Global Water Research Coalition

Membrane Bioreactors for Municipal Wastewater treatment

State of the Science Report

GLOBAL WATER RESEARCH COALITION
STOWA

MEMBRANE BIOREACTORS

FOR MUNICIPAL WASTEWATER TREATMENT

STATE OF THE SCIENCE REPORT

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GLOBAL WATER RESEARCH COALITION

GLOBAL COOPERATION FOR THE GENERATION OF WATER KNOWLEDGE

GWRC is a non-profit organization that serves as a collaborative mechanism for water research. The benefits that the GWRC offers its members are water research information and knowledge. The Coalition focuses on water supply and wastewater issues and renewable water resources: the urban water cycle.

The members of the GWRC are: the Awwa Research Foundation (US), CRC Water Quality and Treatment (Australia), EAWAG (Switzerland), Kiwa (Netherlands), Suez Environment- CIRSEE (France), Stowa - Foundation for Applied Water Research (Netherlands), DVGW – TZW Water Technology Center (Germany), UK Water Industry Research (UK), Veolia- Anjou Recherché (France), Water Environment Research Foundation (US), Water Research Commission (South Africa), WateReuse Foundation (US), and the Water Services Association of Australia.

These organizations have national research programs addressing different parts of the water cycle. They provide the impetus, credibility, and funding for the GWRC. Each member brings a unique set of skills and knowledge to the Coalition. Through its member organizations GWRC represents the interests and needs of 500 million consumers.

GWRC was officially formed in April 2002 with the signing of a partnership agreement at the International Water Association 3rd World Water Congress in Melbourne. A partnership agreement was signed with the U.S. Environmental Protection Agency in July 2003. GWRC is affiliated with the International Water Association (IWA).

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INTRODUCTION

1.1 BACKGROUND

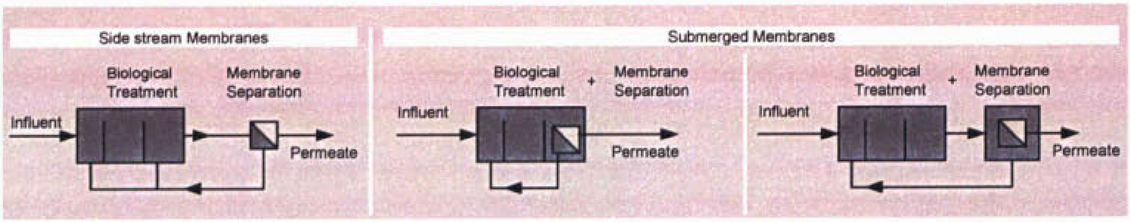
The membrane bioreactor (MBR) technology for wastewater treatment is gaining significant attention from both scientists and practitioners from universities, water boards, industry and even politicians. The expected superior effluent quality and the small footprint make the MBR technique a promising option for future wastewater treatment systems. In Europe some 40 MBRs are in operation for municipal wastewater treatment and new installations are being designed and commissioned. The scientific interest can easily be estimated by the more than 600 scientific articles on MBR for wastewater treatment that have been published during the past ten years (Scirus, 2005).

In industry MBR is being applied for many waste streams and has reached the status of proven technology. For municipal wastewater however, the situation is different. Especially in those cases where rainwater has to be treated, MBR operation can be difficult, MBR operation can be difficult, the more so because large buffering tanks or large membrane surfaces make the application of MBR difficult and more expensive.

1.2 MBR TECHNOLOGY

The membrane bioreactor combines the activated sludge process with a membrane filtration step. The filtration can be in side stream configuration with pressurised membranes or with submerged membranes, either in the aeration tank or in a separate membrane tank, see Figure 1.1.

FIGURE 1.1 MBR IN DIFFERENT CONFIGURATIONS: SIDE STREAM MEMBRANES, SUBMERGED MEMBRANES INCORPORATED IN THE PROCESS AND SUBMERGED MEMBRANES IN SEPARATE MEMBRANE TANK



The applied membranes are microfiltration membranes with pore sizes of 0.1 to 1 μm, or ultrafiltration membranes with pore sizes of 0.001 – 0.1 μm.

In relation to the conventional activated sludge process the MBR technology has two important advantages:

- space requirement is strongly reduced; the secondary clarifiers are not necessary and activated sludge tanks may be designed at a smaller footprint since higher sludge concentrations can be applied within MBR-configurations;
- effluent quality is improved significantly compared to activated sludge systems with secondary clarifiers: the membranes remove all suspended and colloidal materials.

Operation and maintenance costs are still higher compared to conventional activated sludge treatment, mainly caused by replacement cost of the membranes and the aeration equipment needed for membrane air scouring. The higher Mixed Liquor Suspended Solids concentration (MLSS) leads to lower α-values of about 0.5 at 15 g MLSS/L.

The implementation of the technology is growing fast. However, MBR technology faces a number of issues, barriers and impediments that could discourage further development. For example:

- the supposed ability to address the strictly defined effluent quality. For example the limitation in advanced nutrient removal (N and P), removal of endocrine disrupting compounds, biological risks (viruses, bacteria), micro pollutants etc.;
- optimal performance and control of the system (e.g. membrane fouling and the prediction of the permeability of membranes and the filterability of the liquid-solid mixture);
- financial optimisation of MBR (capital and operational costs regarding the required membrane surface, energy, chemicals).

1.3 GOALS AND OBJECTIVES

The development of Membrane BioReactor (MBR) technology has made major steps in the past ten years. As a result of this, the field of application has broadened towards the municipal wastewater treatment sector. To date, about 75 large full-scale installations for the treatment of municipal wastewater are in operation or under construction worldwide.

In conjunction with this development there has been a lot of research activity in the field of MBR technology. The Board of Directors of the Global Water Research Coalition (GWRC) determined this technology to be of priority for collaborative research and decided to conduct a project with the aim to:

- determine the current state of the science in the field of MBR;
- develop a phased research strategy represented by priority research projects.

STOWA, the Dutch organisation co-ordinating the research activities on behalf of the Dutch Water Authorities, was as GWRC member assigned with the lead of the project. Witteveen+Bos Consulting Engineers was contracted to prepare a State of the Science report with regard to MBR technology.

1.4 STATE OF THE SCIENCE REPORT

This report describes the state of the science with regard to membrane bioreactor technology for application in municipal wastewater treatment.

The report consists of the following parts:
- database analysis;
- a literature review on recent publications (from 2000) on MBR with regard to municipal wastewater treatment;
- results from a questionnaire sent to all GWRC-members.

1.4.1 DATABASE ANALYSIS

Several search engines available on the World Wide Web were used to obtain an indication of the developments in MBR research over the past five years.

Based on Internet search for the selected search terms an MBR-specific database was created. By analysing this database on specific keywords (e.g. flux, TMP, filterability, fouling, cleaning, operation, energy, cost), related to publication date, trends in specific research fields were identified. An overview over these trends represents the importance and actuality of a certain research subject.

1.4.2 LITERATURE REVIEW

The literature review on MBR was conducted with regard to municipal wastewater treatment starting from the year 2000. For this purpose English, German, French and Dutch publications were searched for and screened on keywords and content. Since the amount of publications on MBR is quite extended a step-wise approach was applied.
Per identified important field of research regarding MBR the present status of research is summarised. Within these summaries, an overview of actual research conclusions, research questions and recommendations are presented.

1.4.3 EXPERT JUDGEMENT

A questionnaire was prepared asking the GWRC members about their views, ideas and research projects on MBR. Input has been given by representatives of KIWA Water Research (the Netherlands), Water Environment Research Foundation (USA), Berlin Centre of Competence for Water, Technologie Zentrum Wasser (Germany), Cooperation Research Centre for Water Quality and Treatment (Australia), Thames Water Utilities Ltd (UK), Water Research Commission (South Africa).
The same questionnaire was also distributed among the members of the MBR Platform in the Netherlands. The results of both these questionnaires are presented in *Chapter 3*.

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LITERATURE REVIEW

At this time optimisation (of MBR systems) is not possible since we lack a fundamental understanding of the different interactions between the membrane performance and the process operating conditions (Ben Aim and Semmens, 2002).

2.1 INTRODUCTION

The large amount of scientific and commercial information on MBR was approached in five different ways, subdivided in two categories:

1 database analysis (see Appendix I):
  - a general information search via Google;
  - a scientific information search via Scholar.Google and Scirus;
  - a scientific information search via the multidatabase search engine WebSPIRS;
  - analysis of a database containing some 150 articles on MBR from the period 2000-2005;

2 evaluation of review articles on MBR from 2000 to 2005.

2.2 RESULTS DATABASE ANALYSIS

GENERAL

MBR is a hot item, reflected by the large amount of information available on the World Wide Web (see Appendix II for a detailed description and results). More than 40,000 websites contain information on this technology. Refining the search to scientific content decimates the amount of hits, to a few thousands. Further excluding other results than scientific papers leads to about 200 papers for the period 2000-2005. A further selection with respect to the topics relevant for this research results in 133 papers that were screened and evaluated by means of a database (see Appendix III and IV).

RESEARCH TOPICS

The results from the search engines as well as the database analysis reveal comparable trends with respect to important research topics.

Most important topic of research is the hydraulic functioning of the MBR. *Membrane fouling* and its causes form the core of the scientific literature on MBR. Almost every paper contains a section describing the hydraulic performance and aims at optimising it.

The second important research topic is the achievable *effluent quality*. Many researchers try to optimise the biological process to remove as much pollutants as possible.

Oxygen transfer has received a lot of attention at the end of the nineties, but the number of papers investigating this topic has been decreasing over the past three years. Membrane *aeration* is closely related to this topic, since firstly it was assumed that the aeration needed to scour the membrane would reduce the overall aeration needs.

Interestingly *cost considerations* are not regarded as important as would be expected. Although cost is often mentioned as one of the disadvantages of MBR, it is not really a research topic. Of course, many researchers draw the conclusion that to minimise operating and investment cost of MBR, hydraulic performance must be optimised. In this way cost are implicitly taken into account in many studies. In fact, many 'introductories' mention this consideration as a reason to carry out the research.

2.3 LITERATURE REVIEWS

The database with scientific papers also contains eleven review papers. These papers are summarised in this chapter to obtain a summary of the state of the science with regard to MBR. These papers discuss the MBR according to different topics, almost the same as used for the database analyses. The same order is used for the set up of this chapter. All review articles used in this chapter are listed in Appendix V List of Review Articles.
For reference purposes Appendix VIII presents the review articles that are published yearly by the Water Environment Research Federation (WERF (US) a GWRC member) in the journal Water Environment Research. For the past 4 years those parts of the Review that are concerned with MBR are presented.

2.3.1 MBR-GENERAL

The advantages offered by membrane processes are well known and repeated, mantra-like, by suppliers, contractors and less sceptical users (Judd, 2004): they provide treated water of reliable quality almost independent on influent quality, at a relatively small footprint.

They are considered too costly for widespread large-scale bulk application in the municipal sector. Since fouling impacts directly on both capital and operating costs, its minimisation is critically important in determining cost effectiveness.

The submerged configuration has achieved significant market penetration: the 1000th Kubota MBR plant was installed May 2003 and the market leader (in terms of global capacity), Zenon, has increased its capacity from 1000 m^3/day in 1993 to almost 1.5 Mm^3/day currently (2004).

2.3.2 RESEARCH APPROACH

For MBR research many approaches are being applied. Much research is carried out on the treatment of real municipal wastewater, on pilot and full scale. This applied research is concerned with feasibility questions, like: is the system able to perform the desired biological conversions and is the effluent quality good enough in terms of total solids, disinfection and nutrients, are the operational cost within certain boundaries, what is the achievable flux, which cleaning strategy should be applied, etc.? In most cases, this approach has a broad scope.

Another type of research is more fundamental and focuses on one or a few aspects of the total process. Within this group of research approaches, research into fouling and fouling phenomena is predominant. Fouling research on its own can be subdivided in several classes. Some researches aim at controlling and avoiding fouling, others try to connect fouling with operational situations and to discover the mechanisms that cause fouling.

Pilot plant experiences and trial and error have led to improvements in design and operation by the two leading MBR suppliers resulting in lower overall costs. Fundamental research conducted by academic institutions has tended to be limited to model feed waters and small scales, and the obtained knowledge is rarely transferable to full scale plants (Judd, 2004).

2.4 MAIN TOPIC OF RESEARCH

2.4.1 MEMBRANE FOULING

hydraulic optimisation

Studies into the hydraulic optimisation of an MBR system are primarily concerned with avoiding or controlling fouling. Fouling is caused by the accumulation of dissolved and suspended matter, such as EPS, on the surface of or within the membrane. In submerged MBRs, generally only three strategies are available for limiting fouling:

1 reducing the flux;
2 increasing the membrane aeration;
3 employing physical or chemical cleaning, i.e. backwashing or filtration breaks.

There have been several approaches to cope with fouling in MBR. These approaches can be divided in two groups:

1 optimisation of the existing process via operational measures;
2 fundamental research into fouling mechanisms, fouling substances and their origin.

OPTIMISATION VIA OPERATIONAL MEASURES AND DESIGN

In the past ten years several guidelines and ideas on operation philosophy emerged, resulting mainly from pilot scale experiences. There is a general trend from controlling fouling towards avoiding fouling.

In the traditional side stream cross flow systems, operation aimed at controlling fouling by continuously removing the fouling layer. With the introduction of submerged membrane systems and the experiences with these systems it turned out that avoiding fouling is more effective (van der Roest, 2003). The flux is kept at a low level (in the range 10-30 l/m^2h) to increase filtration run length and to avoid a progressive increase in required TMP. This type of operation is usually referred to as sub critical operation.

To support this aim an intensive *pre-treatment* was found to be indispensable (Kraume, 2003; Daigger *et al.*, 2004). Particularly in hollow fibre submerged membrane systems, large particles and fibrous structures in the wastewater tend to accumulate and hamper system performance. Currently, hollow fibre membrane systems are preceded by perforated screens with characteristic size of less than 1 mm. Plate and frame membranes are usually equipped with a pre-treatment with a characteristic size of 2-3 mm.

Furthermore, cross flow aeration was optimised by means of intermittent aeration, intermittent permeate extraction (relaxation), membrane module optimisation and double deck configurations.

Totally avoiding membrane fouling seems to be impossible however, while working in a practical operating window (i.e. acceptable flux, acceptable energy input for crossflow aeration). Even when operating under sub critical conditions, a long term fouling process usually takes places. Therefore several steps were made to optimise *cleaning strategies*. Here, there is a trend towards avoid-fouling policy. This is done by periodical so called maintenance cleanings with relatively low concentrated cleaning solution, if possible 'on air'. Depending on the type of wastewater to be treated different cleaning agents can be used.

FOULING MECHANISMS, FOULING SUBSTANCES AND THEIR ORIGIN

The two most important fouling mechanisms in MBR are cake layer formation and adsorption to the membrane. Cake layer formation can usually be controlled by a continuous coarse bubble aeration. Adsorption is regarded a function of the total produced volume, and can be addressed by a chemical cleaning, if needed (Wintgens *et al.*, 2003).

Inorganic fouling in aerobic treatment can occur in the form of calcium carbonate scaling which was observed in flat plate and hollow fibre MBRs. Control is difficult, mostly by ex situ cleaning or elimination of the source of the problem.

Organic fouling is studied more extensively. The high solids concentration, coupled with varying levels of colloidal and dissolved extra-cellular polymeric substances (EPS) are widely acknowledged as being key foulants in MBR processes (Defrance *et al.*, 2000). In the search to identify the exact substances that cause organic membrane fouling, the latest results indicate the importance of polysaccharides in the liquid phase of the mixed liquor (Rosenberger *et al.*, 2005). Starting from the rather vague parameter extracellular polymeric substances a step forward was made by pin-pointing polysaccharides as being involved in membrane fouling. An almost linear relationship was observed between fouling rate and polysaccharide concentration in the water phase (Rosenberger and Kraume, 2002). Here the water phase of the activated sludge was analysed for polysaccharides. The filterability of the mixed liquor was assessed in a cross flow filtration cell.

