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A Discourse on Feasibility of the Membrane Bioreactor Technology for Wastewater Reuse in Saudi Arabia

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Abstract: The ultimate aim of this study was to assess the feasibility of the membrane Bioreactor (MBR) technology for wastewater reuse in Saudi Arabia. Treatment performance and economy as well as environmental aspects were taken into account. Investigations conducted at a pilot scale MBR plant revealed excellent organics, nutrients and pathogen removal performances irrespective of the applied Mixed Liquor Suspended Solids (MLSS) concentrations and Hydraulic Retention Times (HRT) without encountering severe membrane fouling. This study also provides an in-depth comparison of the MBR process with application of membrane technology following conventional activated sludge process. During this comparison economical aspects were discussed based on literature reports, while environmental aspects were elucidated by means of a simple Environmental Impact Assessment (EIA). The EIA revealed that MBR poses lesser negative impacts on environment as compared to the alternative option (magnitude of negative impact being 46 and 101, respectively).The analyses presented in this paper as a whole manifest the superiority of Membrane Bioreactor technology over the available alternatives in the context of Saudi Arabia.

Key words: Economy, environmental aspect, feasibility, membrane bioreactor, Saudi Arabia, wastewater reuse

INTRODUCTION

Membrane Bioreactor (MBR) process consists of a biological reactor integrated with membranes that combine clarification and filtration of an activated sludge process into a simplified, single step process (Visvanathan *et al*., 2000). MBR offers the advantages of suspended solids and macro-colloidal material-free permeate as well as a combination of high biomass concentration (requiring a small footprint) and complete retention of solids allowing the process to be operated at low F/M ratio, hence, yielding reduced excess sludge production. Operating as an MBR allows conventional activated sludge plants to become single step processes, which produce high quality effluent potentially suitable for reuse. Accordingly, over the past decade, submerged MBR processes have experienced unprecedented growth in domestic and municipal wastewater treatment/reuse (Yang *et al*., 2006). Figure 1 shows the scope of wastewater reuse associated with MBR technology (Howell, 2002).

Saudi Arabia is desert country with scarce renewable water resources (111 m^3/capita/year) and relies on non-renewable groundwater and desalination for fresh water supply (Haddadin, 2002). Figure 2 (USEPA, 2004), showing comparative water stress existing in different countries, provides an insight into the magnitude of the problem in case of Saudi Arabia. Quenching of the growing

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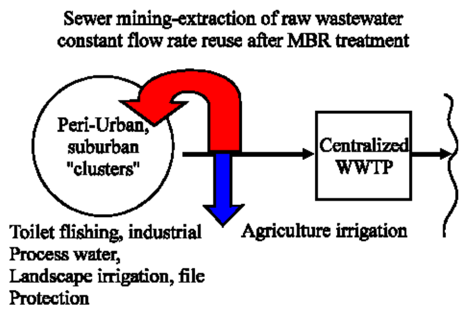

Fig. 1: Wastewater reuse in decentralized MBR systems (Adapted from Howell, 2002)

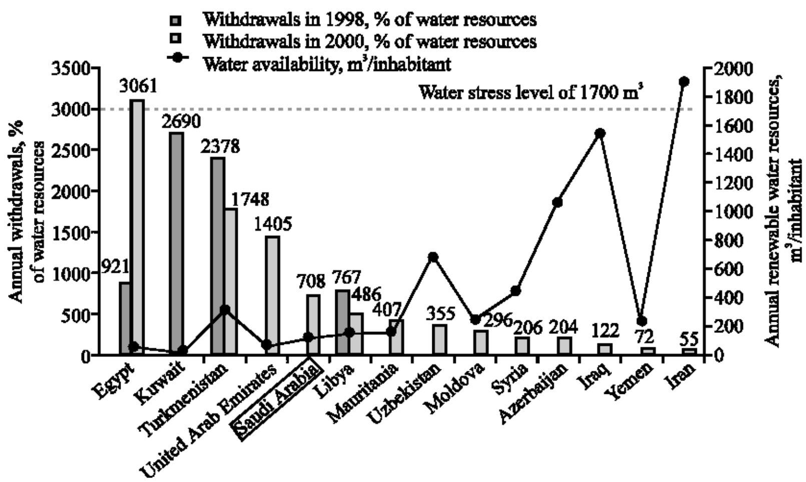

Fig. 2: Comparative water stress existing in different countries (Adapted from USEPA, 2004)

water demand entails, besides the conservation efforts, retrofitting of the existing desalination plants and setting up of the newer ones along with development and support of renewable water resources and the increased application of appropriate wastewater treatment plants realizing wastewater reclamation. To date water reuse has been practiced to a limited extent throughout the country, mainly in the big cities. The dwindling performance of the existing treatment plants along with the recent stringent disposal standards necessitate introduction of more effective treatment processes.

