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Membrane bioreactor technology for wastewater treatment and reuse

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Abstract

Treatment technology for water recycling encompasses a vast number of options. Membrane processes are regarded as key elements of advanced wastewater reclamation and reuse schemes and are included in a number of prominent schemes world-wide, e.g. for artificial groundwater recharge, indirect potable reuse as well as for industrial process water production. Membrane bioreactors (MBRs) are a promising process combination of activated sludge treatment and membrane filtration for biomass retention. This paper will provide an overview of the status of membrane bioreactor applications in municipal wastewater reclamation and reuse in Europe and will depict their potential role in promoting more sustainable water use patterns. Particular attention will be paid to the impact of MBR technology on emerging pollutants. A case study will be presented on a full-scale MBR plant for municipal wastewater which is operated by Aquafin in Belgium.

Keywords: Wastewater reclamation; Water reuse; Membrane bioreactors; Trace pollutants

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1. Membrane technology for wastewater treatment — general features of MBR systems

A membrane bioreactor (MBR) combines the activated sludge process with a membrane separation process. The reactor is operated similar to a conventional activated sludge process but without the need for secondary clarification and tertiary steps like sand filtration. Low-pressure membrane filtration, either microfiltration (MF) or ultrafiltration (UF), is used to separate effluent from activated sludge [1]. The two main MBR configurations involve either submerged membranes or external circulation (side-stream configuration) (Fig. 1).

This paper will focus on submerged MBRs as this is the configuration more often applied in municipal wastewater treatment. Membranes applied in submerged MBRs can be either hollow fibre membranes or plate membrane module design. The main operating conditions are summarised in Table 1.

Sufficient pre-treatment has to be installed to prevent clogging of the membranes by fibres, hairs, or other extreme contents. Pre-filtration with a grid distance of maximum 3 mm has been advised.

As in most membrane filtration processes the flux declines during filtration. This is mainly caused by membrane fouling. Controlling membrane fouling is the key issue in the operation of an MBR. Membrane fouling is significantly influenced by the hydrodynamic conditions, by membrane type and module configuration and by the presence of higher molecular weight compounds,

Table 1
Operating conditions for submerged MBR [2–6]

Parameter	Value
Flux	
instantaneous, L/(m² h)	25–35
sustainable in long term operation, L/(m² h)	15–30
Transmembrane pressure, kPa	20
Biomass concentration, gMLSS/L	5–25*
Solids retention time (SRT), d	>20
Sludge production, kgSS/(kgCOD d)	<0.25
Hydraulic retention time (HRT), h	1–9
Food/micro organisms ratio (F/M), kgCOD/(kgMLSS d)	<0.2
Volumetric load, kgCOD/(m³ d)	up to 20
Air flow rate, Nm³/h per module	8–12
Operational temperature, °C	10–35
Operating pH	~7–7.5
Backwash frequency, min	5–16
Backwash duration, s	15–30
Energy consumption for filtration, kWh/m³	0.20–0.40
for membrane aeration, %	80–90
pumping for permeate extraction, %	10–20

*12–15 g/L is advised, higher concentrations can cause operational problems like clogging of the membrane and decreased oxygen transfer efficiency

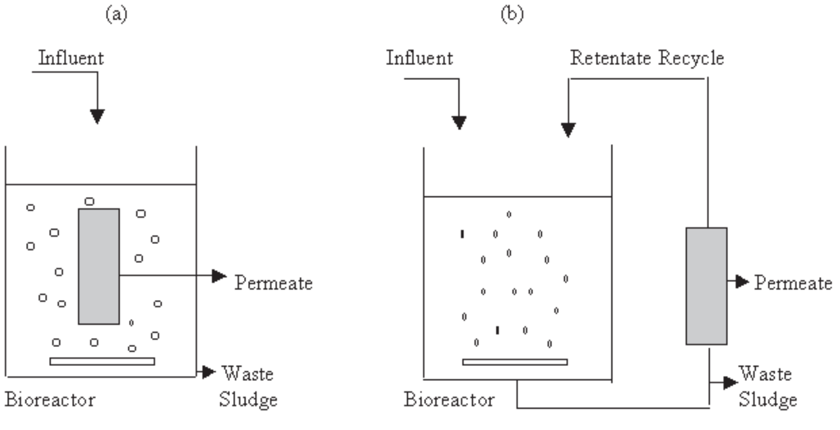

Fig. 1. Configuration of MBR systems: (a) submerged MBR, (b) side-stream MBR configuration.

which may be produced by microbial metabolism or introduced into the sludge bulking process (e.g. poly-electrolytes).

