Desalination and Water Treatment
www.deswater.com
1944-3994/1944-3986

4 (2009) 287–293

Advancing membrane technologies for wastewater treatment and reclamation in selected Arab MENA countries

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Received 30 December 2007; Accepted 6 April 2009

ABSTRACT

Membrane technology (MT) is advancing rapidly as a powerful tool to abate the looming water crisis and reduce quality degradation of water resources in the Mediterranean zone. Despite several national membrane research activities, the general trend in promotion of MT is not satisfying and requires further analysis. This article compiles and critically analyzes the current research efforts in the field of membrane technology in selected Mediterranean and North African countries (MENA). A total of 114 research papers published in peer-reviewed literature from 1980 to 2007 and 22 laboratory- and full-scale membrane-based treatment plants in the MENA countries were used as the database for the analysis introduced in this paper. Results revealed few published scientific works (20% of total articles compiled) and pilot-scale studies on membrane bioreactors where further research and development pertinent to MT cost effectiveness and sustainability are needed. Advancing MT research has particular relevance to the decision makers in facilitating investment allocations and choosing sustainable treatment processes and demonstration projects for both effluent reclamation and reuse.

Keywords: Membrane processes; Wastewater treatment; Membrane bioreactor; MENA countries; Reclamation

1. Introduction

The complex dimensions of the Mediterranean freshwater resources, their fragility and their scarcity have been highlighted and received considerable attention as a primary priority issue politically, technically and scientifically. Membrane technology (MT), with its different applications in water treatment (desalination, drinking water treatment, wastewater treatment and reuse) has proven to be a reliable technique to abate the water crisis, worldwide in general, and in the Mediterranean region in particular [1–24]. During the last 5 years, this technology has received much attention by researchers and manufacturers, resulting from an improvement of membrane materials and techniques, which provide higher fluxes, longer lifetime, partly improving the fouling and high

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costs. However, in spite of several national and international membrane research activities, the general progress is not satisfying. Lack of cooperation, limited know-how exchange and an uncoordinated use of resources lead to ineffective research and development (R&D) activities [1–3].

PROMEMBRANE is a Specific Support Action, funded by the EU INCO Mediterranean Partner Countries. Its consortium involves four partners from Mediterranean countries as well as three institutes from the EU that specializ in water and wastewater treatment using various membrane technologies. The project started on 15 August 2006 and was completed by 14 August 2008. The primary objective of PROMEMBRANE (http://www.promembrane.info) was to support the current R&D activities in MT focused on water treatment in the Mediterranean area in order to promote international cooperation among research organizations and universities devoted to the development of membrane technologies in the following areas: municipal and industrial wastewater treatment, brackish and sea water treatment as well as surface water purification for drinking purpose. The first stage of the project covered the identification, mapping and evaluation of the on-going research, with the objective of proposing future research strategies which will help to overcome the current technical barriers of application. The second stage was the diffusion and dissemination of the successful experiences and research activities, through the organization of local seminars in targeted countries and an international conference, in order to encourage the further research activities in membrane technologies.

Increased population growth, rapid urbanization and industrialization associated with living standards improvement in most Mediterranean and North Africa countries (MENA) has aggravated the water balance gap between the available water supplies and the water demands. In MENA countries, especially those with limited water resources, there are challenges of satisfying rapid and substantial increases in water demand for industrial, domestic and agricultural purposes. The annual precipitation in MENA countries ranged between 150 and 600 mm, while the available water resources are limited, overexploited, polluted, politically confronted. A recent survey [1] on the present water uses in these regions revealed an average of 22% for municipal use, 3% for industrial use and 75% for agriculture use. Non-conventional resources such as seawater and brackish water desalination, in addition to limited reclaimed effluent, can alleviate the looming water crises in the MENA zone. In the Gulf region and South Mediterranean countries, experts [2,3,13] have already realized the nature of these challenges and recommended several key policies for water stressed countries, including a reduction of water subsidies, an increase reclaimed effluent reuse, aquifer recharge, advancement of local industrial bases and building capacity in sustainable membrane processes for both water and wastewater treatment [14,15,18].