Based on the above discussion, MBR appears to be an appropriate choice for wastewater management and water reuse in Saudi Arabia. However, although the suitability of the MBR technology in producing reuse standard effluent has already been demonstrated in different parts of the world, this technology is rather new in Saudi Arabia. Only a handful of investigations, if any, regarding MBR from this region of the world may be pointed out. Also not only the technical aspect, but also the economical and environmental aspects, which are site-dependent, needs to be considered before proposing a technology for a particular site.

With the ultimate aim of assessment of the suitability of the MBR technology for wastewater reuse in Saudi Arabia, this study conducted investigations at a pilot scale MBR plant. The investigations conducted within the scope of this study may be split into two conspicuous streams-pilot plant exploration to assess the technical viability of MBR technology in Saudi Arabia and analyses of secondary data obtained through intensive literature review to assess the economy and environmental aspects of this technology. The present study adds invaluable information in terms of the suitability of the MBR technology in Saudi Arabia and may serve to provide great momentum to this slowly progressing branch of research in the country.

MATERIALS AND METHODS

Wastewater, Equipment and Operating Conditions of the MBRs

This study conducted investigations at a pilot plant MBR system located in Al Khomra, Jeddah for a period of three months. The pilot plant was constructed in a compound receiving wastewater from a residential area and adjoining workshops. The operation of the pilot plant was initiated on July 15, 2004. The pilot plant consisted of three parallel MBR units (Fig. 3), all receiving wastewater from the same storage tank, which, in turn, received wastewater from a residential area. Ultrafiltration hollow fiber membranes (Zenon) with pore size of 0.04 micron and nominal surface area of 0.93 m^2 were utilized in this study. In each MBR, a membrane was placed within a 204 L polyethylene tank, the water level of which was controlled by a float valve. Air was supplied to the fine bubble diffusers located at the bottom of each of the process tanks as well as to the coarse bubble diffusers built-in at the bottom of the membrane. The membranes were backpulsed periodically (permeation: 9.75 min, backpulse: 0.25 min) with permeate stored in backpulse tanks.

To study the performance of MBR under different operating conditions, different mixed liquor suspended solids (MLSS) concentrations (10, 15 and 20 g L^{-1}, respectively) were built up within the three parallel MBRs (MBR 1, MBR 2 and MBR 3, respectively) (Table 1). During Phase 1, all units were operated at a hydraulic retention time (HRT) of 8 h for one month. During Phase 2 and Phase 3, all units were operated at a HRT of 6 and 3 h, respectively. Different levels of MLSS in

Table 1: Plan of operation (Year 2004)

	Phase I (Aug.15-Sep.14)		Phase II (Sep.15-Oct.14)		Phase II (Oct.15-Nov.14)	
MBR unit	MLSS conc. (mg L^{-1})	Retention time (h)	MLSS conc. (mg L^{-1})	Retention time (h)	MLSS conc. (mg L^{-1})	Retention time (h)
MBR 1	10,000	8	10,000	6	10,000	3
MBR 2	15,000	8	15,000	6	15,000	3
MBR 3	20,000	8	20,000	6	20,000	3

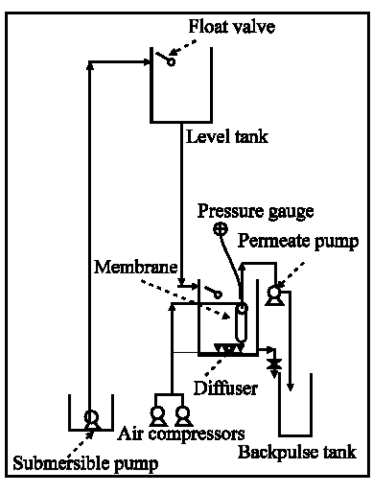

Fig. 3: Schematic of the Pilot Plant (Three MBR units in parallel)

different MBR units were maintained by varying sludge withdrawal rate (SRT of 40, 60 and 80 days) in each unit, while HRTs were varied by varying the flow rate of the permeate pumps (0.375, 0.5, 1.0 L min^{-1}, respectively), hence, varying the quantity of permeate.

Analytical Methods

Samples collected on every third day through out the whole period of continuous operation were analyzed for organics, nutrients and pathogen removal following the standard methods. Organics removal efficiency was assessed by monitoring and comparing the Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) in the influent municipal wastewater and the MBR permeate. In order to ascertain the Nitrogen and Phosphorus removal performance by the pilot plant MBRs following parameters were monitored: Ammonia Nitrogen (NH_3-N), Nitrate Nitrogen (NO_3-N), Total Kjeldhal Nitrogen (TKN), Total P (TP). Observation of the Total and Fecal Coliform content provided insight into the extent of disinfection of wastewater achieved by MBR. In this study membrane fouling was indirectly assessed by monitoring the transmembrane pressure (TMP) throughout the whole period of observation of three months.