High performance size exclusion chromatography (HPSEC) can provide information on molecular size distributions of the sample. Results from measurements support the idea that polysaccharides are involved in membrane fouling.
Microscopic observation of fouled membranes with environmental scanning electron microscopy (ESEM) and electron dispersive x-ray analysis (EDAX) yields information about the extent and the character of fouling, the latter only with inorganic fouling. Disadvantage is that a lot of samples have to be investigated to be representative (Jefferson *et al.*, 2004).

It was found that too much hydraulic stress would lead to floc damage, resulting in loss of filtration performance (Lee *et al.* 2003). Positive displacement pumps are favourable to avoid these problems.

COMBINING BIOLOGICAL AND HYDRAULIC OPTIMISATION

Results from lab scale experiments, confirmed by pilot plant trials, indicate the importance of microbiological aspects in relation to hydraulic performance, i.e. membrane fouling (e.g. Chang *et al*, 2001; Lee *et al*, 2003). Although conclusive results are quite scarce there is strong evidence to support the statement that fouling is directly related to the state of the biomass, provided that the other boundary conditions are optimal in terms of equipment, shear rate, etc. (Chang *et al.*, 2002, DeWilde *et al*, 2003).

Recent studies discovered the relation between sludge age and fouling rate; a higher sludge age leads to a lower fouling rate, shifting from 8 to more than 25 days resulted in considerably less fouling.
During pilot plant trials transient conditions in terms of hydraulic and biological loading rates turned out to be detrimental for MBR operation. For example when treating sewage from a mixed sewer system, storm weather events are known to temporarily cause high fouling rates (van der Roest *et al*, 2002).

To date the relation between biological parameters and membrane performance can not be quantified, only some qualitative indications are presented. This subject is in almost all review articles identified as one of the most important research topics.

2.4.2 EFFLUENT QUALITY

The most frequent research question in the screened articles is primarily or secondarily focused on the treatability of a wastewater. For many cases a pilot or labscale study is set up, with the aim to identify the removal efficiency of parameters like COD, BOD and nutrients. These parameters are monitored in almost all studies as reference or background information.

Due to the absolute barrier provided by the membrane COD can usually be reduced by at least 95% in an MBR (Stephenson *et al*., 2000). Nitrification can generally be achieved to levels with NH_4-N concentrations lower than 1 mg/l (Kraume and Bracklow, 2003; Stephenson *et al*, 2000). Denitrification can be achieved by including an anoxic zone, in a separate tank or with intermittent aeration. Total nitrogen effluent concentrations smaller than 10 mg/l can be achieved (Stephenson *et al*, 2000).

The fact that the membranes keep all biomass in the system was thought to favour the growth of otherwise absent species. Although this was proved to be the case (Witzig *et al*., 2002), the biological conversions are not shown to be different from conventional systems. The higher effluent quality can be contributed to the absence of suspended solids.

Because of the pore size of the membrane, the MBR has rather good disinfecting capacities. Specific measurements show log-removals of total coliforms of more than 6.6 (Mansell *et al*, 2004).

Recently, treatment techniques to remove endocrine disrupting compounds (EDC) (e.g. STOWA28, 2004), organic and inorganic micro pollutants (Xing *et al*, 2000; Innocenti *et al* 2002; Mansell *et al*, 2004), have obtained a lot of attention. Many experiments were carried out, in different set-ups. From the many results that were obtained, the conclusion can be drawn that MBR does not remove these substances to the desired levels. For some substances the removal capacity is higher compared to conventional activated sludge systems, others do not show a difference at all (STOWA28, 2004; Joss 2004). This seems to be related to the form in which these substances occur, either bound to colloids, the biomass or particles, or dissolved in the water phase. This aspect needs further research. A problem in this field is that the concentration range is often below the detection limit.
The main conclusion is that what a conventional activated sludge system can do, is also possible with an MBR, with a slightly higher and definitely more stable effluent quality.

The major driving force for application of the MBR technique is the disinfected effluent.

2.4.3 SLUDGE HANDLING

Due to the presence of the membrane, all activated sludge can be kept in the system, as long as the membrane can handle the MLSS concentration properly. Apart from possible problems with filtration, also aeration may cause problems at high MLSS concentration, see also 2.4.4.

For application in municipal wastewater treatment MLSS concentrations between 10 and 15 mg/L seem practical, with respect to sludge production and excess sludge discharge.

The amount of excess secondary sludge produced by an MBR is somewhat lower than or equal to conventional systems (Günder and Krauth, 2000). When long SRT's are applied, sludge production of course decreases (Wagner and Rosenwinkel, 2000).

The primary sludge production is higher, because of the higher degree of pre-treatment. Sludge treatment is almost the same compared to conventional activated sludge systems.

Recent developments in the USA show a trend towards lower MLSS concentration (<10 g/L) while the plant sizes are increasing (> 40,000 m^3/day). SRT is selected based on the biological process requirements (Daigger *et al*, 2004).

The dewaterability of waste activated sludge from MBR seems to be no problem, compared to aerobic stabilised waste sludge from conventional activated sludge systems (Kraume and Bracklow, 2003).

The problem of waste sludge treatment in Europe is essentially different from the situation in the USA, where waste sludge has to be treated with the aim of reusing it. Within Europe the approach to sludge treatment is also different per country. Some countries reuse the sludge in agriculture as fertiliser, in other countries sludge is dewatered and ultimately incinerated.

2.4.4 AERATION AND OXYGEN TRANSFER

Aeration efficiency and the required energy input for this seems to be the limiting factor for the maximum MLSS concentration of around 15 mg/L. (Krampe and Krauth, 2003). Higher MLSS concentration will increase too much the amount of energy for oxygen transfer (Cornel *et al.*, 2003), as well as increase the risk of sludging of membrane modules and aerators. Measured α-values in full-scale installations show α-values of 0.6 at 12 g MLSS/L.
Apart from these considerations, there may be a lack of space to place all the required aeration equipment when MLSS is increased too much. This problem becomes more urgent when space reduction is required and deep tanks are necessary.

2.4.5 COST CONSIDERATIONS

Generally MBR is regarded as being slightly more expensive than conventional activated sludge treatment. Both investment and operating cost are at the moment higher. The amount of energy that is consumed per unit volume of produced permeate is in the range of 1.5 - 2.5 kWh/m^3, which can be 50% more than for conventional systems.

Of course MBR has to be compared with a system that can produce the same effluent quality, which is not just an activated sludge process. At this point the calculations may differ, depending on the process to which MBR is compared (Adham *et al.*, 2001).

2.4.6 MEMBRANE TYPE

MEMBRANE MODULE

Several membrane types can be applied in MBR which can be divided in side-stream systems and external systems. Most commonly applied in municipal wastewater MBRs are the submerged membranes. To date two types of submerged modules are available on the market for MBR applications: flat sheet membranes and hollow fibre membranes. An analysis of the current applications for municipal wastewater treatment shows that the flat sheet system is competitive for smaller units (below 20,000 p.e.) whereas larger plants are favourably equipped with the hollow fibre system (Lesjean *et al.* 2004).

MEMBRANE MATERIAL

The choice of membrane material for activated sludge filtration is in practice limited to organic membranes, like hydrophilised polyvinylidenefluoride (PVDF) or chlorinated polyethylene. Organic membranes are still less expensive than ceramic membranes, and have the advantage that they can be operated submerged, i.e. with air scouring and low suction pressure. Ceramic membranes are commonly tubular which still requires more energy for recirculation.

Tubular organic membranes are up until now only applied in industrial MBRs but with recent process developments will become competitive with submerged systems.

2.4.7 MISCELLANEOUS

The following topics are not really investigated but are mentioned by some researchers as issues that need further attention.

- membrane life time. This is of major importance in determining amortisation cost;
- the quality of excess sludge varies with time, which affects the dewatering process;
- the effect of the addition of sludge conditioners on fouling properties of the activated sludge broth;
- cleaning agents. The type of cleaning agents determines the environmental impact to a high extent, as well as the total down-time and operational cost.

3

EXPERT JUDGEMENT

3.1 INTRODUCTION

Parallel to the State-of-the-Science desk study a questionnaire was prepared and sent to the participating GWRC members and other, by GWRC members, invited partners. The objective of the questionnaire is to directly solicit input from the GWRC members on MBR research to support the development of a State-of-the-Science report. The survey focuses on scientific research as well as practical applications. The questionnaire contains 11 questions (see Appendix VI) and aims to identify the bottle-necks and knowledge gaps in the field of MBR technology for municipal wastewater treatment as indicated by research institutions worldwide.

3.2 RESULTS OF INTERVIEW BY QUESTIONNAIRE

The questionnaire was also presented to the Dutch MBR platform group in which representatives of water boards and consultancy firms meet each other for exchange on operational experience and research projects. The response of the Dutch MBR platform group is summarised as one voice in the total rankings. The integral results of the Dutch Questionnaire are presented in Appendix VII.

RESPONSE RATE

From the 7 questionnaires that were sent around, 6 were returned. The seventh was only partially filled out.

QUESTION 3C. PLEASE PROVIDE A (PRIORITISED) LIST OF YOUR ORGANISATION'S CURRENT RESEARCH NEEDS RELATED TO MBRS.

This open question concerning current research needs resulted in the following list of topics, with in the last column the frequency of mentioning. Each answer can be categorised in one of the mentioned topics. It is remarkable that almost all answers can be summarised with three topics, of which the second and third can even be condensed to one, leaving only two main topics: Effluent quality and hydraulic optimisation. By combining the second and third, they become of course first in the ranking, with 11 times mentioned.

ranking	Topic	times mentioned
1	Effluent quality (micro's, nutrients, EDC, MTR)	8
2	Fouling (control) & Cleaning	6
3	Flux en TMP optimisation	5
4	Compactness / small footprint	1
5	Costs	1
6	Energy	1
7	Solids / concentrate handling	1

QUESTION 4. IN MY OPINION, THE DRIVING FORCE FOR THE CURRENT GROWTH IN MBR APPLICATIONS IS: MAX. 2 OUT OF 8 OPTIONS

The eight options are listed below, with their respective scores.

Here the effluent quality is not merely a research need, but a reason to apply the MBR technique. Supposedly, the two must be combined: the membrane will surely supply high quality water, but the exact quality still has to be determined. Surprisingly, the large amount of pilot experiments with which operational experience was obtained is not regarded as decisive for MBR application.

driving force	Score
Increase in fundamental knowledge	0
Increase in operational experience	3
Effluent quality	5
Small footprint / capacity upgrade	3
MBR is fancy, new, innovative	0
Decreased investment costs (membrane costs)	2
Increased quality of membrane modules	0
Others (Water Framework Directive, lower operational cost)	1

QUESTION 8. FROM A SCIENTIFIC POINT OF VIEW, THE MOST IMPORTANT RESEARCH QUESTION(S) IN MBR RESEARCH THAT NEED(S) TO BE ANSWERED IN THE NEAR FUTURE IS/ARE...

This open question resulted in the following list, again with ranking and frequency. Again hydraulic optimisation and effluent quality are regarded as most important topics for future research.

ranking	Topic	times mentioned
1	Fouling (control), cleaning	7
2	Effluent quality (esp. EDC removal)	6
3	Solids / concentrate handling	4
4	Optimisation fluxes & TMP	4
5	Membrane lifetime	3
6	Others (simple operation, pre-treatment, MBR as pre-treatment)	3

QUESTION 9. THE RESEARCH QUESTIONS MENTIONED IN QUESTION 8 CAN BE ADDRESSED MOST APPROPRIATELY BY: MAX TWO OUT OF 6 OPTIONS

The six options are listed below in the order of times mentioned. Pilot plant research is considered the best tool for further development of MBR research.

ranking	topic	Times mentioned
1	pilot plant	6
2	lab scale	3
3	demonstration+applied research	3
4	others (depending on goal)	1
5	cost evaluation studies	0
6	Modelling	0

COMPARING THE ANSWERS OF CURRENT AND NEAR FUTURE RESEARCH NEEDS

In the following list, the two rankings from question 3 and 8 are compared. The ranking of the first three topics is not changed, effluent quality and hydraulic process performance are held to be the most important research topics for now and the future.

Topic	ranking current research needs	ranking future research needs
Effluent quality (micro's, nutrients, EDC, MTR)	1	1
Fouling (control) & Cleaning	2	2
Flux en TMP optimisation	3	3
Compactness / small footprint / upgrade	4	
Costs	5	
Energy	6	
Solids / concentrate handling	7	4
Membrane lifetime		5
Others (simple operation, pre-treatment, MBR as pre-treatment)		6

However costs and energy considerations are ranged 5 and 6 as being current research needs, it is notable that these topics are no longer mentioned as future research needs.

3.3 CONCLUSIONS EXPERT JUDGEMENT

The results of the questionnaire confirm the results from the database analyses about current research activities: membrane fouling and effluent quality are the most important issues at this time. For the future no big change is expected: fouling control and improving the effluent quality are expected to be topics requiring the most attention.

Although higher cost is a major impediment for further application, cost minimisation as such is not mentioned as one of the future research items. Here again, it is supposed that it is implicitly accounted for by hydraulic optimisation.

When fouling prevention and flux optimisation are combined, the third important point of research becomes: sludge handling. There are several aspects that need further research in this field. Because of the absolute barrier formed by the membrane, a fraction of small particles is retained in the system which would be washed out with a conventional activated sludge system. This fraction can only exit the system together with the discharge of excess sludge. It is supposed that this fraction interferes with the further treatment of the excess sludge. Furthermore, the sludge is likely to contain a higher content of priority substances that need further treatment.

4

CONCLUSIONS

4.1 AVAILABLE KNOWLEDGE

The research efforts from the past five years can be characterised by the following prioritised list of research topics:

1 membrane fouling;
2 effluent quality;
3 energy consumption (Aeration);
4 cost considerations.

Stable hydraulic operation of an MBR system treating municipal wastewater is still not fully under control and needs optimisation and further research. As a consequence, the design flux of MBR is relatively low, leading to large membrane surfaces, affecting total and operational cost.

Regarding the effluent quality that can be obtained with MBR, it can be concluded that the most important advantage of MBR is its disinfecting capacity. Furthermore, the effluent is always free of suspended solids.

Aeration of the membranes to prevent membrane fouling is an energy intensive process, which account for a great part of the operational cost of MBR. About 65% of the energy input in the system is consumed by the membrane separation step.

For municipal application, the MLSS concentration can be increased from the conventional values of 3 to 5 g/L to 10-15 g MLSS/L. The increase is limited by the oxygen transfer rate.

Much of the research activities are repeated more than once by research groups world wide. This is only partially caused by a lack of exchange between researchers. Since much of the research is carried out at pilot scale, the results can not easily be translated to other situations.

4.2 KNOWLEDGE GAPS

The research needs for the near future as identified with the questionnaire are comparable to the main topics of research as identified in the literature review:

- membrane fouling is still the main problem requiring thorough attention from scientists;
- effluent quality is a main driver for the application of the technology. There remain some important questions however, with regard to the removal of EDC, micropollutants etc.

Due to more stringent effluent standards, the effluent concentrations of nutrients and other components will be very low. It is until now unknown in which form these substances will be present in the effluent. This makes it difficult to reach the required concentrations and require changes in measuring methods.

The exchange between scientists, practitioners and decision makers is not optimal, which makes it difficult to learn from experiences elsewhere in the world. Furthermore, a common accepted method to compare MBR with other treatment techniques is lacking, which complicates good evaluation of alternatives.

Lastly, there is an expectation that with the ongoing research activities and developments in the market and legislations, new applications of innovative MBR concepts may emerge.

5

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APPENDIX I

DESCRIPTION OF SEARCH ENGINES

1.1 SCIENTIFIC INFORMATION ON MBR

Scientific information can be approached in several ways. Usually a search session starts with searching common search engines available on the web. Three of these search engines were utilised, leading roughly to the same results and trends.

Two publicly available search engines were used: Scholar.Google and Scirus; one multiple database search engine was used, WebSPIRS, which was accessed via the library of Delft University of Technology. In the following lines, the three search engines are described.

1.1.1 SCIENTIFIC SEARCH ENGINES

SCHOLAR.GOOGLE

Google also offers the opportunity to search specific scientific content of the web under the name of Scholar.Google. This engine offers somewhat more refined search options, e.g. per year of publication.