For continuous separation of activated sludge with high MLSS concentrations, only cross-flow filtration is suitable. Shear forces can be used to control the cake layer formation, so that a stable flux is attained. In a submerged MBR, these shear forces are induced by the turbulence of uprising air and liquid in the submerged membrane modules. The air flow-rate used to agitate the membrane fibres is a critical parameter with respect to the rate of membrane fouling. Severe membrane fouling occurs above a critical permeate flux or at too low aeration rate. In case of a temporary increase in the permeate flux, membrane fouling can be controlled by increasing the air flow-rate.

Submerged MBRs are usually operated at low differential pressure and well below the critical permeate flux, where fouling control is more feasible. Removal efficiencies and attainable effluent quality for submerged MBRs are given in Table 2.

Furthermore, MBRs can be operated to provide complete nitrification and denitrification. Simultaneous phosphorus removal by precipitation is also possible. Successful biological phosphorous removal has been reported even under conditions of low sludge loading [7]. Correspondingly, effluent qualities of N_{TOT} <10 mg/L (cool climate); N_{TOT} <3 mg/L (warm climate); and P_{TOT} <0.3 mg/L are attainable.

Table 2
MBR removal efficiencies and effluent quality [2,5,6,8–10]

Parameter	Removal efficiency (%)	Effluent quality
TSS, mg/L	>99	<2
Turbidity, NTU	98.8–100	<1
COD, mg/L	89–98	10–30
BOD, mg/L	>97	<5
DOC, mg/L	—	5–10
NH_3-N, mg/L	80 – 90	<5.6
N_{TOT}, mg/L	36–80	<27
P_{TOT}*, mg/L	62–97	0.3–2.8
Total coliforms, CFU/100 mL	5–8 log	<100
Faecal coliforms, CFU/100 mL	—	<20
Bacteriophages, PFU/100 mL	>3.8 log	—

*with a dosage of ferric

MBR systems offer the option of independent selection of hydraulic retention time (HRT) and sludge retention time (SRT), which permits a more flexible control of operational parameters. High sludge concentrations in the bioreactor allow efficient treatment of high-strength wastewater. The retention of activated sludge containing solids and macromolecules in combination with long sludge age extends the contact time of sludge and critical classes of substrates. This allows the development of specialised, slow-growing microorganisms able to remove low-biodegradable pollutants contained in wastewater, resulting in improved removal of recalcitrant compounds (see Section 2).

Because membranes are an absolute barrier for bacteria and in the case of UF also for viruses, the MBR process provides a considerable level of physical disinfection (see Section 2). The main advantages of MBR technology compared to conventional activated sludge systems are:

- smaller footprint and smaller reactor volume as a consequence of higher MLSS concentration and loading rate (option for low to moderate sludge age);
- decreased sludge production (option for high sludge age);
- higher and more consistent effluent quality as a result of membrane filtration;
- lower sensitivity to contaminant peaks.

The main disadvantages of MBRs are:

- relatively expensive to install and operate;
- frequent membrane monitoring and maintenance;
- limitations imposed by pressure, temperature, and pH requirements to meet membrane tolerances;

- membranes may be sensitive to some chemicals;
- less efficient oxygen transfer caused by high MLSS concentrations;
- treatability of surplus sludge is questionable.

2. Impact of MBR technology on micro-organisms and trace pollutants

2.1. Microbiological parameters

The microfiltration membranes applied in MBRs have proven to achieve consistently high removal rates for microbiological parameters such as total coliforms, faecal coliforms and even bacteriophages. The log removal reported varied between 6–8 log for bacteria and 3–5 log scales for viruses [1] . MBR effluents were found to be compliant with the EU Bathing Water Directive (EC/160/75) including parameters such as total coliforms, faecal coliforms, *Streptococcus faecalis* as *Salmonella spp.* and Coliphages [12]. Experiments conducted by Cicek et al. with indicator viruses MS-2, which have an approximate diameter of 25nm and were spiked to the feed of the membrane , revealed a 94.5% removal [13]. A 5.88 log removal for bacteriophages was observed by Ueda et al. in an MBR treating settled sewage and partially attributed to retention by the membrane and adsorption to activated sludge. A 6.86 log removal was found for faecal coliforms. This compares favourably with a conventional activated sludge treatment plant (CAS), showing only 1.31 log reduction for bacteriophages and 2.34 log for faecal coliforms [14].

