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A Review on Membrane Technologies and Associated Costs for Municipal Wastewater Reuse*

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Abstract: This study seeks to compile data on the technologies and associated costs for wastewater reuse. Reuse of reclaimed water for non-potable applications is currently the rule rather than the exception in many parts of the world. Treatment technology encompasses a vast number of options and membrane processes are regarded as key elements of advanced wastewater reclamation and reuse schemes. The identifiable wastewater reuse schemes using membrane technology worldwide have been critically analyzed in this study. Peer-reviewed journal study, conference papers and information gathered from the internet formed the basis of this review study. Different forms of potential water reuse have been identified. The available cost data was also furnished. Therefore, this study, as a whole adds to both technological and economical aspects of the knowledge-base of wastewater reuse schemes. The membrane technology appears to govern the field of wastewater reuse and this trend is likely to continue in the future. Besides the technical aspect, issues like public acceptance, economic and hygienic risks etc., should be taken into account to counter the obstacles facing implementation of wastewater reuse.

Key words: Cost, technology, membrane technology, review, wastewater reuse

INTRODUCTION

The world wide increasing demands for the exhaustible resource-water have resulted in a critical evaluation of water reuse as means of supplementing municipal and industrial water supplies (Al-A'ama and Nakhla, 1995; Abderrahman, 2001; Howell, 2002; Bixio *et al*., 2006). Wastewater reclamation has been attracting attention as a potential countermeasure for alleviating water shortage problems. To ensure the safety of reclaimed water, however, advanced treatment is required. Various technologies for different wastewater reclamations have been used to date in various countries (Jefferson *et al*., 2000; Wintgens *et al*., 2005; Qin *et al*., 2006; Bixio *et al*., 2008). Both the available/emerging technologies and the associated costs are yet to be well documented in a single volume.

In this study, before presenting a brief review of contemporary reports on tertiary treatment costs, the importance of wastewater reclamation/reuse and available/emerging technologies to realize wastewater reuse have been illustrated.

IMPORTANCE OF WASTEWATER RECLAMATION

Reuse of reclaimed water or recycled wastewater for non-potable applications is currently the rule rather than the exception in many parts of the world (Abderrahman, 2000; Alaboud and Magram, 2008; Al-Jayyousi, 2003). Such uses include crop and landscape irrigation, industrial and recreational uses and ground water recharge. Although, direct potable reuse of reclaimed water is still not accepted, it is obvious that the obstacles are rapidly being overcome by relentless R and D initiatives.

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By reclaiming wastewater, the circulation of water through the natural water cycle can be short-circuited, such that a contribution to human water needs is made and the environmental impact thereof limited (Enegess *et al*., 2003; Galil and Levinsky, 2007; Haddadin, 2002). Furthermore, a main characteristic of reclaimed water is that its production is relatively constant during the year, as the production is based on municipal sewage and not on rainfall. Thus, reclaimed water can increase the reliability of a water supply, comprising a further source of water. Similarly, recycled water can be viewed as an independent source of water capable of increasing the reliability of a water supply (Côté *et al*., 2004).

TECHNOLOGIES FOR WASTEWATER REUSE

As mentioned earlier, various technologies for different water applications have been used to date in various countries (Azeem and Magram, 2008; Howell, 2002; Magram and Azeem, 2008; Visvanathan *et al*., 2000). The most common reclamation technologies and reuse applications are shown in Fig. 1 with the number of water reuse schemes per field of application and the level of treatment are secondary, tertiary or quaternary, attached to them in different regions of the world (Wintgens *et al*., 2005). Membrane processes are regarded as key elements of advanced wastewater reclamation and reuse schemes and are implemented in a number of prominent schemes world-wide including artificial groundwater recharge, indirect potable reuse as well as industrial process water production (Qin *et al*., 2006; Wintgens *et al*., 2005). For dual reticulation purposes in urban areas two types of systems have been built, a centralised type of treatment with dual membrane processes, including e.g., microfiltration (MF) and Reverse Osmosis (RO) and small-scale systems using membrane bioreactors (Jefferson *et al*., 2000; Lawrence *et al*., 2002; Bixio *et al*., 2006; Bixio *et al*., 2008).