SCIRUS.COM

Scirus offers searching scientific articles from many publishers active in sientific publishing (see Appendix I), covering almost all-relevant journals. Scirus can also make a distinction between articles and general web content.

WEBSPIRS

With the programme WebSPIRS, which is available in the library of Delft University of Technology, multiple database searches can be executed. Based on the subject to be searches for a selection of databases can be made. Databases that were searched include Current contents, Pascal, EI COMPENDEX, Fluidex, Biotechnology Abstracts, FSTA.

1.1.2 OVERVIEW OF SCIENTIFIC INFORMATION ON MBR

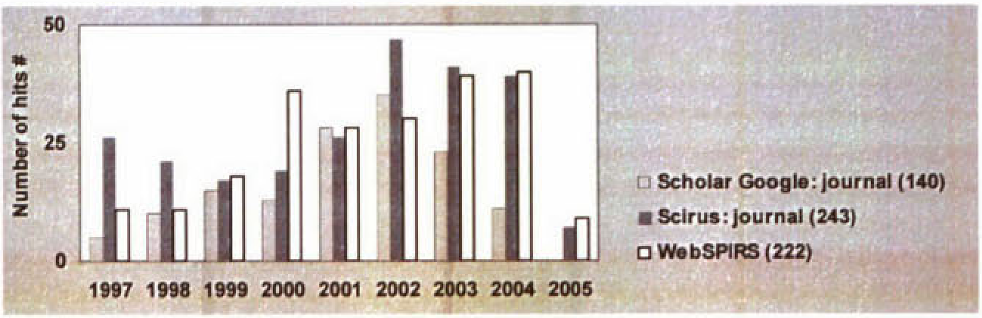
The same search string that was used for Google, excluding unwanted topics, was applied in Scholar.Google, which resulted in 240 sites from the period 2000-2005, as presented in Appendix II. Almost all scientific literature that is covered by Scholar.Google is in the English language.

Refining the search to articles with (part of) the search string in the title resulted in 41 articles and websites from the same period. In the year 2001 the amount of articles more than doubled and from 2003 the amount of material is decreasing again.

In Scirus 487 hits were found from the period 2000-2005, subdivided in 179 articles and 308 web sites, applying a rather restrictive search string. A somewhat broader search string searching *in titles* yields 183 articles and 44 web sites for the same period.

A comparison of the results from searches with Scholar.Google and Scirus is presented in Figure 1. Both search engines indicate a peak in publications for the year 2002, although it is possible that some publications from the year 2004 are not yet online, which may change the view a little bit. All results are presented in Appendix II.

FIGURE 1 RESULTS FROM SEARCH ENGINES SCHOLAR.GOOGLE, SCIRUS AND WEBSPIRS



1.2 IDENTIFYING RESEARCH TRENDS WITH SEARCH ENGINES

1.2.1 METHODOLOGY

To identify trends of research into MBR, the search engines described in 1.1.1 were used. Each of the search engines performs search actions based on a search string that is entered. The search string can consist of operators like AND, OR, ANDNOT, which makes it usable to refine the results.

For several keywords a set of search strings was tested and the resulting number of hits signifies the importance of the respective topic. To explain the followed method, the search string to determine developments with respect to the topic 'research approach' is given:

wastewater AND treatment AND pilot AND municipal OR domestic OR synthetic OR "waste water" AND "membrane bioreactor" ANDNOT (full-scale OR labscale OR oil OR tannery OR "drinking water" or extractive)

This search string returns documents without the terms 'full-scale' and 'labscale' whereas all documents contain the word 'pilot'. By exchanging the terms "pilot" and "labscale" in the search string, only publications on labscale are returned. These results provide a general impression on the topics that are important in MBR research and visualise some trends. A specification was made for the year in which the research papers were published, to identify developments in time, yielding numbers of hits for each year since 2000.

This method was applied with WebSPIRS and Scirus, for all keywords, yielding comparable results and trends. All results of this search approach are summarised in Appendix II. The following paragraphs present the results returned by Scirus. Scirus covers almost all publishers of scientific material and omits double hits, which is not the case with WebSPIRS.

1.2.2 RESULTS

TRENDS IN RESEARCH APPROACH

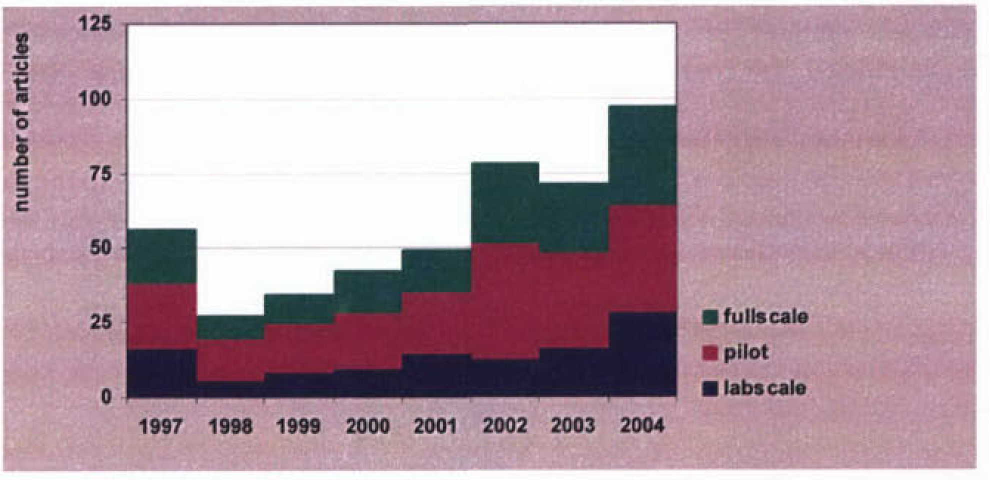
First of all it is interesting to see whether there is an evolution in the scale of research that is published. Three types of research approach were included:

- labscale;
- pilotscale;
- full-scale.

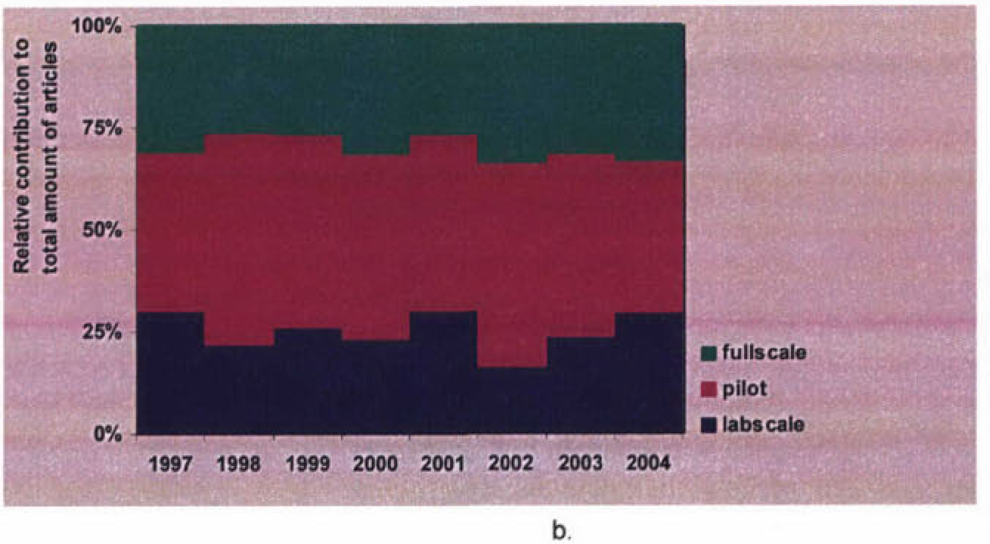
It can be expected that the amount of publications on full-scale applications is increasing over time, as a result of labscale and pilotscale research.

Figure 2 shows the results of searching for the research approach that is applied in MBR research. From the year 1997 until 2004 there is firstly a steady increase in total number; the division over the different scales of research are not changing too much in time. Remark that the total numbers as presented in Figure 2a are higher than the figures from Figure 1. This is caused by the fact that some articles are counted in each category, resulting from the search algorithm by Scirus.

FIGURE 2 RESULTS FROM TREND SEARCHES REGARDING RESEARCH APPROACH



a.



b.

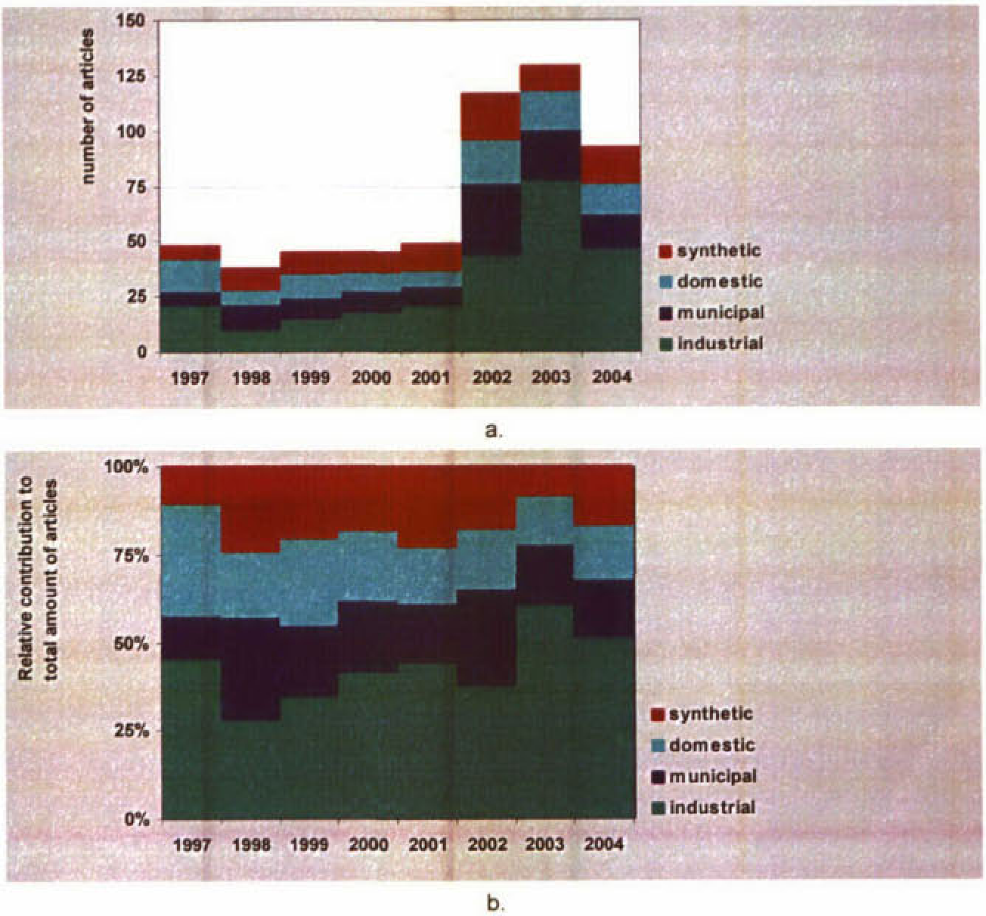
TRENDS IN TREATED WASTEWATER

Because MBR is applied in many different ways, also the research can be focused on different applications. For example in the industry, MBR is already applied numerously. The search was carried out for four types of water:

- synthetic wastewater;
- domestic wastewater;
- municipal wastewater;
- industrial wastewater.

There is an increased amount of articles on MBR treating municipal wastewater from 2002 (see Figure 3), maybe this can be correlated to the amount of MBR installations that were commissioned during the past three years. It is interesting to see that there is a jump in the amount of articles from 2001 to 2002. The relative distribution of research approaches does not change that much, almost 50% of the published material is concerned with industrial applications, the remaining part is divided over synthetic, domestic and municipal wastewater. Even with the relative established application of MBR in industry, there is still a lot of research dedicated to this subject.

FIGURE 3 DEVELOPMENT IN TREATED WATER



TRENDS IN RESEARCH TOPICS

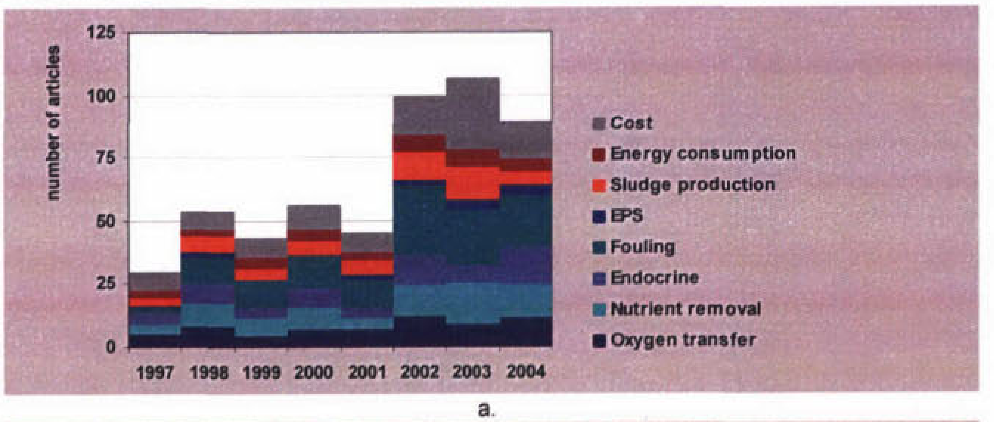
From literature a standard list can be compiled of subjects that are of special interest in MBR research. These issues are:

- cost - since MBR is often not cost competitive with conventional techniques, much research is dedicated to decreasing operational costs;
- energy consumption - related with the former point is the need to decrease the amount of energy to operate an MBR installation;
- sludge production and handling - decreased sludge production is often mentioned as an advantage of MBR, treatability of waste sludge is questionable;
- EPS - extracellular polymeric substances are frequently correlated to membrane fouling;
- fouling - one of the bottle necks in MBR operation;
- endocrine disrupting compounds (EDS) - one of the reasons to look for new treatment technologies is the occurrence of medicine residuals in sewage that have to be removed;

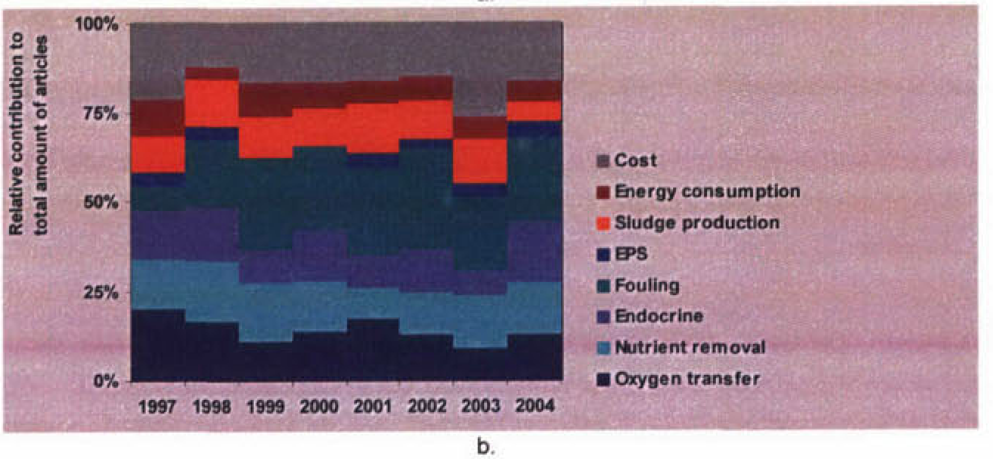
- nutrient removal - with stricter regulations lower effluent concentrations have to be achieved;
- oxygen transfer - one of the problems related with intensifying the biological process.

With these issues almost all-scientific papers on MBR can be classified. The same list of issues was used to identify relative importance of each of the issues. The results of this search are presented in Figure 4. Here again from the year 2002 there is a sharp increase in the amount of published material. During 2002 and 2003 there was a significant higher amount of articles about fouling and cost, decreasing in the year 2004. To better visualise this trend, the absolute amounts of articles are presented in Figure 5.