The membrane-based activated sludge technology, referred to as membrane bioreactor (MBR), is the combination of activated sludge process with effective sludge separation using either microfiltration (MF), ultrafiltartion (UF), nanofiltartion (NF) or effluent reclamation utilizing reverse osmosis (RO) stages. In Europe, the application of membrane-based wastewater treatment systems, mostly the MBR type as indicated by Rachwall and Judd [4], is promoted under official legislations to meet the Drinking Water and European Union Bathing Water Directives. Two types of submerged modules are available today on the market: flat-sheet membranes and hollow-fiber membrane modules. An analysis by Lesjean and Luck [5] on the current MBR applications for municipal wastewater treatment revealed that flat-sheet systems are feasible for medium-size WWT plants, while hollow-fiber systems are adequate for large urban sewage works. In Europe, the largest MBR plant equipped with Zenon modules was installed in 2004 to serve the City of Kaarst (Germany) with an 80,000 population equivalent. A quick development and application of MBR technology has been illustrated by the establishment of a Zenon membrane bioreactor in Washington (USA) to treat a daily municipal flow of 144,000 m^3. Within the MENA countries, the available knowledge regarding municipal MBR is extremely limited and often very specific for a particular country's wastewater characteristics [19–29].

In this article, we first discuss major challenges facing the Mediterranean and North African countries behind endorsing membrane technologies for wastewater treatment, focusing on currently available published data. Second, the recent technological and current economic advancements of membrane-based treatment technologies are reviewed as the major drivers for the membrane processes promotion. Finally, recommendations pertinent to future research on membrane technologies are suggested to enhance their implementation as advanced sustainable water treatment processes.

2. Applied methodology

The PROMEMBRANE consortium is composed of a research committee from six countries representing a wide range of expertise in desalination technology, environmental engineering, water resources planning, and public health. The project entailed nine selected MENA countries in two geographical regions. The Middle East (Region A) including Syria, Lebanon, Jordan and Palestine and North Africa (Region B) including Egypt, Tunis, Libya, Algeria, and Morocco. Two database files have been created: one to collect information about the current research activities and another to map professional experts, research centers and universities focussing on MT applications for water and wastewater treatment. The findings of this article are based on the authors' own experience, data collected from 114 articles of 550 peer-reviewed papers found on the application of MT for water and wastewater treatment, and 22 installed laboratory- and full-scale membrane-based treatment systems. The authors claim by no means the exclusivity of the database files created. For MBR installations and published works from the countries under study, the WERF-Database and MBR-Network were accessed (http://www.mbr-network.eu/mbr-database/literature.php).

Feedback and discussions with relevant experts during workshops were also collected; however, due to space limitations, the results are not presented. As national R&D programs for the MBR technology applications in wastewater treatment and reclamation have started in some MENA countries, compiled research efforts made in Tunisia, Morocco and Algeria are presented and discussed. However, due to space limitations, it is not the aim of this paper to compare the MT efforts made within the MENA countries with those R&D efforts on MT applications in industrialized countries [4,5,21–24,30,31].

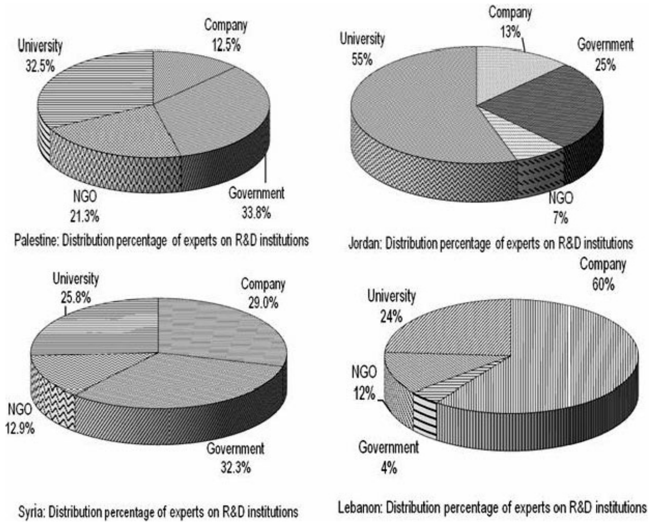

Fig. 1. Distribution of professionals identified as MT experts in region A.

