously the first time in the history of the pulp and paper sector that the consumers' attitudes started deeply to affect the design of industrial processes. Since then, also other technologies, offering environmental advantages, have been developed. These methods compete with biotechnology. To some extent, the competitive advantage of intrinsically cleaner biotechnical processes has diminished. The uniqueness and specificity of biocatalysts offering solutions also for new product design has, however, become even more relevant.

Due to the fast development of new methodologies within biosciences, it is often difficult to judge the competitiveness and economical viability of biotechnical approaches at an early phase. The unforeseeable potential for improvement, generally typical for biotechnical processes, is a relevant argument often presented. It has, however, been observed that the time needed for commercial breakthroughs is unpredictable. Thus, any interesting observation or result achieved may be a starting point for a future success story.

Raw materials

Forest trees are one of the world's most important natural resources. Fast growing trees with low lignin content could provide significant practical benefits. Removal of lignin from the wood cell walls is the most capital intensive and environmentally problematic step in wood processing for pulp and paper. Significant advances in understanding the genetic background of lignin biosynthesis have already been achieved. The genome of major tree species will be sequenced within the coming years. This will slowly lead to improved understanding of the genetic background of various traits, and allows exploration of this knowledge for designing future raw materials for various industries. Any increase of efficiency that allows production of more wood and wood products would help to conserve the natural forests and reduce the environmental impact of processing wood into pulp and paper products. There is still, however, a long way to practical exploitation of these improvements. The future exploitation of genetically modified forest trees will depend on the answers given to the scientific and ethical questions, as well as on the dialogue and consensus reached between industry and the public, especially in Europe. However, basic understanding on the biosynthetic mechanisms of wood components and fibres will help to improve fibre quality even by traditional breeding technologies already used in forestry. In connection with the 8th ICBPPI meeting, a special presymposium was arranged to cover more comprehensively the basic sciences of lignin biosynthesis and biodegradation. Thus, this area, including the latests advances in plant genetics, is not included in this special issue.

Before tackling the raw material quality genetically, the intermediate methodology involves utilization of microbial and enzymatic pretreatment technologies. The most recent results on biopulping technology have shown that the process appears to be economically feasible for mechanical pulp production. Results on benefits achievable by microbial pretreatments for chemical pulping are more contradictory.

Enzymes

Most of the biotechnical applications proposed for pulp and paper industry are based on the use of enzymes. The modifications in fibre material, which can be achieved by enzymes or micro-organisms, have so far been combined with chemical or mechanical treatments. The real challenge for new commercial successes is to identify superior enzymes and their applications. The specificity of enzymes makes them unique tools for targeted modification of specific components of fibres and their catalytic nature makes them efficient even in small dosages. The limitations of the use of enzymes in pulping and papermaking processes are related to the size and properties of the enzymes. The enzymatic action is limited to accessible surfaces of the fibre matrix due to the macromolecular size of enzymes, a fact that has been successfully exploited in the surface analysis of pulp fibres. The inactivation and destruction of protein structure of enzymes in conditions used in many process stages in pulping and papermaking has led to the development of separate enzymatic pretreatments rather than process stages. This concept allows to adjust the conditions more suitable for the enzymes, but does not exclude the constant need for morestable enzymes. The laccase-mediator bleaching concept which aims at direct delignification of pulp would be the first truly enzymatic process phase, enabeling replacement of current bleaching chemical stages such as oxygen or ozone stage.

The enzymatic degradation of lignocellulosic material includes a set of different enzymes. Cellulases have been studied intensively already for decades and the reaction mechanisms of key enzymes have been revealed on molecular level. In spite of the long history, new interesting enzymes are still being found, such as the swollenins and expansins. The various potential uses and effects of cellulose binding domains attract constant interest. The prices of commercial cellulases have decreased several fold due to improved production technologies, and further improvements can be expected. The enzymology of hemicellulases is also well established with the same general trends. Except for xylanases, few applications based on other hemicellulolytic enzymes have been found. Further improvements are expected especially in functionality at extreme conditions. Following the commercial success of hydrolytic enzymes, oxidoreductases are now emerging as the next enzyme generation. Oxidative enzymes have great potential in many applications and first commercial products have been launched. Efficient secretion of oxidoreductases has turned out to be problematic. Detailed mechanistical studies of oxidoreductases have been performed on model substrates, but the reactions on insoluble substrates have not yet been elucidated. There are still many aspects that should be understood in order to improve their performance. The concept of using oxidative enzyme with electron transfering mediator molecules opens up new possibilities for enzyme based oxidation and delignification technologies.