FIGURE 4 DEVELOPMENTS IN RESEARCH TOPICS

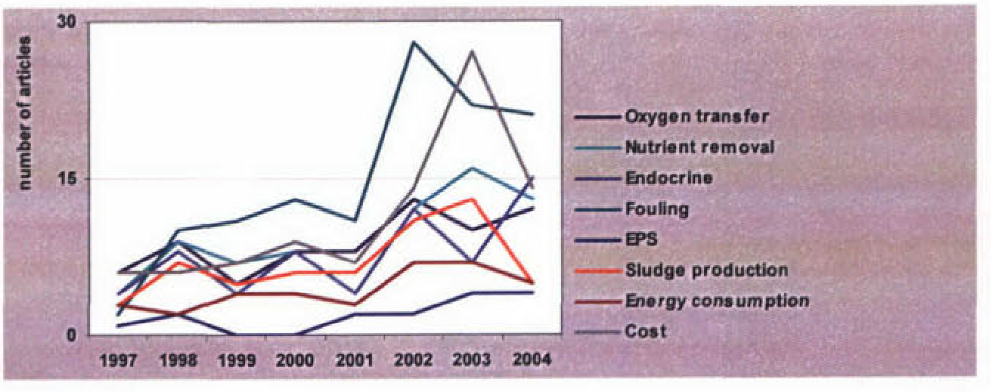


a.



b.

FIGURE 5 DEVELOPMENTS IN RESEARCH TOPICS, PRESENTED AS ABSOLUTE NUMBERS



1.3 IDENTIFYING RESEARCH TRENDS WITH DATABASE OF SCIENTIFIC PAPERS

1.3.1 METHODOLOGY

For a more detailed survey of scientific literature a selection was made of papers published between 2000 and 2005. Each selected article was screened and summarised in a database entry. From each paper the main topics were noted, as well as the research approach, the applied membrane type and the type of wastewater that is treated, see for an example Appendix III.

SELECTION CRITERIA

To obtain more insight in actual research topics and the developments in recent research, a selection of scientific articles was made.
The articles were selected with the following criteria:

1. *Year of publication*
MBR is a relatively new technique, especially in municipal wastewater treatment. Since the year 2000 the number of MBRs treating municipal wastewater is increasing considerably which is held to be an indication of the maturity of the technology. Therefore only articles published from 2000 and onwards are included in the database.

2. *Subject: MBR*
The article is relevant for MBR and deals with activated sludge and membranes (microfiltration/ultrafiltration) for sludge-water separation. Extractive MBRs and aeration MBRs are left out of this study.

3. *Scientific relevance*
This report describes the state of the science, therefore only papers with a certain scientific content were selected. The paper has to be published either in refereed journals or presented at scientific conferences.

4. *Subject: (Municipal) Wastewater*
The described MBR is treating wastewater. The research should be aiming at applications in municipal wastewater treatment or its results are useful for this application. Industrial applications are therefore included only to a limited extent. Decentralised MBRs are not included since this study aims at large scale centralised MBRs.
In this way 133 scientific papers were selected for further analysis with a database. The distribution of year of publication is presented in Table 1. For the year 2005 only two articles were found, these articles are not included in the further database analysis. The amounts of articles that was returned with Scirus and WebSPIRS for the period 2000-2005 were respectively 179 and 182.

TABLE 1 DISTRIBUTION OF SELECTED ARTICLES PER YEAR OF PUBLICATION

Year	Number of articles
2000	37
2001	14
2002	39
2003	25
2004	16
2005	2

1.3.2 RESULTS

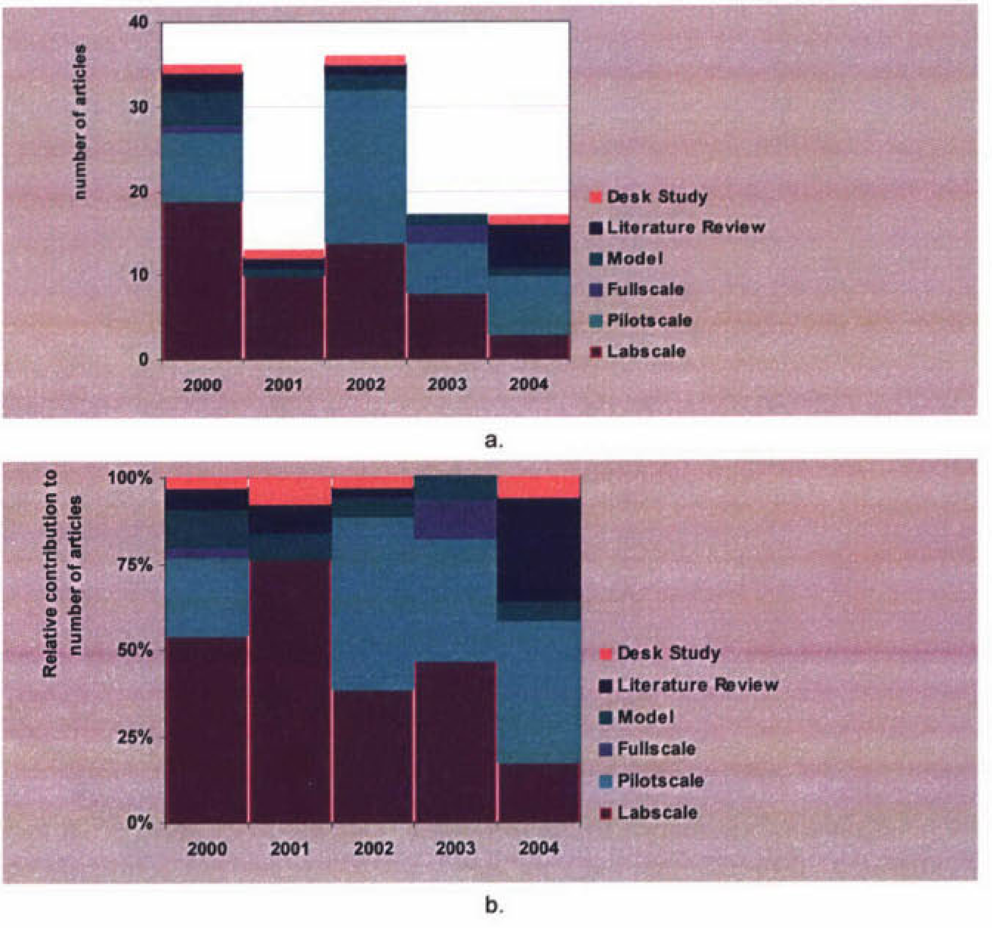
RESEARCH APPROACH

The research approach as described in the selected articles can be divided in five categories:

- desk study;
- literature review;
- model;
- full scale;
- pilot scale;
- lab scale.

The graphical presentation is shown in Figure 6. Some articles apply a double approach, for example labscale research combined with a computational model. Remarkable is the dip in publications for the year 2001.

FIGURE 6 DISTRIBUTION OF RESEARCH APPROACHES AS OBTAINED FROM LITERATURE DATABASE

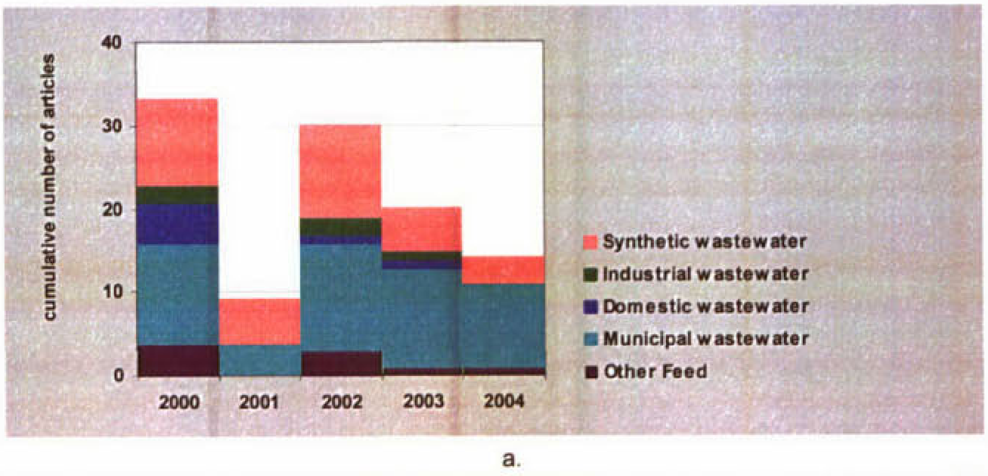


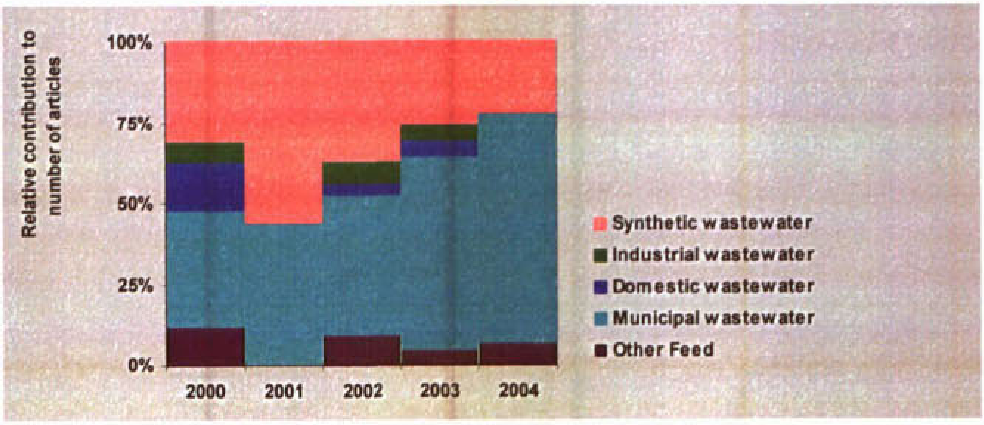
TREATED WASTEWATER

The distribution of the different types of wastewater that is treated with the described MBR is presented in Figure 7. Both the total amount and the relative contribution of papers describing synthetic wastewater are decreasing over the past 5 years.

The number of papers on municipal wastewater did not change very much, but with the decreasing part of the other types its relative contribution increases.

FIGURE 7 DISTRIBUTION OF TREATED WATERS AS OBTAINED FROM LITERATURE DATABASE





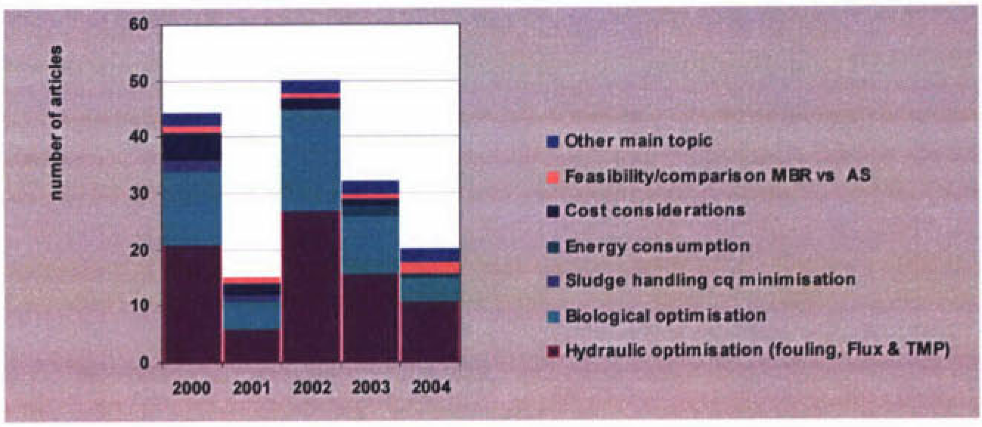
MAIN TOPIC OF RESEARCH

All articles were classified with respect to the main topic of the research. From the list of topics in the database form maximally two choices could be selected, the list was as follows:

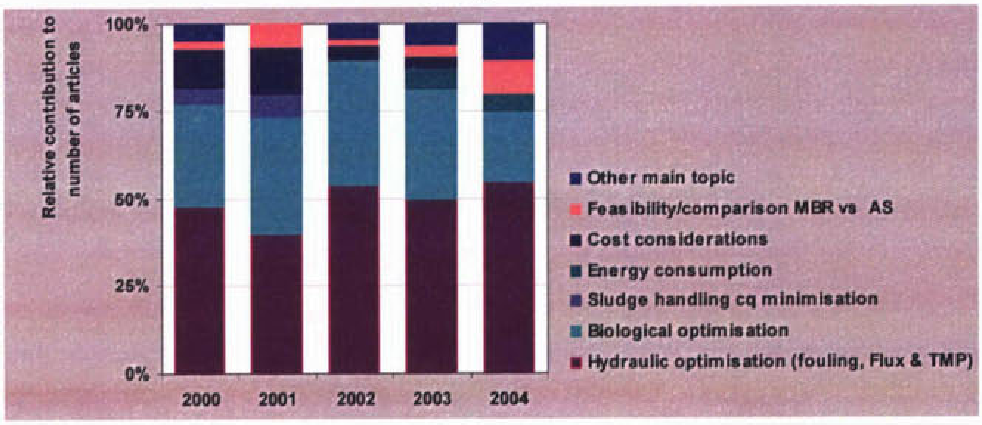
- hydraulic optimisation. This topic includes fouling studies, studies to optimise-applied flux and TMP, cleaning regimes, etc.;
- biological optimisation. Treatment efficiency, treatment of micropollutants, etc.;
- sludge handling and waste sludge minimisation;
- energy consumption;
- cost considerations;
- feasibility/comparison MBR-conventional AS;
- other main topic.

Figure 8 shows the distribution of the respective main topics, treated in the research papers. Hydraulic optimisation is definitely the major topic in all studies. Almost every researcher is firstly interested in achieving a high throughput with low input. Next interesting research item is the quality of the effluent and system optimisation with respect to this. Interestingly, even in 2004 some 10% of the studies was dedicated to comparing MBR with conventional AS.

FIGURE 8 DISTRIBUTION OF MAIN TOPICS IN MBR RESEARCH AS OBTAINED FROM LITERATURE DATABASE



a.



b.

DESCRIPTION OF GOOGLE

Google stands alone in its focus on developing the "perfect search engine," defined by co-founder Larry Page as something that, "understands exactly what you mean and gives you back exactly what you want." To that end, Google has persistently pursued innovation and refused to accept the limitations of existing models. As a result, Google developed its own serving infrastructure and breakthrough PageRank™ technology that changed the way searches are conducted.

From the beginning, Google's developers recognised that providing the fastest, most accurate results required a new kind of server setup. Whereas most search engines ran off a handful of large servers that often slowed under peak loads, Google employed linked PCs to quickly find each query's answer. The innovation paid off in faster response times, greater scalability and lower costs. It's an idea that others have since copied, while Google has continued to refine its back-end technology to make it even more efficient.

The software behind Google's search technology conducts a series of simultaneous calculations requiring only a fraction of a second. Traditional search engines rely heavily on how often a word appears on a web page. Google uses PageRank™ to examine the entire link structure of the web and determine which pages are most important. It then conducts hypertext-matching analysis to determine which pages are relevant to the specific search being conducted. By combining overall importance and query-specific relevance, Google is able to put the most relevant and reliable results first.

- PageRank Technology: PageRank performs an objective measurement of the importance of web pages by solving an equation of more than 500 million variables and 2 billion terms. Instead of counting direct links, PageRank interprets a link from Page A to Page B as a vote for Page B by Page A. PageRank then assesses a page's importance by the number of votes it receives.

  PageRank also considers the importance of each page that casts a vote, as votes from some pages are considered to have greater value, thus giving the linked page greater value. Important pages receive a higher PageRank and appear at the top of the search results. Google's technology uses the collective intelligence of the web to determine a page's importance. There is no human involvement or manipulation of results, which is why users have come to trust Google as a source of objective information untainted by paid placement.

- Hypertext-Matching Analysis: Google's search engine also analyzes page content. However, instead of simply scanning for page-based text (which can be manipulated by site publishers through meta-tags), Google's technology analyses the full content of a page and factors in fonts, subdivisions and the precise location of each word. Google also analyses the content of neighboring web pages to ensure the results returned are the most relevant to a user's query.