3. Results and discussion

3.1. Researchers and experts working in the field of membrane technology

In Palestine, a total number of 80 researchers identified their filed of expertise in membrane technology including desalination application in water and sanitation facilities. Fig. 1 illustrates the distribution of the researchers on R&D institutions where about 67% are working in both academic and governmental agencies. The non-governmental organization (NGO) sector is actively working in the field of MT where about 22% of experts are engaged in both local and foreign NGOs. The industrial sector has about 12% of experts employed. Almost half of the Jordanian academic staff (55%) are professionals working in the governmental sector (25%), leading to 80% of the experts are working by the public sector.

Compared to Jordan and Palestine, the situation in Lebanon is totally different where the vast percentage (60%) of membrane professionals is employed by industry. Despite many attempts to collect technical data on academic and governmental experts, only a few were identified. About 24% of MT experts were found working at academic institutions and even less (4 %) are encaged in governmental departments. For Syria, Fig. 1 shows a similar percentage of expert's distribution working in academic departments, however with a smaller share (29%) of industry involved in MT technology planning and marketing. It is worth mentioning that a total percentage of 58% of MT identified themselves as employed within the public sector (academia and government), compared with 80% and 67% in Jordan and Palestine, respectively.

Compared with compiled published works (data not shown) from North Africa (Area B: total 70 articles), the total publications of 44 mapped in Area A were grouped into the following application areas: (1) drinking water treatment; (2) wastewater treatment (domestic, grey wastewater, industrial, municipal, leachate and effluent reclamation). The grouping was performed according to the main objective of the PROMEMBRANE project. As the number of professionals specialized in MT is limited in Area A, and the region is characterized as a water scarce zone, the main focus of publications was on use of MT applications for drinking water treatment (Fig. 2). Among the drivers for MT professionals to focus on drinking water treatment rather than wastewater purification are water demands increase, groundwater overexploitation, surface water pollution increment, ineffective service delivery and aging of water infrastructures [4–7,32,33]. During the 5 years 1996–2000, only six papers tackled MT for water and wastewater treatment.

A rapid increase of published articles is identified during the five years 2001–2005 where about 52% of the papers were on the use of MT for both water desalination of brackish water and marine water sources for drinking water purposes. Also a marked increase of 25% of published scientific work is made on use of MT in wastewater treatment and effluent reclamation. This definitively shows the importance of membrane processes as a part of water scarcity and production of reclaimed effluent suitable for agricultural irrigation. This might be induced by annual drought periods, limited quantity and degraded quality of available freshwater resources due to over-

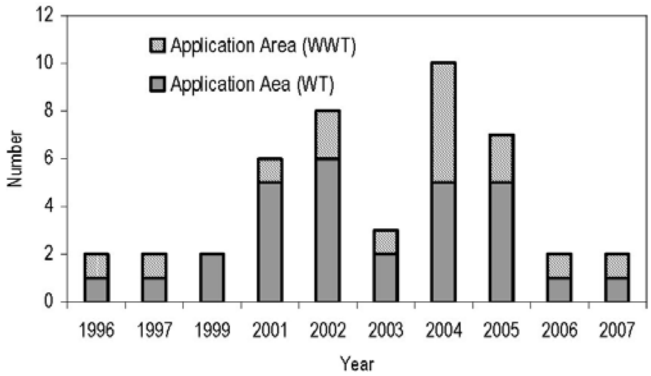

Fig. 2. Research publications on application areas of MT technology in region A.