The favourable microbiological quality of the effluent of MBRs is a major factor in their frequent selection for water reuse, even if full disinfection can not be expected, particularly considering the distribution and storage components of a full-scale system, which can be prone to re-growth of micro-organism and contamination from various sources. But the MBR effluent will be adequate for many water reuse applications with little residual chlorine disinfection for subsequent distribution. A point that has to be raised is integrity monitoring, which is of critical importance for MBRs in reuse schemes. While online-integrity testing is becoming a standard procedure in most membrane processes for drinking water applications [15], it is implemented in wastewater treatment schemes relatively rarely. The biggest MBR system of the world to date, the municipal wastewater treatment plant in Kaarst, Germany, features online particle turbidity measurement in the main effluent discharge line. Periodical integrity testing can be performed with full-scale modules with bubble point or pressure-decay tests.

2.2. Organic micro-pollutants

Several researchers have reported enhanced elimination efficiencies of MBRs compared to conventional activated sludge systems with respect to endocrine disrupting trace pollutants (EDCs) which exhibit estrogenic activity [16,17]. To this date, it is not fully explained what the reasons are for this phenomenon. The nominal molecular weight cut off (NMWCO) of ultrafiltration membranes showed no influence on the elimination [18]. A potential reason could be the shift of NMWCO of the membranes due to the gel layer formed during the operation. Due to the physical properties of these substances it is expected that adsorption onto biosolids and organics of activated sludge may occur. Several studies confirmed that assumption [19–23]. Investigations on the effect of pH on adsorption by several researchers have shown that higher pH values (pH >11) led to an almost complete desorption of EDCs (example: bisphenol A), which generally exhibit phenolic character [19,23]. A further reason could be enhanced biodegradation. Batch experiments investigating this have shown that higher solids retention time led to lower effluent concentration [24,25]. Furthermore, low sludge loading increased the elimination of micro-pollutants. Latest studies on full scale treatment plants confirmed these findings. Therefore it can be stated that usual conditions for the operation of

MBRs, low sludge loading combined with higher solids retention time (>10 d), enhance the elimination of estrogenic micropollutants [19].

3. Small-scale and de-centralised wastewater treatment and reuse options with MBR technology

Since the early MBR installations in the 1990s, the number of MBR systems has grown considerably; projected total European revenue for the MBR market is around €40 million in 2005 with a steady growth rate of 9% thereafter. One key trend driving this continued growth in the next 5–10 years is the use of MBR systems for decentralised treatment and water reuse. Around 60 companies now offer MBR solutions with the majority of the systems originating from 9 main manufacturers. The majority of the currently operating and commissioned plants are small- to medium-size with a large percentage employed for decentralised treatment or water recycling duties.

Comparison with other technologies used for water recycling reveals that MBRs not only produce lower residual concentrations but do so more robustly than the alternatives [28,29]. That is to say the distribution of effluent qualities produced shows less variation in MBR processes compared to the other technologies. In the case of grey water treatment with a submerged flat plate MBR, a UF tubular membrane and a biologically aerated filter (BAF), the MBR was the only technology to meet the reuse standard of 10 mg/L BOD 100% of the time. The BAF also met the standard over the majority of the monitoring period, but exceeded the limit 5% of the time (Fig. 2). This reduces the need for downstream chlorination as 99.5% of the chlorine demand comes for the oxidation of organics rather than the disinfection of microbiological contaminants.

The successful introduction of MBR systems into small scale and decentralised applications has led to the development of packaged treatment solutions from most of the main technology suppliers. Commercially available systems include the package treatment plant Clereflo MBR (Conder Products, UK), designed to service populations up to 5000 and the ZeeMOD® (Zenon Environmental Inc.) which is available for flow rates of up to 7500 m^3/d. Most of the manufactures offer similar systems which has meant that effluent qualities of 5:5:5 [mg/L] (BOD: NH_4-N:SS) are

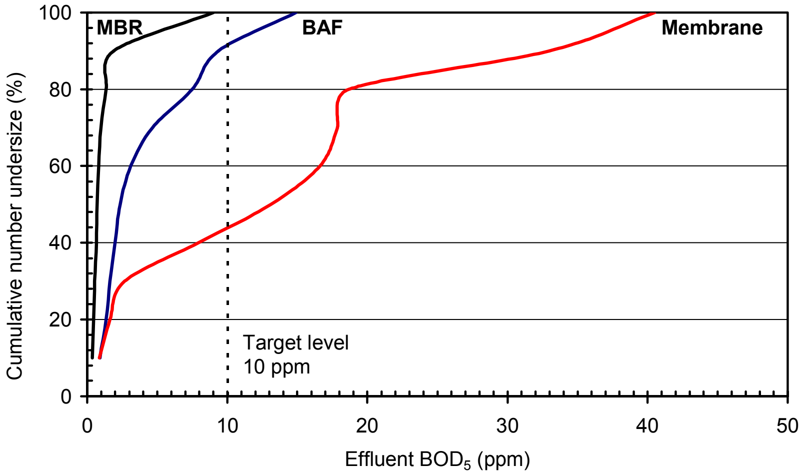

Fig. 2. Distribution of effluent quality for different technologies for the treatment of grey water.