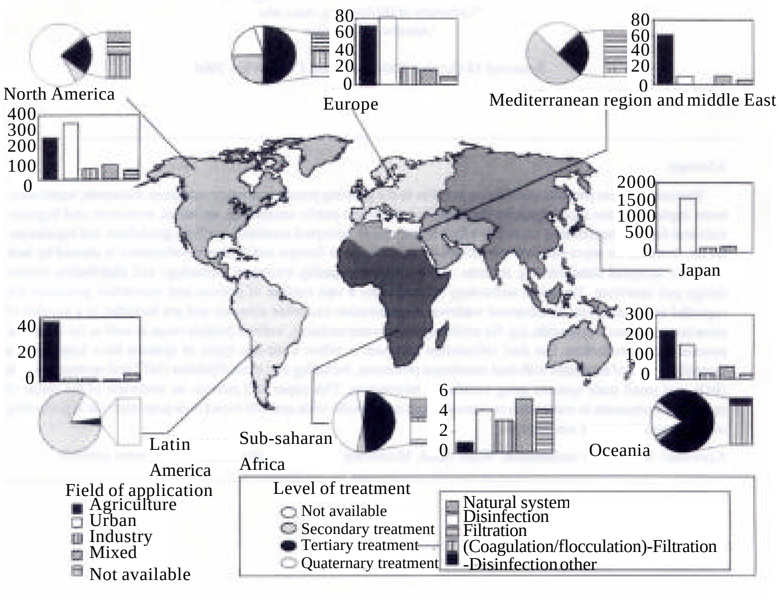


Fig. 1: Water reuse schemes per field of application (bar-charts) and level of treatment (pie-charts with attached bar for main tertiary treatment processes) in different regions of the world (Adapted from Wintgens *et al*. (2005))

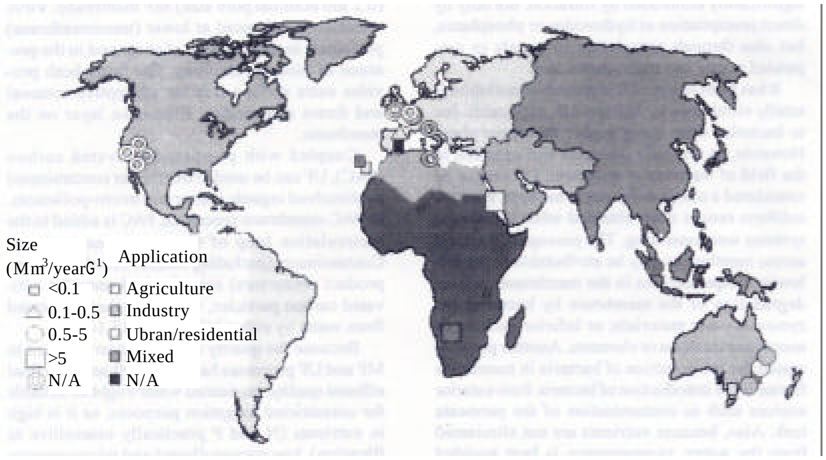


Fig. 2: Existing water reclamation schemes using membrane systems world wide (Adapted from Wintgens *et al*. (2005))

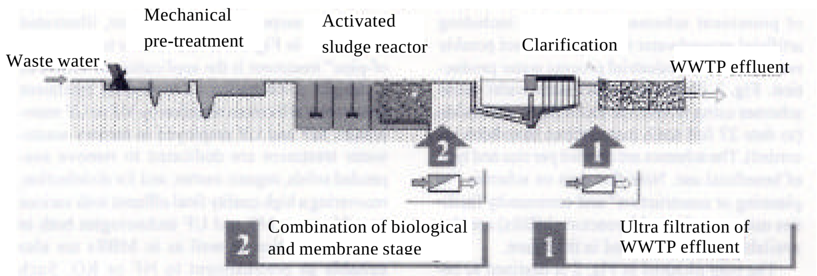


Fig. 3: Application options for membranes in municipal waste water treatment (Adapted form Wintgens *et al*. (2005))

Figure 2 shows identifiable water reuse schemes using membrane technology world wide reported by Wintgens *et al.* (2005). The schemes are divided per size and type of beneficial use. Data on schemes in planning or construction and community facilities using membrane bioreactors (MBR) are not reported in the Fig. 2.