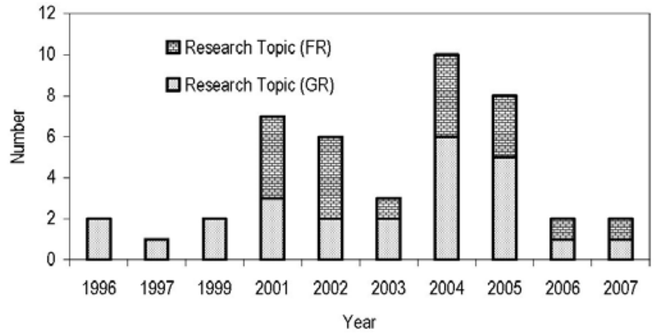

Fig. 3. Research publications on application areas of MT technology in region A.

exploitation, additions of allocthonus pollution loads and salt intrusions, stringent local and regional standards on treated effluent destined to agricultural irrigation.

As indicated earlier, few NGOs and companies working in the field of MT in the area can have a positive impact on enhancing MT applications in various fields. However, the link between experts in research institutions and the private sector (industry) is still very weak, thus few efforts are being made from industry to invest in R&D of membrane technology. Also, the current professional batch within this region come directly from either M.Sc. or Ph.D. programs with little practical experience in engineering offices or MT companies working at the international level.

3.2. MT research topics within area A

In a similar way, the 44 total publications found in region A were classified and grouped into the following main research fields: (1) general research (GR) papers on review and theoretical aspects of MT use in water treatment and wastewater treatment; (2) fundamental research aspects, which include operation and design parameters, fouling, cost, modeling, membrane-aided treatment systems, hybrid modules, pre- and post-treatment. As the number of research papers is few, the papers were grouped in only two application areas without differentiation on the type of water or wastewater. Fig. 3 illustrates chronologically the distribution of published papers within the two research topics of MT applications: GR issues and specialized applied research themes (FR).

It is obvious that only GR papers on MT applications were written during the 1990s (1996–1999); this is clearly due to the limited human and financial resources available in the region. However, FR has been published from conducted research on MT applications in both water and wastewater treatment since 2000. There are sharp variations in the number of published works among the individual countries in Area A. For example, only four papers were found published by the experts in both Lebanon and Syria, while Palestine and Jordan have published 10 and 29 respectively. GR papers constitute about 57% while applied FR entailed only 41% of the total published articles in this region. This is a good sign that MT has gained interest from the research community and policy makers for the provision of drinking water and improving effluent quality.

3.3. Technical advancements of membrane technologies in region B

Compared to MT applications in water treatment (desalination), the introduction of wastewater membrane and reclamation facilities in the MENA region has been, if any, more regionally based. While in the Mediterranean zone (region A) a larger number of research studies were conducted in the area of potable water desalination than for wastewater treatment, the situation was reversed in North Africa (region B). This could be attributed to the existence of well established research groups, availability of funds, and enforcement of national laws pertinent to protection of tourist coastal areas. This enabled MBR research and applications to flourish at laboratory, pilot- and full-scale installations for high strength industrial flows, municipal sewage treatment and tourist sites [6–18,34–50].

It is assumed that the caution of North African municipalities to consider advanced treatment systems as MBRs to the well established conventional treatment options might have delayed the application of MBRs into the municipal arena. However, the promotion of MBR in industrial applications, particularly for high strength, difficult to treat waste streams, allowed for alternative technologies such as MBRs. This has been reflected in more than 70 published articles from research groups in Tunis, Algeria, and Morocco only (data for Egypt and Libya ongoing) the installation of three full-scale installations for industrial wastewater treatment in Tunis, and Algeria (e.g. [8–12,46]). As of May 2007, the total number of installed membrane-based wastewater treatment plants

Table 1
Number of membrane-based WWTPs in the Mediterranean and North Africa zone

Number	Full scale	Country	Number	Laboratory scale	Country
3	Domestic	Egypt	0	Domestic	None
3	Municipal	Palestine, Israel	4	Municipal	Tunis
3	Industrial	Tunis, Algeria	9	Industrial	Tunis, Morocco, Algeria
9	Total		13	Total	

(immersed and external MBRs, UF/RO) in laboratory- and full-scale applications (domestic, industrial and municipal) has reached 22 (Table 1).