now routinely available to end users as standard treatment options. Sports stadiums, shopping complexes and office blocks are becoming typical end users, especially in areas of water stress.

For instance, one of the earliest reported case studies is on grey water recycling facilities in the Mori building, Tokyo [1]. The plant consists of a side stream Pleiade MBR (Ubis) to treat the building flow of 500 m^3/d. The selection of an MBR over a traditional treatment process saved the equivalent area as 25 car parking places. The treated grey water contained less than 5.5 mg/L BOD and below detection level of suspended solids, colon bacilli and n-hexane extract, enabling reuse of the grey water.

A more recent example is in eastern San Diego County, California where expansion of an existing casino and development of a shopping mall required extension to the existing treatment facilities. The existing extended aeration system was converted to a ZeeWeed® MBR allowing to almost tripling the capacity of the infrastructure [30]. The scheme has been operational since July 2000 with the water quality meeting the California tertiary effluent standards for water reclamation plants; BOD values are regularly below 1 mg/L with average effluent turbidity, nitrate and total coliforms concentrations of <0.1 NTU, 5–11 mg/L and <2.2 MPN/100 mL respectively. Currently the main use of the water is in plant process operation. However, future plans include reuse for restricted irrigation, casino and mall landscapes, and ground water recharge through percolation fields.

Another growing market for MBR technologies is in the production of high purity water were the use of a MBR process upstream of reverse osmosis has been shown to be highly effective [26]. An example of such an application is at the N food frozen vegetable processing plant in Yokosuka city, Japan [27]. The plant treats a flow of 140 m^3/d through a polyethylene hollow fibre MBR at a constant flux of 5 L/(m^2h). Half the treated effluent feeds an RO plant to produce final water for boiler feed with a conductivity of 125 mS/cm. The plant has been operational since May 1998 and the scheme has generated an annual cost saving of $80,000 after offsetting to allow for equipment depreciation.

4. Experience with medium to large MBRs for municipal wastewater treatment in Europe

The first series of MBRs for municipal wastewater treatment in Europe were commissioned in 1998. The entry of membrane bioreactors into larger sized projects has been slow. Many potential customers were deterred by the lack of full-scale experience and drawbacks such as complexity, the high costs of the membranes, uncertainties on the life expectance of the membranes, the needed operator skills and maintenance requirements as well as the issue of membrane fouling.

It is only in the last couple of years that the use of MBRs for medium to large-scale domestic wastewater applications is beginning to show some of the initial promises. A list of medium to large sized full-scale projects is set out in Table 3. The main factors that contributed to their development were the experience gained with pilot/small-scale projects, the drastic decrease in the cost of membranes, the availability of subsidies and the improvements in membrane performance. Other important aspects were footprint limitations, discharge into sensitive/bathing water and the development of guarantees on membrane lifespans and of maintenance contracts.

Table 3 shows obviously that in the United Kingdom and Germany the application of the MBR concept is gaining momentum. Taking the implementation of MBR technology in the Federal State of North Rhine–Westphalia, Germany as an example, because the most implementations are there, the role of the different institutions in a key environmental technology sector can be exemplified. The close co-operation between the regional government, water industry players, technology suppliers and universities coupled with a high degree of public participation led to a rapid boost

Table 3
Large-/medium-scale (>2000 m³/d) municipal wastewater treatment with MBRs in Europe