There is a clear trend for new larger scale plants to use dual membrane processes and MBRs (Lesjean *et al.*, 2004). As indicated in the earlier chapter membrane processes are mostly applied as effluent polishing stages of municipal wastewater treatment plants, taking a secondary or tertiary effluent as feed with rather low suspended solids content, illustrated as option 1 in Fig. 3, (Wintgens *et al*., 2005). An alternative to this end of pipe treatment is the application of MBRs as a straight combination of biological treatment processes and biomass retention by MF or UF membranes (Jefferson *et al*., 2000). Microfiltration (MF) and UF employed in tertiary wastewater treatment are dedicated to remove suspended solids, organic matter and for additional disinfection, recovering a high quality final water from the effluent for various possible uses. Microfiltration (MF) and UF technologies both in effluent filtration as well as in MBRs are also suitable as pretreatment to NF or RO. Such physical barrier-processes are attractive in wastewater treatment because any technology employed must be able to produce reused water of stable quality, regardless of the normally wide variation in the concentrations or physicochemical properties of the wastewater influent and the absence of chemicals addition is of economic and ecological benefit.

According to Stephenson *et al.* (2000), membrane bioreactor technology was proven to be very relevant in water reclamation and reuse, particularly in small-scale, decentralized applications e.g., in the densely populated urban in centres in Japan. The Japanese government joined in 1989 with a number of the large companies to promote the development of a low footprint, high product quality treatment that would be suitable for wastewater reclamation and reuse. City Legislation, such as in Fukuoka, required large buildings to adopt water saving measures including rainwater harvesting and in-building greywater treatment and reuse systems. This was partly demonstrated through the Aqua Renaissance program '90 that led to development of systems such as the Kubota flat-sheet submerged MBR and the mitsubishi rayon hollow fibre submerged MBR (Stephenson *et al.*, 2000).

Two generic types of MBR have been used for in-building greywater treatment: initially these were sidestream systems, but more recently submerged systems have been introduced following their development by Japanese companies of the 500 operational MBRs identified by Stephenson *et al.* (2000), almost 25% were used for in-building wastewater treatment, mostly in Japan. It was found that MBR generally provide significant advantages over alternative biological treatment processes in water recycling, particularly in terms of pathogen removal and process robustness (Jefferson *et al.*, 2000).

Based on the development of MBR, a new concept with the addition of RO after MBR recently has been developed to reclaim municipal wastewater. Comparison of the new MBR-RO process to the conventional ASP-MF-RO process was made by Qin *et al.* (2006). The results showed that the new MBR-RO process demonstrated the capability of producing the same or more consistent product quality (in terms of TOC, NH_4 and NO_3) compared to the CAS-MF-RO process in reclamation of domestic sewage. Reverse Osmosis (RO) membranes in the MBR-RO process could be operated at 22 Lm^{-2} h^{-1} without Cleaning In Place (CIP) during the whole study period of 5 months, which was 30% higher than that ($17/Lm^2/h$) in the ASP-UF-RO process for NEWater production. Reverse Osmosis (RO) permeate quality was improved with increasing the membrane flux. It was concluded that the MBR-RO process could be a new option for NEWater production. If MBR is applied in NEWater production, MBR will compress the conventional activated sludge process composed of aeration unit and final clarification, MF/UF pre-treatment into one as shown in Fig. 4. This may also lead to cost reduction.