More than half of the membrane-based WWTPs installed within the MENA countries are installed for R&D activities including membrane development, process performance optimization, and fundamental research. Table 1 shows that all installed membrane-based treatment systems, except two pilot-scale systems (Palestine and Israel) utilizing UF/RO as a post-treatment stage are MBRs. Six out of nine of the full-scale installed MBRs, of which 50% serve the municipal sector, are membranes immersed with a hollow-fiber configuration [6,19–20,48].

Compared to conventional WWT systems, MBRs are advantageous in terms of small footprints, process flexibility and excellent hygienic effluent quality, which is suitable for various purposes including unrestricted agricultural irrigation. However, MBRs show higher energy demand, require a higher level of automation, skilled operational staff and frequent cleaning due to fouling and scaling. To modify colloidal fractions in primary and secondary treated wastewater, which plays a significant role in membrane fouling, coagulation and adsorption were found to increase the efficiency of UF with reduction needs for membrane regeneration [8–11].

To date, much of the research efforts made within the African countries on membrane-based treatment systems have mainly focused on bench- or pilot-scale studies [34–36] and short-term operations in municipal applications. Laboratory-scale studies on industrial applications with particularly high strength and difficult to treat waste streams, however, were conducted as alternative technologies such as MF/UF/NF [8–11,37–42]. However, regardless of the source of wastewater, whether it is municipal or industrial, very few publications involved full-scale studies for long-term operational periods [43,44]. For pathogen removal and municipal wastewater pre-treatment, anaerobic MBRs have proven to be a particularly reliable technique [45,46]. Few research studies were made on development of local material to improve membrane structure, control fouling, and improve flux permeate at lab scale experiments using dual-membrane systems (MF/UF) and MBR units [17,18,50–55]. Membrane biofouling is considered a crucial problem in MT application for both water and wastewater treatment with potential impact on annual operating costs and water quality. A review on process design, fouling reduction and proper operation of MBR systems implemented worldwide can be found else where [56–63].

3.4. Future research in membrane technologies

The results of this project identified wide research areas related to the types of scientific and technical advances that are crucial for membrane water treatment technologies to find broad acceptance and application in the countries under study. To achieve sustainable, affordable and adequate wastewater treatment facilities in the MENA zone, allocation of regional research funds to guide membrane processes research in the MENA region are required. In this article, we discussed various aspects of current research efforts within the MENA countries including the challenges of MT for wastewater treatment and reclamation. It was demonstrated that the availability of experts and well-trained practitioners, well-equipped research facilities, availability of funds, affordability and technical feasibility of MT, as well as the official commitment and endorsement of stringent effluent standards on treated effluent for intended uses depend on each other.

Protecting the quality of surface and groundwater requires sustainable management on a watershed basin scale to consider every impact on the water. Of equal importance is public health protection, which calls for safe brine disposal or effluent reuse [64–67]. This implies use of advanced treatment technologies, among which are the membrane-based processes. However, because water quality criteria are dependent on local conditions within the MENA region, it is necessary to define groups of similar rivers by clustering them as eco-regions. As protection of the aquatic environment and public health pertinent to emergent pollutants more often lacks a confirmed scientific, financial and managerial basis, further research and updating of criteria based on large-scale MBRs are needed [68–70].

Forming cooperation between technology developers and leading companies is a crucial approach that dramatically shortens the time required to promote MT and address some of today's key business problems and challenges. The approach provides ready access to professionals best qualified to provide commercial development guidance for new MT-based options [19,20]. It enables development or co-development of new membrane-based systems through collaboration or joint development with trend-setting companies who are expert and leaders in their fields [71–73].