Location	Size (m^3/d)	Type of membranes	Start-up	Comments
Rödingen, DE	2,400	Zenon	1999	Discharge of effluent into a small creek
Ile de Yeu, FR	2,260	Zenon	2000	In Zenon reference list. No info available
Markranstädt, DE	3,600	Zenon	2000	MBR only has to treat dry weather flow.
Swanage, UK	12,720	Kubota	2000	Environmentally sensitive area nearby a bathing beach
Campbeltown, UK	2,678	Zenon	2001	By selecting MBR technology, effluent can be discharged directly to the Campbeltown Loch, thereby eliminating the need for the long sea outfall if a conventional activated sludge (CAS) system was constructed.
Westbury, UK	3,536	Kubota	2002	MBR was built in parallel to the existing trickling filters to treat increased domestic flows and the effluent produced by a new dairy facility for compliance with new Environment Agency discharge consent.
Lowestoft, UK	14,160	Zenon	2002	Three separate secondary treatment streams were developed so that appraisal of new treatment systems and optimisation of future treatment strategies is possible: 60% of the flow is treated in a CAS plant, 20% in a Moving Bed Biological Reactor, and the remaining 20% is treated in an MBR plant.
Brescia, IT	42,000	Zenon	2002	Upgrading of one of the three existing CAS treatment lines. Very limited available land to extend the plant footprint possibility of reusing the water for irrigation in the future.
Monheim, DE	2,400	Zenon	2003	Strict requirements because discharged wastewater percolates through carstic soil
Schilde, BE	6,520	Zenon	2003	Extension of the CAS system to comply with a more stringent effluent regulation and an increase in load. MBR is operated at constant flow in parallel to the existing conventional activated sludge system.
Kaarst, DE	45,144	Zenon	2003	Largest operational MBR in the world. To produce EU “bathing water” quality effluent. Possibility to use the receiving canal for water sports
Waldmössingen, DE	2,160	Zenon	2004	Sensitive receiving surface water because of (very) low flows in summer.
Guilvinec, FR	2,600	Kubota	2004	Effluent can be discharged directly in the harbour i.e. offshore outfalls. It meets the bathing water norms of best quality
La Bisbal, SP	3,240	Zenon	2004	In Zenon reference list. No info available
Riells I Viabrea, SP	5,160	Kubota	2004	In Kubota reference list. No info available
Uerikon, CH	5,200	Zenon	2004	In Zenon reference list. No info available
Cardigan, UK	8,640	Kubota	2004	In Kubota reference list. No info available
Buxton, UK	10,627	Zenon	2004	Replacement of the existing WWTP. The scheme is driven by 1) the Fishery consent as part of the UWWTD. 2) the fact that several obstacles posed problems for an expansion, including a road and the unusual topography of the site.
Varsseveld, NL	18,120	Zenon	2004	Demonstration installation, co-financed by a number of innovation subsidies

in initiatives in this field. These initiatives range from fundamental research and development activities of different universities to the full-scale implementation of the technology up to the largest municipal wastewater treatment plant in the world in Kaarst. Although the key technological elements were provided by European subsidiaries of international players first, a number of SMEs entered the scene, motivated by the promising market perspectives and based on the innovation potential provided by the universities, and enhanced European competitiveness in this sector.

Note that the list is destined to become quickly incomplete as many projects are about to be commissioned. The particularly large number of pilot and demonstration installations can also give a clear indication of the growing interest in the technology.

4.1. Implementation and operational experiences with full-scale plants

Although MBR technology for domestic wastewater treatment is often claimed to be entering the growth stage of its lifecycle, still a lot of uncertainties and operational problems exist. Rarely are these reported in the literature.

The following section will provide an overview of some relevant full-scale operational problems not yet referenced in the literature. The case study of Schilde is taken as an example. The MBR of Schilde is the first MBR for domestic wastewater treatment in the Benelux and is run by the regional wastewater company AQUAFIN NV. The facility is operated at a constant flow of 230 m^3/h, the remaining flow being treated in the existing conventional activated sludge (CAS) system. Although the system was conceived by experienced external and in-house designers, it turned up to have some important operational problems, partly due to the inherent nature of a plant start-up, but for a significant other part because MBR technology for medium-large scale domestic wastewater treatment was still in the development stage of its lifecycle.

4.1.1. Pre-treatment

Pre-treatment appeared to be one of the most critical factors for guaranteeing a stable and continuous MBR operation. While it was clear from intensive long-term pilot plant trials that influent sieving of at least 1 mm was necessary, still two severe problems occurred while the 1 mm drum sieve was scaled up:

1) The wedge wire sieve (slots) showed quite low removal efficiencies. Later it was replaced by the much better performing woven mesh type sieve. The type of sieve installed is very important regarding the total screening removal, especially towards hair and fibres.
2) After replacement of the drum, severe and frequent clogging of the mesh type sieve occurred, caused by an inadequate automated cleaning system. Frequent manual high pressure cleaning by the operators was necessary to guarantee a continuous operation.