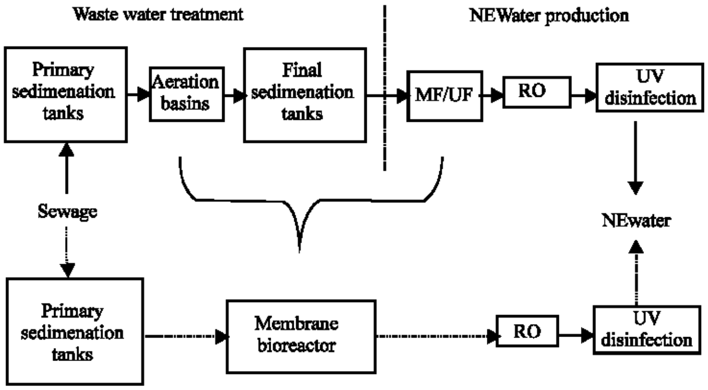


Fig. 4: Schematics of Newater production with the conventional and MBR processes (Qin *et al.*, 2006)

REVIEW OF CONTEMPORARY REPORTS ON TERTIARY TREATMENT COSTS

Tertiary treatment obviously necessitates investment of additional costs. Considerable number of reports on estimation of the associated rise in cost exists in literature. For instance, Olivieri *et al.* (2005) put forward cost curves for estimating incremental capital/ operational and maintenance costs associated with upgrading to tertiary treatment using direct or contact filtration (Fig. 5, 6).

Special focus has been given here on cost values pertaining to different combinations of membrane applications for tertiary treatment.

Efforts aiming at the application of membrane-based technologies in the field of wastewater treatment have focused on tertiary treatment so as to obtain a high-quality final effluent that can be reused for different purposes. Nevertheless, while technical viability of membrane filtration is very well documented, its implementation is constrained by the high investment and operational costs involved.

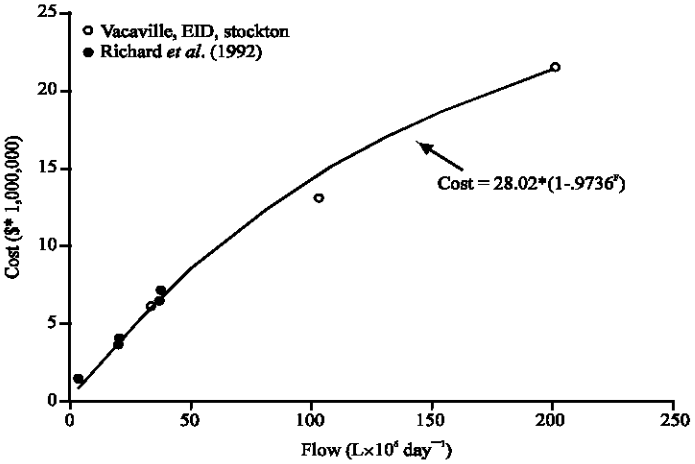


Fig. 5: Cost curves for estimating incremental capital costs associated with upgrading to tertiary treatment using direct or contact filtration (Olivieri *et al.*, 2005)

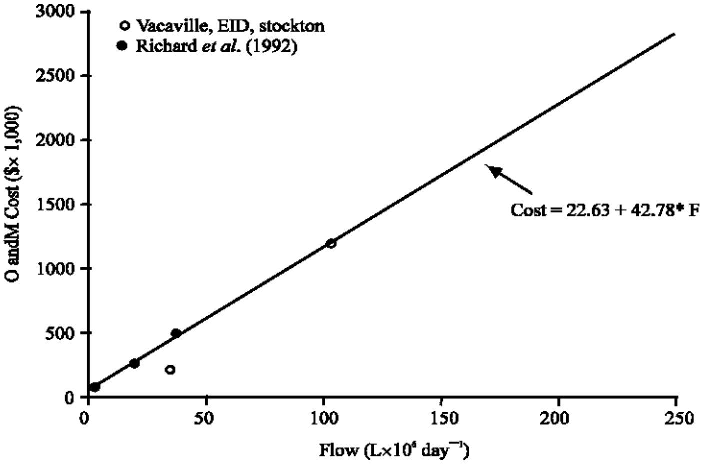


Fig. 6: Cost curves for estimating incremental operational and maintenance costs associated with upgrading to tertiary treatment using direct or contact filtration (Olivieri *et al.*, 2005)