Google's innovations don't stop at the desktop. To bring its accurate and speedy search results to users accessing the web through portable devices, Google also pioneered the first wireless search technology for on-the-fly translation of HTML to formats optimised for WAP, i-mode, J-SKY, and EZWeb. Currently, Google provides its wireless technology to numerous market leaders, including AT&T Wireless, Sprint PCS, Nextel, Palm, Handspring, and Vodafone, among others.
http://www.google.com/intl/en/corporate/tech.html

DESCRIPTION OF SCHOLAR.GOOGLE BETA

Google Scholar enables you to search specifically for scholarly literature, including peer-reviewed papers, theses, books, pre-prints, abstracts and technical reports from all broad areas of research. Use Google Scholar to find articles from a wide variety of academic publishers, professional societies, preprint repositories and universities, as well as scholarly articles available across the web.

Just as with Google Web Search, Google Scholar orders your search results by how relevant they are to your query, so the most useful references should appear at the top of the page. This relevance ranking takes into account the full text of each article as well as the article's author, the publication in which the article appeared and how often it has been cited in scholarly literature. Google Scholar also automatically analyses and extracts citations and presents them as separate results, even if the documents they refer to are not online. This means your search results may include citations of older works and seminal articles that appear only in books or other offline publications.
http://www.scholar.google.com/scholar/about.html

DESCRIPTION OF SCIRUS

Scirus is the most comprehensive science-specific search engine on the Internet. Driven by the latest search engine technology, Scirus searches over 167 million science-specific Web pages, enabling users to quickly:

- pinpoint scientific, scholarly, technical and medical data on the Web;
- find the latest reports, peer-reviewed articles and journals that other search engines miss;
- offer unique functionality's designed for scientists and researchers.

Scirus has proved so successful at locating science-specific results on the Web that the Search Engine Watch Awards voted Scirus 'Best Specialty Search Engine' in 2001 and 2002.

Scirus returns results from the whole Web, including access-controlled sites that other search engines don't index. Scirus currently covers over 167 million science-related Web pages, including:

- 58.5 million .edu sites;
- 18 million .org sites;
- 6.8 million .ac.uk sites;
- 18.6 million .com sites;
- 5 million .gov sites;
- Over 45 million other relevant STM and University sites from around the world.

In addition to Web pages, Scirus indexes the following special sources:

- 311,065 e-prints on ArXiv.org;
- 6,515 BioMed Central full-text articles;
- 2,175 e-prints through Cogprints;
- 1,500 documents via DiVa;
- 28,510 full text articles from Project Euclid;
- 56,310 full-text articles on Crystallography Journals Online;
- 13 million patent data via LexisNexis;
- 33,050 course ware from MIT OpenCourseWare;
- 12,265 NASA technical reports;
- 15.2 million MEDLINE citations via PubMed;
- 285,500 articles via PubMed Central;
- 163,800 documents via RePEc;
- 5.6 million ScienceDirect full-text articles;
- 318,760 full-text journal articles on Scitation;
- 7,300 articles via SIAM;
- 2,080 documents via T-Space.

http://www.scirus.com/srsapp/aboutus/

DESCRIPTION OF WEBSPIRS

Using Multi-database searching you can search in one single action in multiple databases. This environment offers you access to 20 databases amongst which Current Contents, Compendex, Inspec and Pascal. You can combine these databases according to your own needs.

APPENDIX II

RESULTS FROM INTERNET SEARCHES

RESULTS FROM SCIRUS.COM

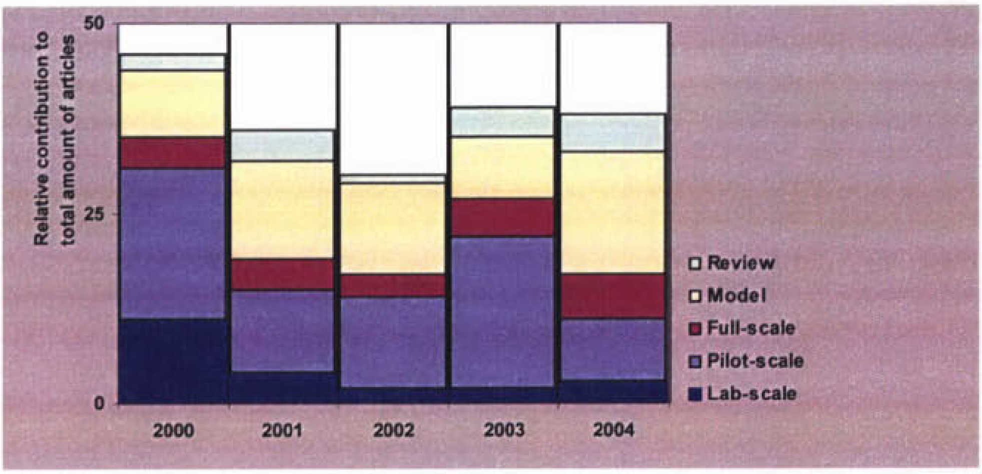
		journal	web
752	wastewater or waste AND water AND membrane AND bioreactor and (municipal or domestic or synthetic) ANDNOT (extractive OR tannery OR "drinking water")	280	472
1997		26	1
1998		21	0
1999		17	8
2000		19	8
2001		26	12
2002		47	23
2003		41	57
2004		39	331
2005		7	27
404	title:membrane AND title:bioreactor ANDNOT (title:extractive OR title: tannery OR title:"drinking water") (1997 – 2005)	289	115

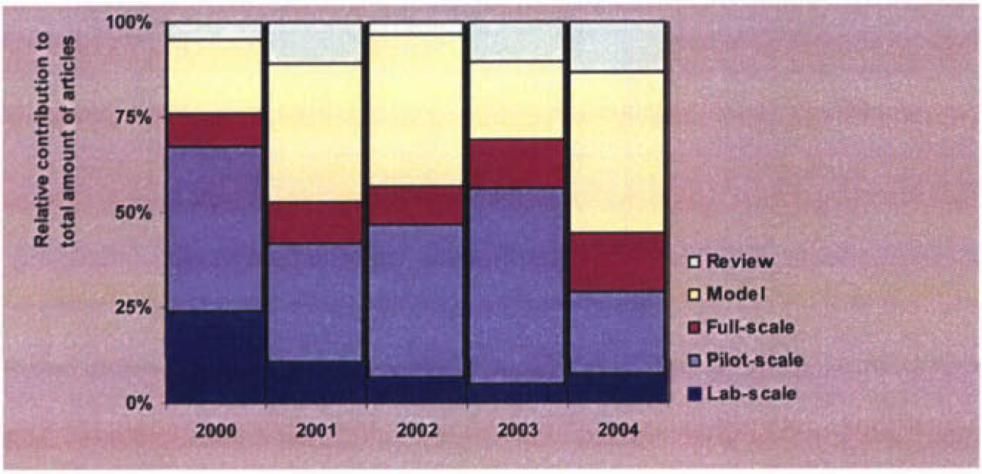
RESULTS FROM SCHOLAR.GOOGLE

1,170	for membrane bioreactor wastewater		
231	municipal OR domestic OR synthetic "membrane bioreactor" -extractive -oil -tannery -drinking-water	1997	5
		1998	10
		1999	15
		2000	13
		2001	28
		2002	35
		2003	23
		2004	11
23	for **all in title**: wastewater OR waste OR water OR municipal OR domestic O synthetic "membrane bioreactor" -oil -tannery -drinking-water -extractive	1997	0
		1998	1
		1999	3
		2000	1
		2001	2
		2002	2
		2003	2
		2004	1
6	for membranbelebungsverfahren		
1	for membranbioreaktor		
9	for bioréacteur à membrane		
1	for traitement eau BRM		
0	for membraanbioreactor		

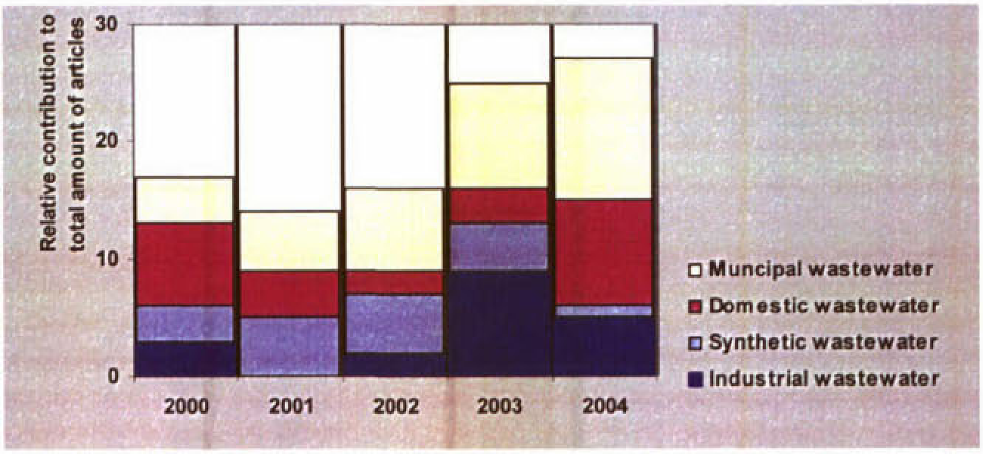
RESULTS FROM TREND SEARCHES WITH WEBSPIRS

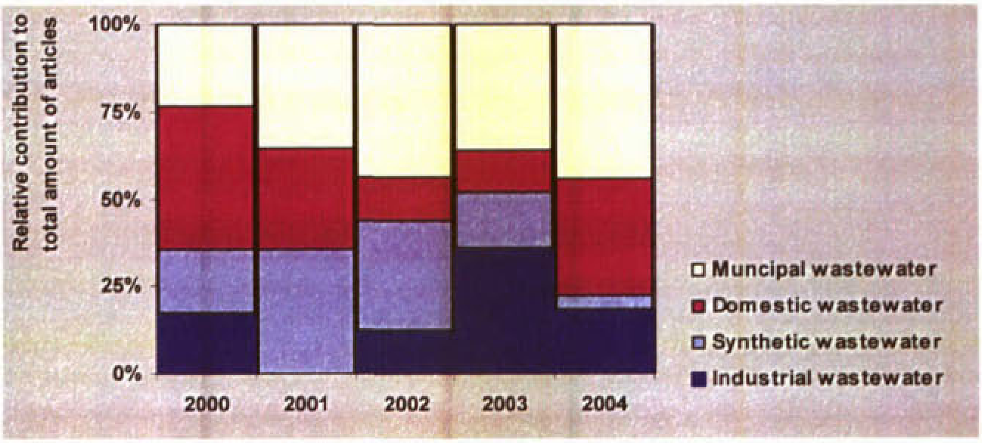
RESEARCH APPROACH



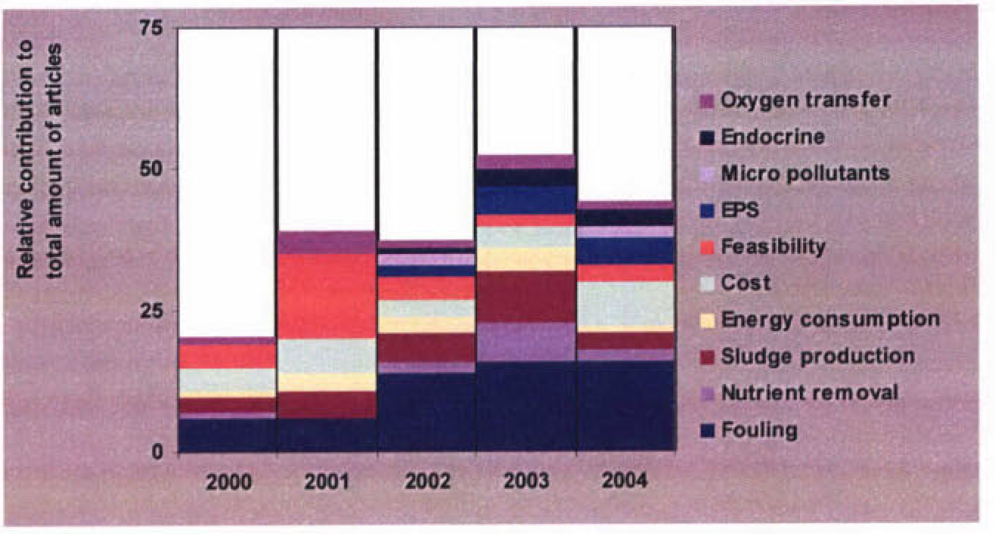


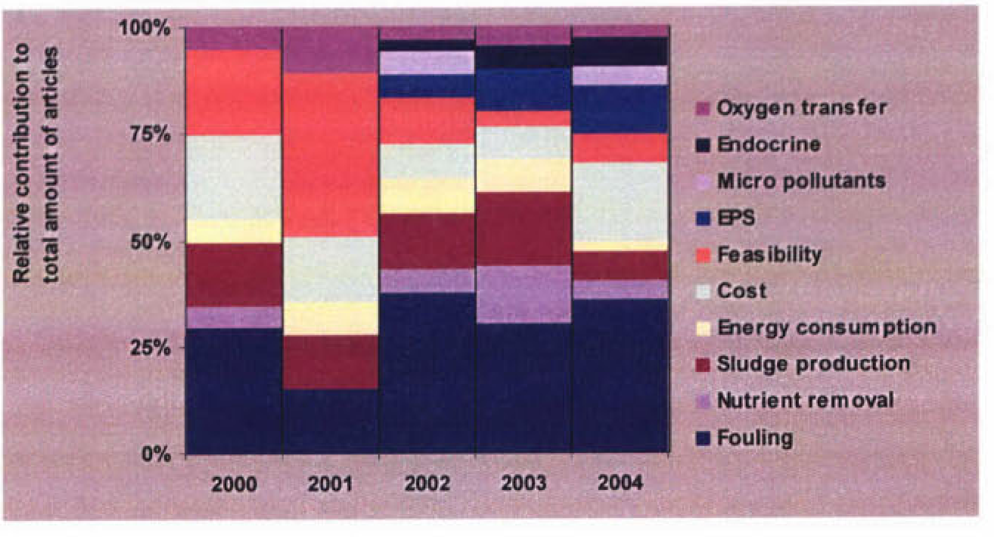
TREATED WATEWATER





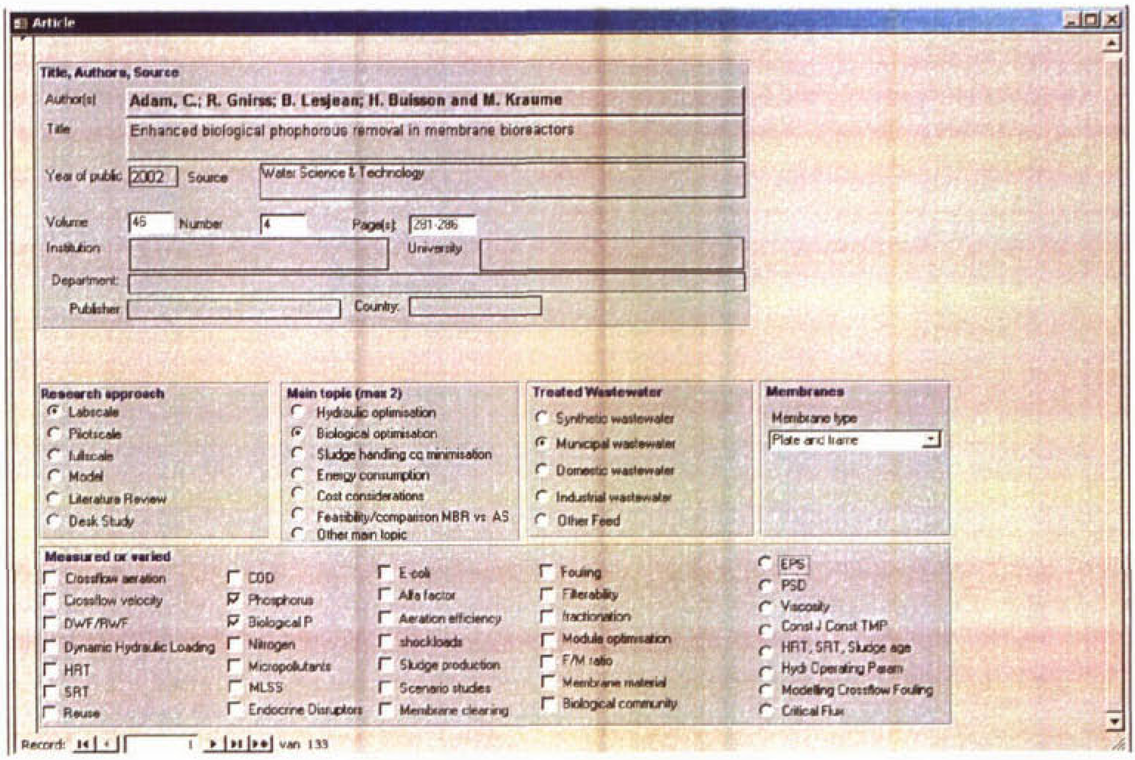
MAIN TOPIC OF RESEARCH





APPENDIX III

DATABASE FORM FOR DATABASE SCIENTIFIC PAPERS



Article

Title, Authors, Source

Author(s): Adam, C.; R. Gnirss; B. Lesjean; H. Buisson and M. Kraume

Title: Enhanced biological phophorous removal in membrane bioreactors

Year of public: 2002 Source: Water Science & Technology

Volume: 46 Number: 4 Page(s): 281-286

Institution: University:

Department:

Publisher: Country:

Research approach
- Labscale
- Pilotscale
- fullscale
- Model
- Literature Review
- Desk Study

Main topic (max 2)
- Hydraulic optimisation
- Biological optimisation
- Sludge handing cq minimisation
- Energy consumption
- Cost considerations
- Feasibility/comparison MBR vs AS
- Other main topic

Treated Wastewater
- Synthetic wastewater
- Municipal wastewater
- Domestic wastewater
- Industrial wastewater
- Other Feed

Membranes

Membrane type: Plate and frame

Measured or varied
- Crossflow aeration
- Crossflow velocity
- DWF/RWF
- Dynamic Hydraulic Loading
- HRT
- SRT
- Reuse
- COD
- Phosphorus
- Biological P
- Nitrogen
- Micropollutants
- MLSS
- Endocrine Disruptors
- E coli
- Alfa factor
- Aeration efficiency
- shockloads
- Sludge production
- Scenario studies
- Membrane cleaning
- Fouling
- Filterability
- fractionation
- Module optimisation
- F/M ratio
- Membrane material
- Biological community
- EPS
- PSD
- Viscosity
- Const J Const TMP
- HRT, SRT, Sludge age
- Hydr Operating Param
- Modelling Crossflow Fouling
- Critical Flux

Record: 1 van 133

APPENDIX IV

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APPENDIX V

LIST OF REVIEW ARTICLES

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APPENDIX VI

QUESTIONNAIRE

Global Water Research Coalition

stowa

QUESTIONNAIRE

'RESEARCH NEEDS IN THE FIELD OF MEMBRANE BIOREACTORS'

to be used as input for the
Research Strategy Workshop on
Membrane Bioreactors for Wastewater Treatment
to be held April 25-27, 2005 in the Netherlands

INTRODUCTION

The application of membrane bioreactors (MBR) for wastewater treatment is gaining significant attention, reflected by the large amount of scientific articles (several hundreds) that have been published on this subject during the past five years. All over the world pilot plant trials are being carried out and every month new full-scale applications are being commissioned.

The start-up of the full scale MBR at the Varsseveld wwtp in the Netherlands has been seized by the Global Water Research Coalition (GWRC) as an opportunity to evaluate the current State of the Science with regard to MBR technology in the year 2005 in order to streamline future research and applications. To support this aim a literature review is being prepared, which will be discussed at the workshop "*Research Strategy Workshop on Membrane Bioreactors for Wastewater Treatment*", to be held in conjunction with the opening of the Varsseveld MBR, April 25, 26 and 27 2005. The project is conducted by Witteveen+Bos Consulting Engineers under supervision of STOWA.

QUESTIONNAIRE

Parallel to the State-of-the-Science desk study this questionnaire is being sent to all GWRC members and other, by GWRC members, invited partners. The objective of the questionnaire is to directly solicit input from the GWRC members on this topic to support the development of a State-of-the-Science report. The survey focuses on scientific research as well as practical applications. The questionnaire contains 11 questions and aims to identify the bottle-necks and knowledge gaps in the field of MBR technology for municipal wastewater treatment as indicated by research institutions world-wide. The results of this questionnaire will be used as input for the discussion during the mentioned workshop.

In case you intend to redirect or distribute this questionnaire to other or partner organisations with expertise on MBR for municipal wastewater treatment,
please inform STOWA as soon as possible by e-mailing uijterlinde@stowa.nl

INSTRUCTIONS

Please complete the questionnaire by *March 15, 2005* and (e-)mail or fax the form to:
Cora Uijterlinde *uijterlinde@stowa.nl*

STOWA
Stichting Toegepast Onderzoek Waterbeheer
P.O. Box 8090
3503 RB Utrecht
The Netherlands
TELEFAX: +31 (0)30 232 1766

QUESTIONS

If you have any questions or remarks about this questionnaire, do not hesitate to contact:
ir. C.A. Uijterlinde at *uijterlinde@stowa.nl* or +31(0)30 232 1199, or
dr.ir. A.F. van Nieuwenhuijzen at a.vnieuwenhuijzen@witbo.nl, or +31(0)570 69 73 17 / 74 67

GENERAL QUESTIONS

1a Please provide the following information:

Name

Organisation

E-mail

I will be attending the GWRC Research Strategy Workshop on Membrane Bioreactors for Wastewater Treatment, April 25, 26 and 27, 2005, Varsseveld, the Netherlands[1]. Yes / No

1b If others from your organisation are planning to attend the Workshop, please provide the following information:

Name

Title

E-mail

2a I am involved in MBR research as:

2b My involvement in MBR-research dates back to:

3a Please list available reports or publications by your organisation that provide an overview of MBRs for municipal wastewater treatment (indicate if electronically available).

3b Please provide a list of your organisation's completed, ongoing and planned research activities on MBRs.

3c Please provide a (prioritised) list of your organisation's current research needs related to MBRs

TECHNICAL QUESTIONS

4 In my opinion, the driving force for the current growth in MBR applications is (choose max. 2 options):
- the increase in fundamental knowledge obtained by research during the past ten years
- the increase in operational experience, obtained by pilot plant research and full scale references realised during the past ten years
- the effluent quality that the MBR produces
- the reduced foot print of the MBR compared to conventional activated sludge systems
- the fact that MBR technology is fancy, relatively new, innovative
- the decreased investments cost, due to cheaper membranes
- the achievements in the development of membrane materials and modules
- others, explain:______________________________________

5a From all the scientific articles on MBRs I have read, the following I remember as presenting the best *scientific research approach*, yielding the most valuable results/insights:

Title:

Author(s):

Published/Presented in/at:

Title:

Author(s):

Published/Presented in/at:

5b The strong point(s) of the research mentioned under 5a. is/are:

6a Of all articles on the MBR I have read, the following I remember as presenting the most valuable results/insights for *practical application* of MBR to municipal wastewater treatment:

Title:

Author(s):

Published/Presented in/at:

Title:

Author(s):

Published/Presented in/at:

6b The strong point(s) of the research mentioned under 5a. is/are:

7 In my opinion, further implementation of the MBR in municipal wastewater treatment is :
- not to be expected
- limited to specific cases
- expected
  Please, explain your choice:

8 From a scientific point of view, the most important research question(s) in MBR research that need(s) to be answered in the near future is/are:

1. ______________________________

2. ______________________________

3. ______________________________

9 The research questions mentioned in question 8. can be addressed most appropriately by (choose max. 2 options)
- lab-scale research
- pilot plant research
- up-scaling to demonstration scale, together with applied research
- computational modelling of the MBR process
- cost evaluation studies
- other,

10 The following issues associated with MBR, specific for my country/region, need special consideration in the State-of-the-Science report:

11 I would like to make the following remark(s) regarding MBR research:

Thank you kindly for your co-operation,

Cora Uijterlinde

[1] costs for travel and accommodation are for own expenses

APPENDIX VII

RESULTS QUESTIONNAIRE DUTCH MBR PLATFORM

The Questionnaire was also presented to the Dutch MBR platform group in which representatives of water boards and consultancy firms meet each other for exchange on operational experience and research projects. The response of the Dutch MBR platform group is presented in the following lines. From the 11 questions 4 questions are selected.

RESPONSE RATE

From the 24 questionnaires that were sent around, 16 were returned, from a total of 15 organisations including water boards, consultancy firms and universities.

CURRENT RESEARCH NEEDS

The open question concerning current research needs resulted in the following list , with in the last column the frequency of mentioning.

ranking	topic	times mentioned
1	Effluent quality (micro's, nutrienten, MTR)	9
2	Flux en TMP optimisation	7
3	Fouling control	7
4	Compactness / small scale	3
5	Costs	3
6	Combination with other techniques	1
7	Energy	1

DRIVING FORCE FOR CURRENT DEVELOPMENTS IN MBR APPLICATION

This multiple-choice question resulted in the following scores.

driving force	score
Increase in fundamental knowledge	0
Increase in operational experience	8
Effluent quality	7
Reduced footprint	2
MBR is fancy, new, innovative	4
Decreased investment costs	1
Better membrane modules	1
Others (upcoming EWFD, lower operational cost)	2

MOST IMPORTANT RESEARCH QUESTIONS FOR NEAR FUTURE

This open question resulted in the following list, again with ranking and frequency.

ranking	topic	times mentioned
1	Fouling control	10
2	Higher fluxes, lower TMP	6
3	(decrease in) Energy consumption	4
4	Effluent quality	3
5	Membrane lifetime	2
2	others *	8

*simple operation, biology, pretreatment, oxygenation, cleaning, permeate withdrawal, costs

RESEARCH APPROACH TO TACKLE RESEARCH QUESTIONS

This multiple-choice question resulted in the following scores.

ranking	topic	times mentioned
1	pilot plant	9
2	demonstration+applied research	8
3	lab scale	4
4	modelling	2
5	other (looping: lab, pilot, full scale)	2
6	cost evaluation studies	1

COMPARING THE ANSWERS OF CURRENT AND NEAR FUTURE RESEARCH NEEDS

ranking	current research needs	near future research needs
1	Effluent quality (micro's, nutrienten, MTR)	Fouling control
2	Flux en TMP optimisation	Higher fluxes, lower TMP
3	Fouling control	(decrease in) Energy consumption
4	Compactness / small scale	Effluent quality
5	Costs	Membrane lifetime
6	Combination with other techniques	Others *
7	Energy	

*simple operation, biology, pretreatment, oxygenation, cleaning, permeate withdrawal, costs

It is interesting to see that the ranking is changed. The experts expect that operational optimisation will be the most important issue for the coming years. If the mentioned issues are grouped the following ranking comes out for current and future research needs.

Topic	ranking current research needs	ranking near future research needs
Effluent quality (micro's, nutrients, MTR)	1	3
Fouling control	2	1
Compactness / small scale	3	
Costs	4	
Combination with other techniques	5	
Energy	6	2
Membrane lifetime		4
Others		5

APPENDIX VIII

REVIEWS WER 2001-2004, INCLUDING REFERENCES

GENERAL

Membrane-biological processes. Pilot plant studies were carried out using actual wastewater to investigate the applicability of a membrane separation activated sludge process to municipal wastewater treatment (Murakami et al., 2000). No significant difference was observed in the dewaterability of the separated activated sludge between the membrane and conventional systems. An easily installed wastewater treatment plant was developed using a membrane bioreactor (MBR) process (Ogoshi and Suzuki, 2000). The results were satisfactory in all areas, except the durability of membrane permeability in the latter half of the experiment. For both hollow fiber type and plate type, membrane permeability immediately decreased due to the deposit of concentrated sludge cake on the surface, even though continuous bubble washing had been made. A two-stage pilot-scale system comprising secondary sequencing batch reactor treatment and tertiary microfiltration was operated for the treatment of Beer-Sheva municipal wastewater (Messalem et al., 2000). The unit, which has a nominal filtration area of 4 m2, treated 4-5 m3 of sewage per day, at a nominal rate of about 500 L/h. Further treatment by microfiltration resulted in a BOD < 5 mg/L, TSS < 1 mg/L, turbidity < 0.2 NTU, and bacterial counts showed 6-log removal of coliforms and fecal coliforms. A lab-scale experiment on the performance of highly concentrated activated sludge in high strength fermentation wastewater treatment with rotary disk type UF membrane was carried out (Lu et al., 2000). TOC and NH4-N removals were good and intermittent aeration operations increased total-N removal efficiency. Treatment of a 2,4-dichlorophenoxyacetic acid (2,4-D) contaminated wastewater in a MBR was investigated (Buenrostro-Zagal et al., 2000). Overall, the MBR was an effective configuration for removing 2,4-D while at the same time avoiding the active biomass exposure to the low pH and high salinity concentration of the influent.

A cross-flow MBR for raw municipal wastewater treatment, consisting of a suspended growth bioreactor and a ceramic membrane ultrafiltration unit, was run over a period of more than 300 days in a wastewater treatment plant (Fan et al., 2000). At a sludge retention times of 20 days the MBR was successfully run over 70 days without the need for chemical cleaning. However chemical cleaning had to be undertaken every 3-5 days at shorter sludge retention times. In order to elucidate optimum operational parameters, five series of experiments with bench scale MBR devices was carried out (Yoon et al., 2000b). There were no recognisable differences in removal efficiencies for BeD (99%) and total-N (60%). Coupling biological treatment with membrane separation was described for wastewater treatment (Cote and Thompson, 2000). Results from the first year of operation of a 3,800 m3/d plant were presented. In order to verify the treatment performance of newly developed johkasous with membrane separation, for household use, three johkasous of different types were investigated (Ohmori et al., 2000). Periodical cleaning of the membrane by sodium hypochlorite solution and neutralising cleaning wastewater by sodium thiosulfate solution every six months was important to maintain a steady permeability of the membranes. A 162-day pilot-scale operation for reclamation of urban wastewater was conducted using an ultrafiltration MBR (Xing et al., 2000).

Performance of the MBR was investigated at sludge retention times of 5, 15, and 30 days, a hydraulic retention time of 5 h, and membrane fluxes between 75 and 150 L/m2-h. Trials in a MBR with activated sludge concentrations of up to 48 g/L showed that oily wastewater also containing surfactants was biodegraded with high efficiency (Scholz and Fuch, 2000). During the different loading stages of the MBR operation a removal rate of 99.99% could be achieved for fuel-oil as well as lubricating oil at a hydraulic retention time of 13.3 h. A laboratory-scale experiment was conducted to investigate the influence of organic loading rate to a reactor on the biofouling in a membrane separation activated sludge system (Nagaoka et al., 2000). A reactor with higher loading rate showed a sudden increase of transmembrane pressure, while a reactor with lower loading rate showed delayed increase of the pressure.