Note that the investment in a 1 mm pretreatment drum screen is of little use if the bioreactor is open and surrounded by trees as it is the case in Schilde. After the start-up it was decided to cover the bioreactor completely in order to prevent leafs, needles and other debris from falling into the bioreactor.

4.1.2. Necessity of in-line sludge filtration

Unexpectedly, the 10 mm punched hole safety screen placed on the external sludge recycling to the membrane filtration trains gave significant clogging problems, although the influent was treated by a 1 mm drum sieve. This was partly due to the fact that the bioreactor was not covered, but also by the agglomeration of fibrous material in the bioreactor leading to the formation of particles and products much greater than 1 mm. This was made clear by measuring sludge trash content in several particle size classes. Low-flow sludge recycling over the drum sieve appeared to be a successful measure for obtaining a significant sludge trash content decrease. In some other more recent applications this practice has been taken up in the design phase (e.g. Varsseveld, The Netherlands).

4.1.3. Automation requirements and process control

In comparison with a CAS system, an MBR demands much more automation, not only in the design and start-up phase of the plant, but also in the daily plant operation and optimisation. Originally, permeate flow was controlled by the level in the aerobic bioreactor. This led to filtration stability problems, since the intermittent bioreactor aeration gave rise to significant level variations (and membrane flux fluctuations), despite the fact that the influent flow was unchanged. Replacement of the level measurement device to the anoxic bioreactor solved these problems. Another problem was the air accumulation in the pipes which feed the sludge to the membrane filtration trains by gravity [31].

4.1.4. Operator training and attendance

Intensive training and technological support of operators is one of the most critical factors in order to guarantee a quick and efficient start-up and a reliable control and operation afterwards. Operation of a full-scale MBR implies a different way of thinking, observance, operation and problem solving in comparison with conventional systems.

It does not only take well trained operators to do the job in a full-scale MBR plant, it also can be quite time consuming. Especially with a parallel MBR-CAS operated system: on site lab measurements of sludge, influent and effluent parameters have to be done twice, i.e for both the CAS and the MBR line. Checking the MBR filtration stability (permeability) and other important MBR parameters on different filtration trains also requires a lot of time. In addition, operators can only really become familiar with their new kind of treatment technology if they have, apart from their daily follow up and maintenance tasks, enough time left to get to know their MBR system inside out.

4.1.5. Membrane fouling

Contrarily to long-term pilot results, in the full-scale plant little problems with membrane fouling were encountered. Only once the membranes were partly fouled due to a decrease of the MBR sludge quality (deflocculation), probably caused by a toxic influent shock. Although it took several weeks, the MBR managed to recover original permeabilities on its own, through normal daily operation, without application of any special permeability restoring measures (e.g. chemical cleaning) [31].

4.2. Water recycling projects utilising MBR technology

Significant expectations in water re-use and recycling assure MBR technology of a very positive prospect. On the other hand, despite the fact that several MBR plants are now operational in almost every Western European country, the high quality effluent is rarely reused. Identified water reuse projects are summarised in Table 4.

The potential for water reuse offered by MBR technology can also be illustrated through the case

Table 4
Municipal reuse projects with MBRs effluents in Europe

Location	Size (m³/d)	Type of membranes	Start-up	Comment
1. Villefranque, FR	168	Dégrémont BRM1®	1997	Reused for washing water in a tannery
2. Collegno, IT	960	Zenon ZW500®	5/2001	Industrial reuse
3. Rocca Imperiale, IT	960	Zenon ZW500®	5/2003	Demonstration project Agricultural reuse

Table 5
Large-/medium-scale (>2000 m³/d) municipal wastewater treatment with MBRs in Europe

	Frequency	Parameters
Routine	1 × week	BOD, COD, SS, TN, TP, NH_4, KJN, NO_3, NO_2, PO_4, …
Microbiology*	1 × 2 weeks	Faecal Coliforms, Total Coliforms, Faecal Streptococci, Total Germ Count
Chemical	1 × 2 weeks	Heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn), Herbicides (Atrazine, Simazine, Diuron), Anionic detergents, Halogenated, hydrocarbons**

*sterile effluent grab samples were taken directly from the permeate pipes
**only 8 samples/year

history of WWTP Schilde. Although the effluent is not reused, the process performance concerning the most important water reuse parameters is followed up regularly (every two weeks) at 3 different places (influent, effluent CAS and effluent MBR). Table 5 shows the most important measured water reuse parameters.