Table 1: Overall cost (in £) estimates of different tertiary treatment options

Estimated costs	Cross flow microfiltration	Sand filtration	Coagulation+ sand filtration	Coagulation+sedimentation+ sand filtration
Capital	485,000	228,170	374,950	801,190
Operating cost	46,400	No data	No data	12,350
Maintenance and chemicals	10,000	No data	No data	37,140
Membrane replacement	6,200	N/A	N/A	N/A
Annual cost	63,600	No data	No data	49,490
Present worth	174,950	N/A	N/A	1,891,960

Al-Malack *et al.* (2003). N/A: Not available

Al-Malack (2003) investigated the technical and economic aspects of crossflow microfiltration processes by making a comparison with those of conventional tertiary wastewater treatment facilities. Crossflow microfiltration processes were found to produce a reliable permeate quality, while in the case of conventional processes, the quality of the produced water is largely dependent on operational compared to those of conventional filtration processes. The economic study (Table 1) showed that the capital cost of conventional tertiary treatment processes is more than 65% greater than that of crossflow microfiltration, while the annual operation and maintenance costs were 21% less. The PW value showed that 8% of the projected cost could be saved over the coming 40 years when crossflow microfiltration processes are implemented as an alternative scheme. Finally, selection of either scheme depends on many factors such as money available, flow of wastewater to location and size of available availability of skilled personnel.

Alonso *et al.* (2001) reported that treated water obtained through micro or ultra filtration of secondary waste water was characterized with high nutrient concentration (nitrogen and phosphorus are practically insensitive to filtration); low micropollutant content; a favorable structure of concentration for sodium, calcium and magnesium ions; moderate salinity; and a lack of microorganic pollution. Therefore, physical, chemical and biological analytical attributes of permeated water - by means of any of the two systems -make it especially suitable for irrigation reuse, when restrictions are slight or moderate, as well as for reuse in park and sport field irrigation. They also reported that, from an operational point of view, MF offers very superior advantages compared to UF. With a cost of 0.062 US \$ kwh^{-1}, 1.5 US \$ L^{-1} of basic reagent and 1.65 US \$ L^{-1}, of acid reagent, the total cost of the MF operation was 0.093 US \$ m^{-3}, while an estimated cost of 0.92 US \$ m^{-3} resulted for the UF process.

Abdel-Jawad *et al.* (1999) assessed the technical viability and economic feasibility of implementing Reverse Osmosis (RO) technology to renovate Kuwait's treated wastewater effluent (Fig. 7). The results indicated that municipal wastewater can be treated by advanced technologies to produce excellent water which is almost devoid of salts, pollutants and microorganisms. The total cost of such treatment is estimated to be almost half of the distillate cost produced by multistage flash (MSF) plants, whereas the cost of treating the tertiary treated wastewater alone by additional advanced treatment constitutes only 25% of the MSF distillate costs.

The MBR technology endows various possibilities of wastewater reclamation (Fig. 8). Two very recent reports on MBR technology cost are henceforth portrayed through Fig. 8 and 9.

Information on costs is also available from different feasibility studies in which the costs for an MBR and a traditional installation under different circumstances were compared.

Lesjean *et al.* (2004) taking into account current knowledge, anticipated a future market share as follows: for municipal applications, it is expected that the hollow-fiber submerged configuration would be competitive for medium-to-large size plants. For small-to-medium sizes, plate and frame technologies would have an advantage, whereas larger applications could be designed with secondary/tertiary treatment followed by MF/UF membrane filtration.