Membrane Bioreactors. Lubbecke (2001) reported on the growing interest in the concept of membrane biology for industrial wastewater treatment. With membrane techniques, unlike conventionally used sedimentation, freely selectable operationally safe retention and upgrading of biomass with significantly less space was possible. The physical and biological characteristics of a tangential-flow membrane bioreactor (MBR) for the treatment of municipal wastewater were presented (Xing et al, 2001). Average removal of COD, ammonia nitrogen, and suspended solids were 95, 96.2 and 100%, respectively. Ozaki and Yamamoto (2001) studied the hydraulic effects on sludge accumulation on membrane surface in crossflow filtration. Maximum sludge accumulation and sludge accumulation rate were dependent on aeration intensity and were less dependent on flow channel width and MLSS concentration. The effects of wastewater quality and mode of operation on the performance of an symmetric, hollow fiber, polysulfone UF membrane (MWCO = 100,000 Da) were investigated (Bourgeous et al., 2001). A conceptual model of the impact of insufficient backwash and constantflux operation on membrane performance was presented to explain the differences in fluxes. A two-phase anaerobic reactor system with a submerged membrane in the acidogenic reactor was designed for the enhancement of organic acid conversion and methane recovery (Lee et al., 2001). COD removal efficiency was 80% and the methane production showed 0.32 m3/kg COD removed for the submerged membrane system in the anaerobic digester. Wastewater high in phenolic content (948 mg/l) and dissolved solids (5.4 g/l) was treated to remove organic material and toxic compounds using a high-pressure bioreactor (HPB) (Male and Pretoruis, 2001). The HPB was more stable than the activated sludge plant. Yamagishi et al (2001) investigated ammonia removal from synthetic wastewater containing phenol, which is inhibitory to nitrification, by using a single-stage activated sludge process with cross-flow filtration. A novel hybrid process combining liquid-liquid extraction and a membrane bioreactor was designed to treat biorefractory organic pollutants in waste streams containing high concentrations of inorganics (Liu et al., 2001). The effects of UF membrane surface properties on Pseudomonas aeruginosa biofilm initiation were investigated (Pasmore et al., 2001). Biofilm initiation by a strain of Pseudomonas aeruginosa increased as the surface became rougher and more hydrophobic, while fouling was minimal when surface charge was minimized. Parameshwaran et al. (2001) studied the MF of secondary effluent from a SBR used to process industrial waste. Crossflow had no effect on flux and intermittent dead-end filtration was less productive than nonintermittent operation.

Chang et al. (2001) studied the feasibility of a submerged membrane bioreactor (MBR) fitted with three pore-sized NWPP (Non-Woven Poly-Propylene) membranes. The performance was compared with that of a conventional polysulfone (PS) membrane material. The PS membrane achieved a 7-log reduction in total coliforms; the NWPP membranes achieved only a 2 to 4-log reduction. Consequently, low-cost NWPP membranes could be considered suitable

for use in MBR processes for municipal wastewater treatment, but were possibly less suited to domestic wastewater reuse where disinfection is a prerequisite.
Membrane bioreactors (MBRs)—the coupling of the activated sludge biological treatment process with the use of a microfiltration (MF) or ultrafiltration (UF) membrane for solids separation—offer several benefits over the conventional activated sludge process when producing water for reclamation. Operating parameters and performance of MBR installations throughout the world were compared (Adham et al. 2001). The first nine months of operation of a 1,890 m3/d (0.5 mgd) MBR showed excellent performance and filtrate water quality (ReVoir et al., 2001). Side by side comparison of the operation of a biologically aerated filter and an MBR treating grey and black water showed that the MBR performed better in terms of effluent turbidity and total coliform concentration (Jefferson et al., 2001). For flow rates up to 18,927 m3/day (5 mgd), an MBR installation was shown to be not cost competitive with a more conventional reclamation process scheme—oxidation ditch followed by granular media filtration—unless the reclamation process requires reverse osmosis (Merlo et al., 2001). During a 135-day pilot trial of an MBR (using an external ceramic membrane), no discernible effect on the stable performance of the MBR system was seen over the range of operating parameters, sludge concentration and loading rates (Xing et al., 2001)

Lee et al. (2001) conducted a study in which alum and natural zeolite were added to a submerged membrane bioreactor (MBR) not only to reduce membrane fouling but also to increase the removal of nitrogen and phosphorus.

A technological assessment of four technologies for in-building water recycling in the United Kingdom showed the membrane bioreactor process to be technically and economically better than the other options studied. The use of MBR technology for inbuilding water recycling, however, was only economically viable when recovering black water (Palmer et al, 2002).

The performance and cost-effectiveness of 19 different treatment trains for producing reclaimed water were compared to the water quality requirements of 12 different reuse applications for King County, Washington. The study showed that treatment trains might be laid out with the flexibility of starting with a simple facility and adding or modifying unit processes to meet the water quality requirements of new reuse opportunities (Bucher et al., 2002). Following this initial screening, two trains were selected for pilot testing: primary treatment/ biological aerated filter/filtration and membrane bioreactor. The testing showed that both trains could successfully meet the State of Washington's Class A water quality requirements (Wallis-Lage et al., 2002). The positive results were confirmed by additional pilot testing with a different MBR system at rates up to 30.4 L/m2/hr (17.9 gfd) (Tekippe et al., 2002).

A number of process combinations were examined for the Loudon County Sanitation Agency's (Virginia) future Broad Run Advanced Wastewater Treatment facility to meet water quality requirements, including phosphorus removal. Membrane bioreactors (MBR), combined with granular activated carbon (GAC) or powdered activated carbon (PAC), were the most cost effective alternatives (Fleischer and Broderick, 2002). Pilot testing, in which the MBR operated at an average flux of 34.6 L/m2/hr (20.4 gfd) and a sustained peak flux of 52.0 L/m2/hr (30.6 gfd), confirmed the results of the study (Fleischer et al., 2002). MBRs can provide cost-effective options for upgrading small wastewater treatment facilities to produce high-quality water suitable for reuse, as illustrated by two case studies (Bernal et al., 2002). Pilot testing of an MBR treating municipal wastewater in Irvine, California showed excellent removal efficiencies for conventional pollutants, no removal of cyanide and 99% removal of mercury (Spangenberg et al., 2002). A 22,700 m3/d (6 mgd) MBR facility is being constructed in Redlands, California to treat primary effluent and produce recycled water for cooling at a power plant (Headrick et al., 2002). Results from MBR pilot trials were submitted for consideration by reclaimed water regulators for the States of California, Arizona, Florida and Washington. While most States would not provide a blanket acceptance for proprietary technology, it was hoped that the submitted information would provide a foundation for accepting the technology on future projects (Adham et al., 2002).

A pilot-scale MBR was operated in parallel with a full-scale conventional activated sludge plant treating polyester textile finishing factor wastewater. The MBR achieved a higher COD and color removal then the conventional plant, and would allow the reuse of the water in the dying process (Malpei et al., 2002).

Constable et al. (2003) compared performances of the MBR with the extended aeration activated sludge system treating a highly saline industrial wastewater. The MBR provided lower effluent suspended solids concentrations. Higher mixed liquor suspended solids concentrations could be maintained in the MBR resulting in effective nitrogen and COD removal. The results of pilot testing provided basic data required for design of a full scale MBR facility. Togna et al. (2003) conducted a laboratory test to determine treatment efficiency and process design parameters of a thermophilic MBR to treat high strength beverage wastewater. The influent COD ranged from 40 000 mg/L to 60 000 mg/L. Therefore, the MBR had to be designed to operate at thermophilic conditions. The results indicated that the BOD removal efficiency could be expected to exceed 95%. As a result of thermophilic conditions, the yield of biosolids was low (0.04 mg TSS per mg COD removed). Hangsrom et al. (2003) discussed the implementation of a modified approach for MBR design and operation. The use of the modified approach resulted in a significant reduction of construction cost and simplified the plant operational strategy. Pilot testing results were presented to confirm new concepts explored as part of the proposed approach. Xing et al. (2003) presented the results of theoretical investigation of excess sludge production in MBRs. Based on mass balances of sludge and substrate, a model for predicting the excess sludge production was proposed and verified by experimental data. The effects of kinetic parameters and operating conditions were discussed for various types of wastewater, and the strategy was proposed to minimize the excess sludge production. Song et al. (2003) investigated the effect of sludge ozonation on excess sludge generation in MBRs. Ozonation was found to be effective for minimisation of excess sludge production as well as for enhancement of nutrient removal. Gui et al. (2003) adopted an orthogonal array design to investigate effects of operational parameters on sludge accumulation on membrane surfaces in a submerged MBR. A set of operating conditions was defined at which no sludge deposits occurred. Rosenberger and Kraume (2003) introduced a procedure determining filterability of activated sludge in MBRs. The results indicated that the filterability was mostly affected by the composition of the liquid phase. No effect of SS concentration, extractable EPS concentration, and sludge viscosity on biomass filterability was found. Ng and Hermanowicz (2003) discussed the performance of an MBR and a completely mixed activated sludge system at an SRT ranging from 0.25 d to 5 d and an HRT from 3 h to 6 h. Even at the shortest SRT studied, COD removal efficiency in the MBR ranged from 97% to 98% compared to the COD removal efficiency of 77.5% in the completely mixed activated sludge system. Experimental data indicated that when nitrification was not required, it was feasible to operate an MBR at short

SRTs producing high effluent quality. Hibiya (2003) observed complete BOD and nitrogen removal in a single MBR where biofilm was fixed on a hollow – fiber membrane. Simultaneous nitrification and denitrification was achieved by using various types of bacteria distributed vertically and horizontally in a single reactor. Baek and Pagilla (2003) compared the performance of aerobic and anaerobic MBRs. The anaerobic MBR exhibited lower solids deposition rate, while the COD removal efficiency in both reactors was similar. The results suggested that an anaerobic MBR could be a feasible and economical option for municipal treatment plants. Thompson et al. (2003) reported the results of operating the MBR wastewater treatment facility in the City of Epping, New Hampshire. The Zenon process was used based on the operating data from similarly sized facilities. High effluent quality and effluent turbidity levels of less than 0.1 NTU were reported.

Submerged MBR. Air-lift was verified to be a more efficient mode to aerate wastewater compared to the air-jet mode in a submerged MBR (Chang and Judd, 2002). With intermittent aeration, a lab-scale submerged membrane activated sludge system was investigated under different aeration intervals. The removal of total Kjeldahl nitrogen (TKN) and ammonium nitrogen varied in the ranges of 87.8-99.1% and 89.4- 99.8%, respectively (Hasar et al., 2002). Respirometric needs of heterotrophic populations developed in an submerged MBR working in sequenced aeration was determined by Rodde-Pellegrin et al. (2002). The results showed that oxygen needs depended on the substrate, the acclimation of the micro-organisms, and the soluble organic traction of the wastewater. Rodriguez et al. (2002) studied the application of anaerobic bioreactor with immersed membrane for wastewater treatment. Aerobic treatment of municipal wastewater in a MBR was studied. After 535-day's performance, the COD was reduced by 95%, nitrification was complete and up to 82% of the total nitrogen could be denitrified (Rosenberger et al., 2002). Using a flat submerged MBR, (Shim et al., 2002b) studied the design and operation considerations for synthetic wastewater. Under operating conditions with 12 to16 h hydraulic retention time and 8000-16000 mg/L sludge concentration, COD removal efficiency was above 98%, nitrification was above 95%. The microbiological aspects of a submerged MBR for aerobic treatment of municipal wastewater was studied by Witzig et al. (2002). The results suggested that bacteria present in the highly concentrated biomass of the MBR used the energy supplied for their maintenance metabolism and were not in a physiological state characteristic for growth.

A comparative study of the aeration systems for submerged MBRs showed that fine bubble aeration is more efficient, concerning oxygen supply, by a factor of three than a coarse bubble system (Cornel et al., 2003). In a related study, Krause et al. compared methods for measuring the oxygen transfer rate (OTR) in full-scale MBR systems (Krause et al., 2003). Filter modules made of common mesh material were submerged in a bioreactor. The reactor removed 30-60% TOC with various molecular weights below 105 (Fan et al., 2003). A submerged tubular ceramic MBR was operated with a prolonged SRT of 200 days in order to achieve a 99% reduction in disposed sludge (Sun et al., 2003). The formation and fate of soluble microbial products (SMP) in membrane bioreactor (MBR) was studied at various sludge retention times (SRT) for 170 days. Acclimated organisms in a long SRT could decompose higher molecular weight organics (Shin and Kang, 2003a). Tay et al. investigated the effect of HRT on the performance of a submerged MBR with a prolonged SRT. The MBR achieved over 90% COD removal regardless of the HRT, but sludge production increased as HRT decreased. An optimal HRT of 12 hours was
suggested (Tay et al., 2003b). Nutrient Removal. An MBR was compared to a conventional activated-sludge process under limiting operating conditions at a wastewater treatment plant performing carbon removal, nitrification and denitrification. For low SRTs of two to seven days and HRTs ranging from five to eighteen hours, the MBR had better carbon and nitrogen

removal than the conventional process. The MBR was more robust under low SRTs since the membrane prevented washout of nitrifiers (Soriano et al., 2003).
High strength ammonium wastewater was treated with an MBR under oxygen limitation, in order to accumulate nitrite for subsequent anaerobic oxidation of ammonium with nitrite (nitritation). Nitritation remained possible at ambient temperatures, with reduced ammonia concentrations, and with nitrogenous wastewater with some biodegradable carbon (Wijffels et al., 2003b). A high strength nitrogenous wastewater was treated successfully using an MBR performing simultaneous nitrification and denitrification. Microelectrode studies showed oxygen penetrating 300-700 µm from the membrane into a 1600 µm biofilm, and FISH studies revealed ammonia-oxidizing located near the outer surface of the membrane (Terada et al., 2003). Similarly, a hollow-fiber MBR functioning as a vertical plug flow performed simultaneous nitrification and denitrification. Nitrification rates were highest near the influent area, and ammonia-oxidizing bacteria were mainly distributed inside the biofilm while denitrifying bacteria were mostly in the suspended sludge (Hibiya et al., 2003). Semmens et al. (2003) reported carbon removal and simultaneous nitrification and denitrification within a hollow-fiber MBR until excess biofilm accumulation caused failure. Autotrophic denitrification in hollow-fiber MBRs is dependent upon the pH, which requires systems to be buffered or have pH-control. Additionally, calcium precipitation acts as a sink for carbonate and offsets alkalinity production from denitrification. Lee and Rittmann (2003) discuss the dependence of field applications on water chemistry. Enhanced biological phosphorus (Bio-P) removal was achieved to effluent concentrations of 0.1 mg/L in bench and pilot scale MBRs treating municipal wastewater. Post treatment with P-adsorption onto activated clay and precipitation achieved the required 50 µg/L effluent standard (Gnirss et al., 2003).

Applications. Wastewater from the beamhouse section of a tannery was treated with a 3.5 L membrane sequencing batch reactor (MSBR). For a wastewater with 550 and 90 mg/L COD and ammonium, respectively, removal efficiencies neared 100% for ammonium and 90% for COD (Goltara et al., 2003). A sequencing anoxic/anaerobic membrane bioreactor was developed to treat household and toilet wastewater. Enhanced Bio-P and nitrogen removal was achieved with 90% and 63%, respectively. When compared with a similar configuration where mixed liquor is recycled between zones continuously, the sequencing reactor had an anoxic phase 2.3 times shorter (Ahn et al., 2003). The increasingly stringent regulation of wastewater discharge from ships was reviewed. Differences in wastewater from cargo, military, and cruise ships are presented along with treatment options (Anon, 2003a). Graywater from ships' galley and laundry water was treated with an 1800 L MBR with approximately 100% recycling of biomass. DGGE analysis of the bacterial population over 100 days revealed a diverse and unstable population with food spikes causing significant changes in community structure, but the MBR met its effluent quality standards 90% of the time regardless (Stamper et al., 2003).

EFFLUENT QUALITY

Nutrients Removal. Enhanced biological phosphorus (Bio-P) removal study was conducted successfully in a bench-scale MBR. Investigations with P-spiking showed higher Bio-P potential as P-removal increased up to 20-25 mg/L while P-TS rose up to >6% (Adam et al., 2002). A Polysulfone hollow fiber bioreactor was proved to be the effective way in the denitrification process. The effect of sludge age on the performances of an ultrafiltration pilot MBR operating with real wastewaters was tested to analyse its ability to remove nutrients and micropollutants and the possible decrease in waste sludge production (Innocenti et al., 2002). Nitrogen removal in a cascaded MBR was investigated by Kubin et al. (2002) in two different plants, it showed that operation without internal circulation and operation with several nitrification chambers resulted in lower ammonium effluent concentrations. Enhanced Bio-P and nitrogen removal process was adapted to MBR in three pilot plants. Efficient Bio-P removal could be achieved in pre- and post-denitrification configurations. When spiking with phosphate, high Bio-P removal of 35-40 mg/L could be achieved and P/TS stabilised around 7.5% (Lesjean et al., 2002). A process coupling membrane electrolysis and electrodialysis is implemented to treat ammonium nitrate wastewater. When nitric acid concentration varied from 1 to 8 mol/L, the average current efficiency was 58 % (Gain et al., 2002). The degradation and elimination efficiency for hardly eliminable and hardly biodegradable polar compounds by MBR was monitored by mass spectrometer. The results showed that the elimination of alkylphenolethoxylates and lipid regulating agents were more successful than the conventional activated sludge process (Schroder, 2002). The effect of aeration and nonaeration time on simultaneous organic, nitrogen and phosphorus removal was investigated using a laboratory-scale intermittent MBR. The MBR consisted of two compartments and with a surface area of 0.35 m2. Results showed that longer non- aeration time in the second compartment provided better performances of biological phosphorus removal (Ujang et al., 2002).