A few main conclusions are:

- MBR effluent complied with the Faecal Coliforms WHO guideline limit for using treated water in agriculture (1989).
- Evaluation of compliance with the Total Coliforms State of California Title 22 Water Recycling Criteria (2000) is somewhat difficult in that sampling was carried out every 2 weeks, while the Title 22 limit for total coliforms is based on a running 7-day median. Of the 24 effluent samples of the first year of operation, 18 were <240/100 mL, 9 were <23/100 mL and 5 were <2.2/100 mL.
- Removal efficiency for
  - Cu, Zn, FC, TC, FS, TGC is much better for MBR than for CAS
  - Anionic detergents and herbicides is slightly better for MBR than for CAS
  - As, Cd, Cr, Hg, Ni and Pb is equal in MBR and CAS

5. Conclusions

The presented paper illustrates that MBR technology has a significant potential to become a key element of wastewater reclamation and reuse schemes world-wide. MBRs for municipal wastewater treatment feature advantages compared to conventional activated sludge plants in terms of effluent quality, reflected in lower values for organics, nutrients and micro-organisms. The application of MBRs in full-scale gained momentum over the last five years and a very large number of installations exist for small de-centralised treatment. Most effluents of the medium to large-scale municipal MBR effluents in Europe are not reused but discharged into sensitive areas. The introduction of MBR technology into larger reuse schemes is delayed but offers a lot of advantages, particularly for new installations.

The operational experience with full-scale MBRs indicates that this relatively new technology poses a challenge to the water utilities. Many areas such as fouling control, pre-treatment, maintenance, and operators training have to be established in the operational procedures and drawbacks are expected in the uptake of this technology, which define the need for more intensive and practitioner-oriented research on MBRs.

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References

[1] T. Stephenson, S.J. Judd, B. Jefferson and K. Brindle, Membrane Bioreactors for Wastewater Treatment. IWA Publishing, London, 2000.

[2] C. Thoeye, M. Weemaes, D. Geenens, K. van Eyck and G. De Gueldre, Ongoing and planned water reuse related projects in Flanders, Belgium. IWA Regional Symposium on Water Recycling in Mediterranean Region, Iraklio, Greece, 26–29 September 2002.

[3] B. Günder and K. Krauth, Replacement of secondary clarification by membrane separation — results with tubular, plate and hollow fibre modules, Water Sci. Technol., 40(4–5) (1999) 311–320.

[4] S.P. Hong, T. Bae, T. Tak, S. Hong and A. Randall, Fouling control in activated sludge submerged hollow fiber membrane bioreactors, Desalination, 143 (2002) 219–228.

[5] STOWA, Vergelijkend onderzoek MBR en zandfiltratie RWZI Maasbommel (in Dutch, Comparing research MBR and sand filtration WWTP Maasbommel), STOWA report 2004-28, November 2004.

[6] STOWA, Van Stonehenge tot MBR, waarin een groot land 'klein' kan zijn. (in Dutch, From Stonehenge to MBR, in which a large country can be 'small'), STOWA report 2004-WO2, October 2004.

[7] R. Gnirss, B. Lesjean and H. Buisson, Biologische Phosphorentfernung mit einer nachgeschalteten Denitrifikation im Membranbelebungsverfahren. Proc. 5th Aachener Tagung Siedlungswasserwirtschaft und Verfahrenstechnik, Aachen, Germany, 30 September – 1 October 2003.

[8] H.F. van der Roest, D.P. Lawrence and A.G.N. van Bentem, Membrane Bioreactors for Municipal Wastewater Treatment, IWA Publishing, London, UK, 2002.

[9] T. Melin and M. Dohman, Membrantechnik in der Wasseraufbereitung und Abwasserbehandlung, Proc. 5th Aachener Tagung, Aachen, Germany, 30 September – 1 October 2003.

[10] B. Jefferson, A. Laine, T. Stephenson and S. Judd, Advanced biological unit process for domestic water recycling, Water Sci. Technol., 43(10) (2001) 211–218.

[11] B. Jefferson, A. Palmer and P. Jeffrey, Reliability of biological processes for urban reuse of grey and black water, IWA Regional Symposium on Water Recycling in Mediterranean Region, Iraklio, Greece, 26–29 September 2002.

[12] B. Günder, Das Membranbelebungsverfahren in der kommunalen Abwasserreinigung. Dissertation at University of Stuttgart. München: Kommissionsverlag R. Oldenbourg, 1999.

[13] N. Cicek, H. Winnen, M.T. Suidan, B.E. Wrenn, V. Urbain and J. Manem, Effectiveness of the membrane bioreactor in the biodegraddation of high molecular weight compounds. Wat. Res., 32 (1998) 1553–1563.