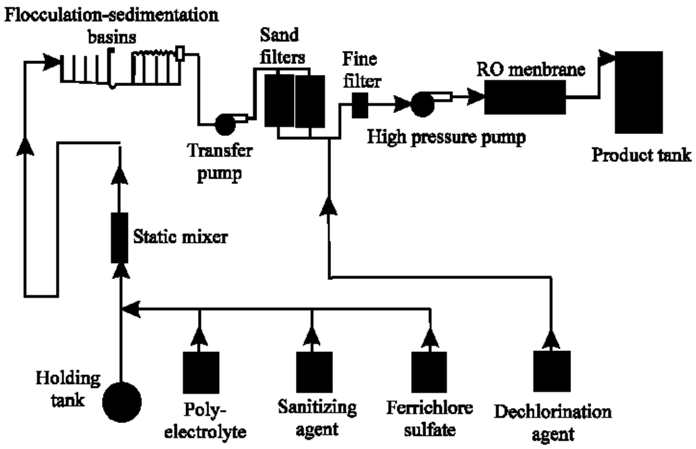


Fig. 7: Block diagram of the advanced pretreatment and RO desalination system at Ardiya, Kuwait (Abdel-Jawad *et al*., 1999)

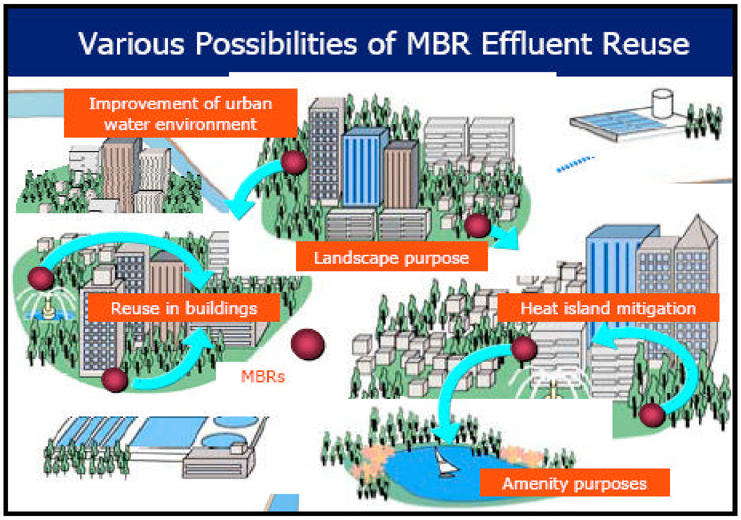
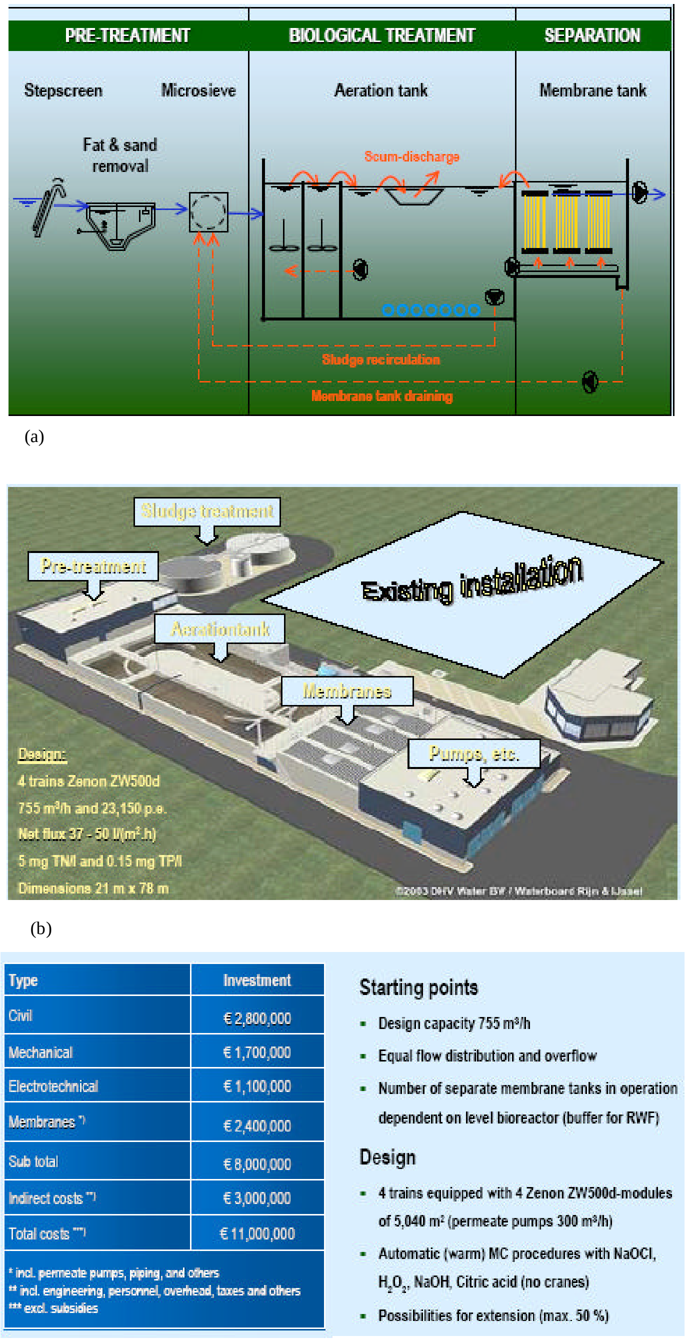