Applications

It is interesting to observe the changing interests in the applied field during the two last decades. A simple statistical analysis based on the oral and poster presentations of the applied research in ICBPPI meetings held in 1983-2001, reveals that a number of approaches seem to attract rather constant interest, such as the biopulping and delignification by enzymes. This study does, however, not include the basic scientific papers which have rather constantly covered cellulolytic, hemicellulolytic and ligninolytic enzymes. The continuing intrerest on some areas reflects the complexicity of the problem and to some extent the failure of commercial breakthrough of the applications. It is noteworth that at present, no single area seems to be dominating. The trends, however can be clearly seen (Fig 1.)

Obviously, the most challenging applications are related to delignification, the basic process step in the production and bleaching of chemical pulps. The interest in lignin degrading enzymes is still remarkable, and continuing scientific efforts are needed for success also in larger scale. On the contrary, applications which have been commercialized naturally attract less interest of the scientific community. Sometimes commercialization slows down further improvement which could be reached by pertinent scientific exploration. The exact mechanisms and scientific basis for some applications still remain unsolved, like in the case of the hemicellulase-aided bleaching.

It will be interesting to see, how the commercialization of biomechanical pulping will proceed. The biopulping concept is one of the longest-term efforts for applying biotechnology in the pulp and paper industry. The development of microbial treatments of wood chips for biopulping purposes or for management of pitch problems is still an interesting issue worldwide. If the problems related to specificity and performance of micro-organisms and technical implementation of the treatment into mill scale processes will be solved, the microbial pre-treatment of chips will be a very tempting method to modify fibres prior to pulping process. Some areas, such as waste water purification have found their own specialized forums, and have not been central interest areas since 1980s.

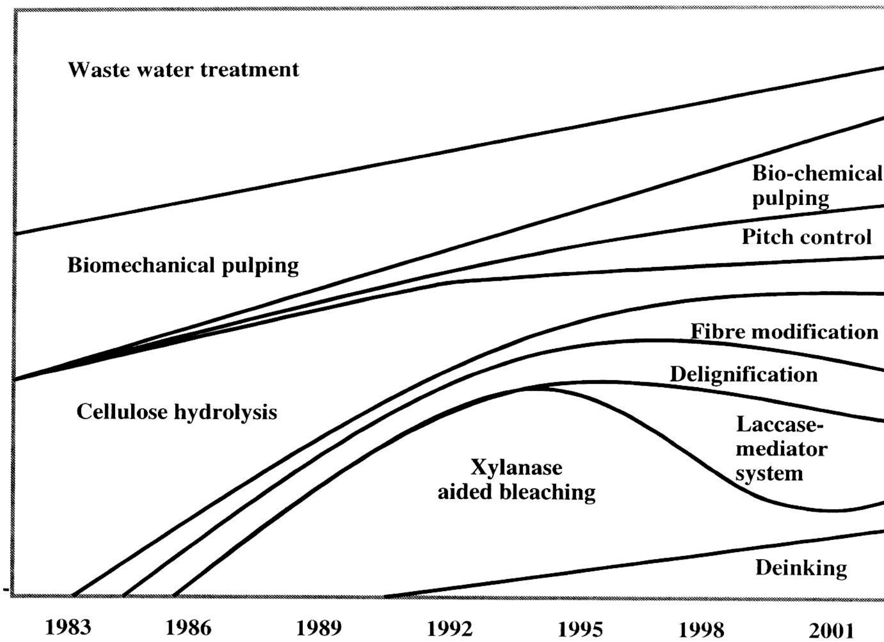

Figure 1. Trends of applied biotechnology in the pulp and paper area. Relative interest based on the number of oral and poster presentations on applied areas of the ICBPPI meetings in 1983-2001.