[14] T. Ueda and N.J. Horan, Fate of indigenous bacteriaphage in a membrane bioreactor. Wat. Res., 34 (2000) 2151–2159.

[15] P. Côté, D. Mourato, C. Güngerich, J. Russell and E. Houghton, Immersed membrane filtration for the production of drinking water: Case studies. Desalination, 117 (1998) 181–188.

[16] S. Zühlke und U. Dünnbier, Langzeituntersuchungen zur Entfernung organischer Spurenstoffe mit zwei Membranbelebungsanlagen im Vergleich zu einem konventionellen Klärwerk. Proc. 5th Aachener Tagung Siedlungswasserwirtschaft und Verfahrenstechnik, Aachen, Germany, 30 September – 1 October 2003.

[17] R.D. Holbrook, N.G. Love and J.T. Novak, Sorption of 17β-estradiol and 17β-ethinylestradiol by colloidal organic carbon derived from biological wastewater treatment systems. Environ. Sci. Technol., 38 (2004) 3322–3329.

[18] H.-Q. Li, F. Jiku and H.-F. Schröder, Assessment of the pollutant elimination efficiency by gas chromatography/mass spectrometry, liquid chromatography-mass spectrometry and tandem mass spectrometry — comparison of conventional and membrane-assisted biological wastewater treatment processes. J. Chromatography A, 889 (2000) 155–176.

[19] M. Clara, B. Strenn, E. Saracevic and N. Kreuzinger, Adsorption of bisphenol-A, 17β-estradiol and 17β-ethinylestradiol to sewage sludge. Chemosphere, 56 (2004) 843–851.

[20] D.R. Holbrook, J.T. Novak, T.J. Grizzard and N.G. Love, Estrogen receptor agonist fate during wastewater and biosolids treatment processes: a mass balance analysis. Environ. Sci. Technol., 36 (2002) 4533–4539.

[21] W. Hegemann, K. Busch, P. Spengler and J.W. Metzger, Einfluss der Verfahrenstechnik auf die Eliminierung ausgewählter Estrogene und Xenoestrogene in Kläranlagen — ein BMBF Verbundprojekt. GWF Wasser Abwasser, 143(5) (2002) 422–428.

[22] H. Yamamoto, H.M. Liljestrand, Y. Shimizu and M. Morita, Effects of physical-chemical characteristics of selected endocrine disrupters by dissolved organic matter surrogates. Environ. Sci. Technol., 37 (2003) 2646–2657.

[23] A.I. Schäfer, M. Mastrup and R. Lund-Jensen, Particle interactions and removal of trace contaminants from water and wastewaters. Desalination, 147 (2002) 243–250.

[24] J. Shi, S. Fujisawa, S. Nakai and M. Hosomi, Biodegradation of natural and synthetic estrogens by nitrifying activated sludge and ammonia-oxidizing bacterium *Nitrosomonas europaea*. Wat. Res., 38 (2004) 2322–2329.

[25] A. Joss, H. Andersen, T. Ternes, P.R. Richle and H. Siegrist, Removal of estrogens in municipal wastewater treatment under aerobic and anaerobic conditions: consequences for plant optimization. Environ. Sci. Technol., 38 (2004) 3047–3055.

[26] P. Lawrence, S. Adham and L. Barrott, Ensuring water re-use projects succeed — institutional and technical issues for treated wastewater re-use. Desalination, 152 (2002) 291–298.

[27] S. Judd and B. Jefferson, Membrane for Industrial Wastewater Recovery and Re-use. Elsevier Science Ltd, Oxford, UK, 2003.

[28] B. Jefferson, A. Laine, T. Stephenson and S. Judd, Advanced biological unit processes for domestic water recycling. Water Sci. Technol., 43(10) (2001) 211–218.

[29] B. Jefferson, A.T. Laine, S. Parsons, T. Stephenson and S. Judd, Technologies for domestic wastewater recycling. Urban Water, 1(4) (1999) 285–292.

[30] Zenon Environmental Inc., Viejas Casino and Shopping Mall Application Note, available from www.zenon.com [accessed 17th January 2004].

[31] W. De Wilde, C. Thoeye and G. De Gueldre, Operational experiences and optimisations one year after start-up of the first full-scale MBR for domestic wastewater treatment in the Benelux. Submitted to 6th Aachener Tagung Siedlungswasserwirtschaft und Verfahrenstechnik 2005, Eurogress, Aachen, Germany.