Fig. 8: Various possibilities of MBR effluent reuse

In a mature, open and competitive market place, the different technologies should place themselves naturally depending on their cost-effectiveness. It is expected that plate-and-frame MBR units will offer advantages for small-size plants for the following reasons:

- They are simpler to set-up, with the absence of backwash system
- Less compact membrane system and for a larger plant, it was demonstrated that the membrane modules may fill-up the whole volume of the aerobic reactor, therefore decreasing the aeration performances and increasing the need of reactor volume. However, smaller plants are often designed with relatively larger reactor volumes, which allows sufficient place for flat-sheet membranes



(a)

(b)

Type	Investment
Civil	€ 2,800,000
Mechanical	€ 1,700,000
Electrotechnical	€ 1,100,000
Membranes *)	€ 2,400,000
Sub total	€ 8,000,000
Indirect costs **)	€ 3,000,000
Total costs ***)	€ 11,000,000

* incl. permeate pumps, piping, and others
** incl. engineering, personnel, overhead, taxes and others
*** excl. subsidies

Starting points

- Design capacity 755 m^3/h
- Equal flow distribution and overflow
- Number of separate membrane tanks in operation dependent on level bioreactor (buffer for RWF)

Design

- 4 trains equipped with 4 Zenon ZW500d-modules of 5,040 m^2 (permeate pumps 300 m^3/h)
- Automatic (warm) MC procedures with NaOCl, H_2O_2, NaOH, Citric acid (no cranes)
- Possibilities for extension (max. 50 %)

(c)

Fig. 9: (a) Treatment scheme considered (Yang *et al*, 2006), (b) Layout of the plant (Yang *et al.*, 2006) and (c) Design considerations and cost data (Yang *et al*, 2006)

Hollow-fibre technology, on the other hand, requires more instrumentation and control, but has a clear head start in terms of scale-up rationalization and normalization (for easy, quick and low-cost maintenance operation, diagnosing of leakage, integrity testing, reparation and chemical cleaning). For large-scale applications, the smaller footprint of hollow-fibre modules clearly will be beneficial. For even larger sizes, it is expected that separated secondary/tertiary treatment, followed by MF/UF membrane filtration will become more competitive than MBR technology in terms of cost and system reliability.