A pilot-scale hollow-fibre MBR was tested for partial or total nitrification, the results obtained can be used for full scale implementation (Delgado et al., 2002a). A combination of cell immobilisation and membrane aeration approaches was used in a MBR to treat NH4 + in wastewater. The reactor removed 95% of ammonium, added at 1.97 g N/m2 • d, with O2 enriching the membrane (Hsieh et al., 2002). A series of pseudosteady-state experiments on a novel hollow fiber MBR used for denitrification of oligotrophic waters were conducted by Lee and Rittmann (2002). The system could achieve nitrate removals between 39% and 92%, effluent nitrate between 0.4 and 9.1 mg N /L, effluent nitrite less than 1 mg N /L, effluent hydrogen below 0.1 mg H2 /L, and a 42 min liquid retention time. Reemtsma et al. (2002) studied the suitability to remove poorly degradable polar wastewater contaminants by testing the removal of sulfurorganics. The data provided no indication that MBR would improve the removal of polar poorly biodegradable organic pollutants. Performance of NH3-rich wastewater nitrification in a membrane-assisted bioreactor system with sludge ages of 40 and 32 days was examined. Shortening sludge age from 40 to 32 days did not cause a significant diversity in number and component of metazoa and protozoa populations (Zabczynski et al., 2002).

Another project carried out in California, USA assessed the new technology of submerged membrane bioreactors (MBRs) for water re-use. The MBRs were examined in both nitrification and denitrification mode and both MBR systems showed good removal of BOD, TOC and micro-organisms. They both produced a high quality effluent that could be used by the RO membranes for water re-use. (Lawrence *et al*, 2003)

A membrane-assisted bioreactor (MBR) for sustained nitrite accumulation was used to treat a synthetic wastewater with total ammonium nitrogen (TAN) concentrations of 1 kg N m3 at a hydraulic retention time down to 1 day (Wijffels et al., 2003). Complete biomass retention was obtained by microfiltration with submerged hollow fiber membranes. A membrane flux up to 189.5 l/m2d could be maintained at a suction pressure below 100 kPa. Oxygen limitation was shown to be the most important factor to sustain nitrite accumulation. Nevertheless, nitrification was possible at ambient temperature (22-24°C), lower ammonia concentration (<7 g-N/m3), and when using raw nitrogenous wastewater containing some biodegradable carbon.

Reclamation and Recovery. A pilot-scale study of MBR treatment for wastewater reclamation permeate was conducted in Denmark and received low COD in the permeate (Andersen et al., 2002). A lab-scale study was conducted to evaluate the feasibility of a combined process of coagulation-flocculation with filtration through hollow-fibre membranes as tertiary treatment of the effluent of a conventional activated sludge plant for crop irrigation reuse (Delgado et al., 2002b). Using the advanced integrated wastewater pond systems R technology and reverse osmosis, Downing et al. (2002) received lower cost and lower energy consumption compared with the conventional activated sludge secondary treatment followed by microfiltration and reverse osmosis. Ferreira et al. (2002) studied the recovery of aromatic amine and phenolic compounds from wastewater using membrane aromatic recovery system by pilot-scale and showed the potential for application of such process. Microfiltration with ceramic membranes was tried out for the activated sludge of a chemithermomechanical pulp mill. Ultrasound and nitric acid were found as effective cleaning methods in the cases studied (Luonsi et al., 2002). Noronha et al. (2002) developed a hybrid process concept (biological COD reduction using MBR, and subsequent bacterial germs, residual organic and inorganic compounds reduction by nanofiltration and UV disinfection) to treat spent process fruit juice wastewater. By testing the on-site operation of a pilot plant, the treated water was partially desalted and fulfilled the Germany chemical and bacteriological standards. A laboratory-scale MBR assisted with granular activated carbon filtration to reclaim the treated domestic wastewater was investigated. The combined process resulted in complete odour removal. A 4.2 log10 CFU and 3.7 log10CFU removal were observed for total coliforms and E. coli, respectively (Van et al., 2002). Xu et al. (2002b) studied the application of turbulence promoters in a ceramic MBR used for municipal wastewater reclamation. The introduction of winding inserts was effective in increasing permeate flux. The average COD reduction was more than 95%.

Malpei et al. tested the ability to upgrade an existing textile wastewater treatment facility in order to reuse the effluent internally. A hollow fiber MBR pilot plant was installed in an extended aeration system, and effluent reached a feasible quality for reuse in the textile plant (Malpei et al., 2003).

EDC. Endocrine disrupter removal from wastewater was studied using MBR and NF technology. Results indicated that more than 90% of nonylphenol and bisphenol were removed (Wintgens et al., 2002).

FOULING CONTROLE

An automated electrophoretic membrane cleaning rig was developed for microfiltration and ultrafiltration to reduce the membrane fouling at different variables (Ahmad et al., 2002). Albasi et al., (2002) conducted an experiment to study the management of membrane fouling and the influence of initial permeability choice of operation conditions. The degree of membrane fouling by different size fractions of particles in the activated sludge wastewater was examined, smaller particles more likely played important role in membrane fouling (Bai and Leow, 2002). Carbohydrates were used to converse cellulose in MBR (Belafi-Bako et al., 2002). The membrane fouling problem was reviewed by Chang et al. (2002). According to Chang, the most important influence factors were biomass characteristics, operation conditions and membrane characteristics. Under variable throughput operation, both the feasibility of designing smaller membrane plants and the fouling reasons were studied (Chua et al., 2002). The impact of various operating factors on membrane fouling in activated sludge submerged MBR was studied. The results showed that membrane fouling was influenced by membrane type and module configuration, rate and extent of permeate flux, and noncontinuous membrane operation (Hong et al., 2002).

A bi-stage fouling hypothesis of channel clogging and gel layer formation was presented. A fouled membrane was restored to 94% of the original permeability with a method for channel clogging prevention and a multi-step chemical cleaning procedure for removal of the gel layer (Hong et al., 2003). Two air sparging techniques were compared in terms of their ability to control membrane fouling in a submerged MBR. The air-lift mode sufficiently removed the cake layer, while the air-jet mode suffered from accumulated sludge clogging. If clogging was prevented by a periodic cleaning regime, air-jet produced a higher flux than air-lift (Chang and Judd, 2003). The role of worm growth or oligochaetes in controlling sludge production was compared in an MBR and a conventional activated sludge reactor. Although worm blooms decrease sludge yield and improve settling in a conventional system, worms did not naturally reproduce in the MBR and had no affect on the sludge production (Wei et al., 2003).
Fouling of a microfiltration MBR removing soil-derived humic substances was reduced by biological pretreatment of the water. The fouling layer thickness was reduced by half after biological treatment, while prechlorination had no impact (Wend et al., 2003). Sludge production was reduced 3 to 10 times in a non-immersed MBR operated with optimised operating parameters (Trouve et al., 2003). Yoon et al. (2003) introduced an MBR - sludge disintegration (MBR-SD) system to prevent excess sludge production. In the system, disintegrated sludge is recycled to the bioreactor as a feed solution, and a mathematical model was developed to describe the process.

HYDRAULIC OPTIMISATION

Modules and Parameters. A submerged hollow fibre membrane module was studied on operational considerations and design aspect (Fane et al., 2002). Separation of rhenium from a dilute aqueous waste stream of a catalyst manufacturing plant by a thin film composite polyamide membrane was studied. The separation data by graphical method of combined film theory-solution-diffusion model was analysed (Lamba et al., 2002). A model was developed for predicting effluent quality and membrane fouling behaviour for the submerged MBR combing the activated sludge model with a membrane fouling model (Lee et al. 2002). A formula for computing hydraulic retention time in a MBR was derived based on the micro-organism kinetic model (Zhang et al., 2002b).

An internal MBR was developed with submerged flat membrane plates, with advantages of compactness, reduced sludge production and high effluent quality (Cornelissen et al., 2002). A yeast MBR had the potential to treat high salinity wastewater containing high organic concentration compared with a yeast pretreatment followed by bacterial MBR (Dan et al., 2002).

Rosenberger and Kraume (2002) investigated the filterability of activated sludge in MBR. The composition of the liquid phase was found to have the most effect on the filterability of activated sludge. If the treated wastewater contained considerable amounts of proteins and polysaccharides, extra cellular polymer substances concentration increased with high mechanical stress in MBR and high F/M ratios.

A development program for the application of the MBR in municipal wastewater treatment was implemented in Netherlands. After two years of intensive research, the MBR had been extended to demonstration scale (van der Roest et al., 2002).

Morrison et al. (2002) used an ultrafiltration membrane bioreactor for biodegradation of MTBE in contaminated water. Within 120 days, the culture adapted to membrane operational conditions and was able to biologically remove greater than 99.95% of both MTBE and TBA. Zoh and Stenstrom (2002a) applied a bench-scale anoxic membrane bioreactor (MBR) for treating wastewater containing alkaline hydrolysis by-products (hydrolysates) of RDX. The MBR system removed 80–90% of the carbon sources (acetate, formate and formaldehyde), and approximately 90% of the stoichiometric amount of nitrate, 60% of nitrite.

Blocher et al. (2003) investigated the performance of a membrane bioreactor treating fruit juice industry wastewater. Net permeate flux of the immersed membranes varied between 5 and 12 L/m2-h at transmembrane pressures ranging from 60 to 200 mbar. The system operation was monitored continuously for a year, however, the weak performance could not be attributable to one single parameter; the results warranted further research. Mosquera-Corral et al. (2003) investigated the treatment of wastewater produced by the tuna cookers of a fish-canning factory. Three sequentially arranged reactors, anaerobic-anoxic-aerobic, were used to treat the wastewater. For the anoxic process, when available carbon was present denitrification percentages of 80% were obtained with a COD/N ratio of 4. The nitrification process was successful, and the removal percentages of COD and N were at 90% and 60% with an R/F ratio between 2 and 2.5. Oyanedel et al. (2003) investigated the performance of a membrane assisted hybrid bioreactor treating an anaerobic effluent from a fishcanning factory. Results indicated that it was feasible to achieve ammonia and COD removals of around 99% at organic loading rate of 6.5 kg COD/m3-day and nitrogen loading rate of 1.8 kg NH4-N /m3-day. This study (Lugowski et al., 2003) tested the applicability of a submerged vacuum ultrafiltration (UF) membrane technology in combination with the biological treatment system to treat foodprocessing wastewater. Results indicated that bioreactors operated at a low solids retention time and in combination with UF can achieve superior effluent quality that may meet reuse criteria at a reasonable cost.

Soriano et al. (2003) compared the performance of conventional activatedsludge (CAS) to the membrane bioreactor (MBR) process at a low solids retention time (SRT) and low hydraulic residence time (HRT). The MBR process provided higher carbon and nitrogen removal efficiency. Zuehlke et al. (2003) operated two MBR pilot plants in parallel to a full scale CAS over a period of 20 months. All the plants were fed with the same wastewater that contained steroids. The two MBR plants achieved significantly higher steroid removal efficiency than the conventional treatment process.

MODELLING

Applying the activated sludge model (ASM3) to a special configuration of a membrane bioreactor, a mathematical model for continuous aerobic membrane bioreactor (MBR) was developed (Gehlert and Hapke, 2003). The model was calibrated by using a global search algorithm to simulate the treatment of an artificial wastewater. A mathematical model for the submerged membrane bioreactor (SMBR) was developed to study the effects of soluble microbial products on membrane fouling (Cho et al., 2003). F/M ratio and SRT were found as major factors of the soluble microbial products (SMP) concentration in a reactor and the results indicated that SMP could play an important role in membrane fouling and water quality simultaneously. Mathematical expressions for filtration resistances like cake layer forming and fouling were combined with an activated sludge model (ASM) to describe biological wastewater treatment in a submerged capillary hollow fiber membrane reactor (Wintgens et al., 2003). The model was successfully used to simulate the long-term decrease in permeability of the membranes and the final effluent quality in terms of standard parameters.

BIOLSOLIDS AND SLUDGEMANAGEMENT

The reduction of sludge production in a two-stage, completely mixed reactor followed by an activated sludge system with two different types of solidliquid separation was tested by Ghyoot and Verstraete (2000). It was illustrated that a membrane-assisted bioreactor (MBR) system for solid-liquid separation yielded a 20-30% lower sludge production than a conventional activated sludge (CAS) system under similar conditions of solids retention time and organic loading rate.

Ghyoot and Verstraete (2000) compared the performance of different two-stage systems for the treatment of synthetic wastewater. The first stage was a completely mixed reactor without sludge retention for the stimulation of dispersed bacterial growth. The second stage was an activated sludge system in which growth of protozoa and metazoa was stimulated. Solid-liquid separation was achieved either by sedimentation (conventional activated sludge system) or submerged membrane filtration (membrane-assisted bioreactor, MBR, system). Overall, the two-phase system based on conventional activated sludge had a major point of weakness in the wash-out of suspended solids, while the one based on the MBR was hampered by too intensive grazing on the nitrifiers, increased N and P concentrations, and wash-out of soluble COD.

Adham et al. (2000) provided an overview of the use of membrane bioreactors (MBRs) for water reuse applications. The performance of thin-film composite reverse osmosis (RO) membranes downstream of four different pretreatment processes—microfiltration (MF), ultrafiltration (UF), MBR, and lime clarification—was tested in San Diego. The results showed consistent and stable performance with the MF and UF processes, consistent performance but with shorter run times with the MBR, and relatively short run times with lime clarification (Gagliardo et al., 2000). The parallel testing of two different immersed MBR units in San Diego produced high-quality effluent suitable for being fed to RO units or water reuse applications (Merlo et al., 2000). Parallel operation of an immersed MBR against a side-stream MBR allowed comparison of several performance indicators; in both cases the effluent quality remained below reuse standards (Jefferson et al., 2000). MBR units were in operation at twenty small-scale treatment facilities to treat wastewater from commercial and residential facilities for direct and indirect nonpotable reuse (Fournier, 2000).

Ghyoot et al. (2000) bioaugmented a conventional activated sludge system (CAS) and a membrane bioreactor (MBR) with a 3- chlorobenzoate (3CBA) degrading Pseudomonas putida BN210. The bioaugmentation in the MBR increased tolerance towards 3CBA shock loading in terms of improved COD removal.

Lab- and pilot-scale activated sludge reactors with integrated microfiltration membranes were analysed with FISH (Rosenberger et al., 2000). Only 40% to 50% of all bacteria emitted probe conferred fluorescence sufficient for detection, compared to around 80% detectable in conventional activated sludge. The authors suggested that membrane bioreactors might be operated with significantly reduced secondary sludge production. In a similar study, the bacterial communities in pilot-scale membrane-separation bioreactors (MBR) using FISH and DGGE were analysed (Luxmy et al., 2000). The authors found that the alpha- and beta-subclass Proteobacteria were the dominant groups, and that ammonia-oxidizers were present, mostly in the form of clusters or aggregates. In addition, DGGE showed that MBR communities were different from conventional activated sludge communities with dissimilarity indexes more than 0.6. The effect of elevated temperature on the bacterial community structure in bioreactors treating synthetic wastewater was studied using DGGE (LaPara et al., 2000). Distinct bacterial consortia were supported at temperatures of 25, 35, 45, 55, and 65^{0}C, and measurable differences in the abilities of the communities to degrade wastewater were reported.

OTHERS

Bacterial community analysis was performed from an MBR treated synthetic municipal wastewater. A significant community shift occurred during the first seven days of operation, and a Flavobacterium-like population dominated the community for the remainder of the experiment. Comparison of reactor effluent and reactor fluid showed that filtration was partially responsible for pollutant removal (Klatt and LaPara, 2003).

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