The use of lignocellulosic waste raw materials as source of sugars for the production of energy and chemicals has been an important goal for research on cellulases and hemicellulases since the start of the ICBPPI meetings in early 1980s. The diminishing activity of this area does not, however, reflect the decrease of importance, neither interest in the area. Rather, it reflects increased specialization and focusing of various conferences. During the last decade, conversion of renewable biomass into fuel energy and chemicals has again received growing attention as a means of replacing energy, chemicals and materials presently derived from fossil fuels. The issues of limited oil supply and the prospects of improvements in the relative economics of biomass feedstock have motivated the research carried out especially in USA. An important driving force is the Kyoto protocol. The price of sugar based on grain or other agricultural products as raw material has up to this date been prohibitive for economical production of several chemicals, but the expected decreasing costs of new biomass based sugar resources have raised interest in developing new production technologies for commodity chemicals, solvents and polymers. The importance of utilizing side streams and waste materials will obviously grow in the future.

The use of different enzymes in fibre modification or "fibre engineering" instead of their use as process aids is an interesting and potential field of application in the case of both chemical and mechanical pulps. By the targeted modification of fibre surface by enzymatic or combined enzymatic and chemical treatments improved fibre properties or completely new fibre characteristics for various applications can be created. Fibre engineering could be used both in improving paper and board manufacturing properties of pulp fibres, as well as for modification of fibres suitable for non-paper applications. Expectedly, this is one of the most fast growing areas in fibre based industries. Fibre modification also reflects the trend of using biotechnical means for product design rather than for process improvement. Successful engineering of different fibres for various purposes will, however, require new concepts and broad cooperation between fibre, polymer and surface chemists as well as papermakers and biotechnologists. New packaging materials and sensors indicating the status of the contents of the package offer challenges for biotechnologists. The safety of processes and products are among the important questions in future. The importance of hygiene and control of microbial growth in paper manufacture has not been reflected in the number of papers presented in the ICBPPI meetings.

Future

Biotechnical applications for pulp and paper industry have been developed for the past twenty years. The first introduction of enzymes at mill scale took place at 1980s, rapidly after the discovery and validation of the xylanase-aided bleaching concept. Since then, the development of industrial enzyme preparations having pH and temperature ranges suitable for target processes has been fast. In addition, novel enzymatic and microbial applications have been investigated for improving the processing of wood fibres, as well as for improving the runnability of the pulping, bleaching and papermaking processes.

There have been high expectations for the rising of new, edge-cutting technologies based on biotechnology in pulp and paper industry. The implementation of economically and technically viable biotechnical stages or treatments to mill scale operation has, however, been found to be difficult. The biotechnical applications competing with the chemical applications must overdue the performance of traditional chemistry and result in economical benefits without compromising the product quality. It seems that the most potential future applications of biotechnical methods will be found in the fields of speciality products, targeted modification of the fibres and controlling the safety of products.

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

Biotechnology in the pulp and paper industry. A challenge for change.

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The globalisation of the pulp and paper industry is a relatively new phenomenon that has been a harbinger of change and opportunities. Today's paper industry employs advanced chemical- and mechanical-based technologies to provide high-quality consumer products that are in worldwide demand and support the lifestyles of our new global economy. And yet, from these successes arise many of the current and future difficulties of the industry. Various paper industry leaders have stated that the capital requirements of manufacturing paper products are too high, are limiting creativity, and the entrepreneurial spirit of the industry. Coupled with these challenges, the emergence of low-cost fiber resources outside the Northern Hemisphere has contributed to further pressures on the paper industry to significantly reduce its manufacturing costs through a major redesign of its core manufacturing technologies. Within these difficulties, are disguised but unparalleled opportunities for researchers to efficaciously develop new biotechnology-based processes for our industry. These new technologies must reduce the capital costs of pulp production, be readily implemented in today's mill, and provide exceptional return for the resources invested if they are to be commercially feasible. The pathway to the future will entail the development of new global alliances between industry, governments, and research organizations. These new research partnerships will be linked by the Web, coordinated by industry and government, and will utilize the best research expertise and facilities available in the world. These collaborative efforts will generate higher value fiber resources, lower total manufacturing costs, and develop new materials from which new products can be designed and manufactured. In summary, the business of pulp and paper has provided R&D a challenge for change, and biotechnology is destined to address this opportunity.