Water scarcity in the MENA region has promoted the use of unconventional water sources, namely seawater, brackish water and treated/reclaimed wastewater, which are actually unlimited. With adequate membrane design, utilizing MF/UF as pre-treatment processes might reveal wastewater desalination costs lower than seawater desalination costs, thus making wastewater desalination as one of the feasible processes to produce water that fits many industrial water quality requirements [6–18,50,51]. In the future, it is likely that direct processing of wastewater in MBRs followed by RO will open up more opportunities for effluent reuse for a wide range of purposes. However, recent studies [30,31,53–55] made on MBRs sustainability revealed an overall sustainability for the MBRs as good; however, the current capital and operational costs of membrane-based treatment technologies may not necessarily satisfy some economic and ecologically sustainability criteria [59,72–77].

The technical feasibility of MT applications in wastewater treatment is very well documented, but the widespread utilization of membrane based processes is constrained by the high capital and operational costs. The price of membranes, their replacement frequency and the electrical energy consumed are the most important factors influencing the costs of the processes [23–30,38–42]. Thus, it is important to select an adequate membrane type as well as to optimize the operational conditions of the preceding treatment stage case by case. However, recent rapid proliferation of MBRs as a result of the technological advances and reduced costs has resulted in many owners, operators and engineers considering them as part of plant upgrades and expansion plans of overloaded sewage works [59,70–77]. Nevertheless, a breakthrough in MT advancement for wastewater treatment and effluent reclamation can be made only if we can prove its cost effectiveness and sustainability for developing counties. A revolution in nanoscience and membrane engineering will have a potential impact on social, environmental and economical development as well as on the political stability in Arab MENA countries in particular.

4. Conclusions and recommendations

Establishing databases on published literature and experts based on a literature survey and distribution of questionnaires to collect reliable data on MT applications from individual MENA countries was a challenge, facing numerous obstacles. These included but were not limited to lack of funding, management commitment, as well as professional experts and practitioner personnel. Other barriers most commonly cited by respondents include:

- absence of competitive industry and less economical motivations
- lack of regulatory motivation at local and regional levels
- un-coordinated training and lack of R&D programs
- limited practical experience by academic and unskilled operating staff
- lack of funds for both investment and operation

These barriers make the implementation of MT for wastewater treatment and reclamation difficult and impede their sustainability and wide-scale promotion in the MENA region. The current membrane-based wastewater treatment systems are almost entirely MBR-based technology at pilot-scale levels for industrial wastewater and are predominantly located in the North African countries. Growth in membrane technologies in the municipal sector is likely to be advanced by a combination of decreasing process costs, increasing stringency of environmental legislation and further process innovation, such as the submerged membrane module. A break-through in the industrial commercialization of membrane-based wastewater treatment technologies in the MENA region will only be possible by converting the MT into a profit-making proposition. This can be enhanced by close cooperation among industries, research communities and decision makers, utilizing committed and reliable multidisciplinary research groups in various R&D fields. The following recommendations can be made:

1. Building on the current efforts and recent technological advancements, a strategic research program should be developed to enhance the R&D activities pertinent to performance improvement and cost reduction of current membrane-based wastewater treatment technologies in the MENA region.

2. A strategic research investment program including budget estimates requires adequate and shared funding from industries, government and the public and private sectors. The funds needed to implement this program will promote innovative research; enhance capacity building, award research efforts, and advance knowledge transfer and communication.

3. Establishing sustainable networking; initiation public–private–partnerships; creation of national, regional and international industrial alliances; public awareness campaigns; and creation of local and regional R&D incubators are among the crucial efforts needed to enhance the promotion of membrane-based wastewater treatment technologies in the MENA countries and worldwide.

Acknowledgements

The PROMEMBRANE project is supported by the EU. This paper was generated partially from data originally provided by the questionnaire respondents and the MBR database of WERF, whose help the authors gratefully acknowledge. Knowledge-sharing on literature data from conference proceedings provided by Prof. Gary Amy of UNESCO–IHE, Delft, is highly appreciated. The authors are indebted to the anonymous referees for their constructive comments.

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