STOWA (2003) compared investment costs for a new WWTP. The annual costs of a MBR installation are strongly influenced by the depreciation for the mechanical equipment and the replacement of the membranes. At the moment the latter is still difficult to predict, practical experiences from 3 to 8 years being not enough for a realistic estimation. With manufacturers, the discussion around the membrane lifetime has led to capacity guarantees. Regarding variable costs, especially the energy consumption is an interesting item, which is mainly determined by the energy for aeration. Cost differences between an MBR and traditional WWTP concerning manpower, chemical consumption and sludge treatment were reported to be minimal.

WERF summarized operating and water quality data obtained over one year from two Membrane bioreactors (MBR) pilot plants located at the Aqua 2000 Research Center at the City of San Diego (California) North City Plant. Preliminary cost estimates of the MBR technology were also developed. MBRs demonstrated that their effluent was suitable to be fed directly into a Reverse Osmosis (RO) process from a particulate standpoint with Silt Density Index (SDI) values averaging well below 3. The MBR effluent water quality was superior to the quality of full-scale tertiary conventional wastewater treatment plant.

The preliminary cost estimate in this report was performed for a 1 MGD scalping facility (wastewater treatment plant drawing a designated amount of flow from the sewer system; excess sewage flow is treated at another plant located at the end of the sewer line). This facility produced an effluent suitable as feedwater for an RO process. Based upon this estimate, the present worth value is \$3.05/kgal, \$3.65/kgal and \$4.38/kgal for the MBR process, oxidation ditch with microfiltration and oxidation ditch with conventional tertiary lime pre-treatment, respectively. Therefore, the MBR process is the most cost-effective alternative for water reclamation where demineralization (RO) is required.

SAWC (2001) reported the costs associated with upgradation of an extended aeration system using immersed microfiltration membrane system. They estimated a total capital cost in excess of \$12.0 million. In addition the membranes have a substantially higher maintenance cost, requiring replacement about every 5 to 10 years at a present day cost of \$3.0 million on each occasion. The existing treatment plant consisted of a screened aerated grit collector, two circular extended aeration tanks operating in parallel and two sludge lagoons. Raw sewage first entered the plant through the screen and grit collector and was then distributed to two circular aeration/clarification tanks via a flow divider. In these tanks, wastewater was aerated in the peripheral compartment and flows to the central clarifier. Effluent from the clarifiers was chlorinated before being discharged to the nearby creek. Sludge which settled out in the clarifiers was discharged to the sludge lagoon through an automated sludge wasting system. Supernatant from the sludge lagoon was returned to the head of the works by a pumping station. The existing plant was effective in reducing Biochemical Oxygen Demand (BOD) and Suspended Solids (SS) and removed about 50% of the influent nutrients, nitrogen and phosphorous. The proposal of the step up was based on an idea of continuing to discharge treated wastewater to the Creek but to upgrade the existing plant to a Biological Nutrient Removal (BNR) process to reduce the level of nutrients in the treated wastewater and to upgrade the hydraulic capacity to accommodate the increasing sewage inflows. The capacity of the upgraded plant was equivalent to a population of 15,000 and accommodated both domestic and winery waste flows. The design average annual flow was

3.60 ML day^{-1} (42 L sec^{-1}). The capital cost of the project was estimated at $8,900,000 (excluding GST). This estimated cost is based on the completed concept design. The cost of the project can be identified in the following major components:

- Completed studies and concept design $ 677,000
- Construction of the plant upgrade $7,047,000
- Detailed design, project management and contract administration $ 976,000
- SA Water management and review costs $ 200,000

An incremental operating cost of $146,000 per annum at the full design capacity had been estimated for the upgraded plant.

CONCLUSION

Wastewater reuse presents a promising solution to the growing pressure on water resources. The review furnished here divulges the importance of wastewater reuse and highlights the technologies and the associated costs. The membrane technology appears to govern this field and this trend is likely to continue in the future. With new innovations, the technologies are expected to be more cost-effective day by day, which will endow the opportunity of their widespread application. However, wastewater reuse implementation faces obstacles that include insufficient public acceptance, technical, economic and hygienic risks and further uncertainties caused by a lack of awareness, accepted standards, uniform guidelines and legislation. These issues also have to be given due consideration.

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