INTRODUCTION

The production and usage of paper products is a cornerstone of modern societies and is interwoven into most major societal activities including education, government, business, and leisure. Indeed, it is well established that the consumption of paper on a national basis can be correlated to a nation's GDP [1]. Although many pulping technologies have been developed over the past century, the dominant pulping process used globally is the kraft process, producing more than 65% of 1997 virgin pulp production [2]. The German chemist C. F. Dahl invented this process in 1879 and the first kraft mill was built in 1890 in Sweden [3]. The discovery and subsequent implementation of the kraft process was undoubtedly broadcast on

Samuel F. B. Morris' "information superhighway" of the day, the telegraph. Interestingly, the telegraph system was patented 30 years before Dahl's discovery. The discoveries of the telegraph and the kraft process were, for their time, quantum leaps in technology that contributed to the industrial revolution. These and other technological advances of the day significantly altered the development of Western civilization. Now, at the beginning of a new millennium, we are experiencing another dramatic change in modern society. The advent of inexpensive, powerful personal computers, broadband telecommunications and other information technologies has begun to dramatically redefine our concepts of business, life-styles, education, and government.

Just as Morris' telegraph developed into today's information technology revolution, recent events now necessitate the development of new breakthrough manufacturing technologies for the pulp and paper industry. These breakthrough technologies need to be revolutionary in design and operation and must positively impact: (1) raw material costs, (2) manufacturing costs, (3) energy costs, (4) environmental performance, and (5) the production of high-quality products demanded by the consumer.

In 1986, Foster [4] analysed the life-cycle of technologies and proposed that most technologies follow an S-curve relationship between productivity and investment of resources. The basic premise was that the older, more established technologies have upper performance limits that are determined by a combination of physical, chemical and/or regulatory rules. As mature technologies approach the top part of their S-curves, major investments are required for only marginal gains in performance. The key to improving the return on investment is to identify and develop new technologies that develop along a new S-curve.

This challenge presents a unique opportunity for our scientific research community to discover a new S-curve of pulp and paper that will provide a new set of "winning" biomanufacturing technologies for our industry. Certainly, biotechnology research in pulp and paper has already demonstrated that new products can be developed that provide distinct operational benefits. For example, xylanase pretreatments for kraft bleaching have developed from laboratory experiments to commercial products [5a-c]. Many North American and Scandinavian mills have performed mill trials with xylanase and some have incorporated their use into routine production operations. Mill use of xylanase usually can reduce chemical bleaching costs up to 20%. For chlorine-based bleaching technologies, xylanase pretreatments of kraft pulps have also been shown to reduce AOX discharges by 5-20% depending on the furnish and the type of pulping system employed. The use of a X-stage has also been successfully incorporated into commercial TCF bleaching operations. A xylanase pretreatment stage has also been shown to reduce chemical bleaching costs, and higher brightness ceilings have been achieved with an X-stage for a variety of bleach sequences.

Cellulases have been studied for drainage [6], deinking [7], and fiber modification. Lab work and mill use have demonstrated the ability of cellulase to enhance drainage properties of recycled furnish. Several commercial ventures have installed deinking facilities in North America, Europe, and Australia over the last decade and have examined the application of enzymatic systems for improved operations.

Fungal and enzyme pitch degradation products have found applications in some TMP and sulfite mills [8]. Lipase has been used in mill operations to control pitch buildup and also found a niche market for deinking applications in cases where the inks contain vegetable oil formulations [9]. Ascomycete albino fungi have been used as chip pretreatment to reduce pitch and save up to 36% of bleach costs [10].