Economic Aspect and Environmental Impacts

Following the confirmation of the technical viability of the MBR process in Saudi Arabia, this study compared the cost efficiency and environmental impacts of two membrane-based options available to treat sewage for water reuse-tertiary ultrafiltration (UF) of the effluent from a conventional activated sludge (CAS/UF) process and an integrated membrane bioreactor (MBR). Owing to the absence of reliable cost information within Saudi Arabia, cost comparison was performed following the report of Côté *et al*. (2004), who utilized the same Zenon membrane system as used in this study.

Environmental aspects were elucidated by means of a simple Environmental Impact Assessment (EIA). In order to make comparison possible, all of the selected environmental parameters were assigned respective weight-values (ranging from 1 to 5) based on their relative importance. The weightage value was then multiplied with the corresponding estimated impact values (ranging from 0 to -5) pertaining to each of the alternatives (MBR and CAS/UF) to ascertain the respective magnitudes of impacts.

RESULTS AND DISCUSSION

Technical Feasibility of the MBR Technology in Saudi Arabia

Organics and Nutrients Removal Performance

In the course of the operation under different HRTs of the MBRs each of which contained different MLSS concentrations, the BOD in the influent wastewater ranged between 198 and 253 mg L^{-1}. The BOD in the membrane-permeate, on the other hand, varied in the range of 4 to 12 mg L^{-1} (Table 2). Conversely, the COD in the influent municipal wastewater fluctuated between 445 and 575 mg L^{-1}, while that in the membrane-permeate ranged from 23 to 56 mg L^{-1} (Table 3).

Table 2: BOD concentrations in influent and permeate

		Permeate range (mg L^{-1})		
HRT (h)	Influent range (mg L^{-1})	MBR 1	MBR 2	MBR 3
8	201-241	6-9	6-8	4-6
6	209-253	7-11	6-9	4-8
3	198-245	10-12	8-10	7-9

Table 3: COD concentrations in influent and permeate

		Permeate range (mg L^{-1})		
HRT (h)	Influent range (mg L^{-1})	MBR 1	MBR 2	MBR 3
8	451-545	25-34	23-33	25-35
6	470-575	43-52	32-41	28-35
3	445-560	46-56	36-45	32-39

Table 4: TKN concentration in permeate under different operating conditions

		Permeate range (mg L^{-1})		
HRT (h)	Influent range (mg L^{-1})	MBR 1	MBR 2	MBR 3
8	19-23	0.0-0.3	0.0	0.0
6	18-26	0.2-0.3	0.17-0.25	0.1-0.17
3	18-26	0.2-0.3	0.17-0.25	0.12-0.17

Table 5: NO_3^--N concentration in permeate under different operating conditions

		Permeate range (mg L^{-1})		
HRT (h)	Influent range (mg L^{-1})	MBR 1	MBR 2	MBR 3
8	0.1-0.3	13.89-16.64	13.87-16.59	13.81-16.54
6	0-0.2	12.31-20.8	12.25-20.75	12.22-20.72
3	0.1-0.3	12.58-20.88	12.53-20.82	12.5-20.8

Diminution of TKN and appearance of NO_3^-N in the permeate indicate excellent nitrification, however, limited denitrification

Table 6: Total and Fecal Coliform concentrations in influent and permeate (HRT = 8 h)

		Permeate range (Cfu/100 mL)		
HRT (h)	Influent range (Cfu/100 mL)	MBR 1	MBR 2	MBR 3
Total Coliform	1×10^7-2.4×10^7	45-70	50-75	45-85
Fecal Coliform	7×10^3-2.2×10^4	32-49	35-52	32-60

On the other hand, the TKN in the influent municipal wastewater ranged between 18 and 26 mg L^{-1}. The TKN in the membrane-permeate, varied in the range of 0 to 0.3 mg L^{-1} depending on the influent TKN and also the reactor MLSS concentration (Table 4, 5). The nitrification efficiency, hence, never dropped below 98.64% and during the best performance a complete nitrification was observed. In absence of any specific means to improve denitrification (Li *et al*., 2008) as expected, it only ranged in between 18.94 and 32.21%. The effect of HRT on the performance of the MBRs with different MLSS concentrations was rather negligible.

Also, in absence of any additional facilities to enhance P removal (Yeoman *et al.,* 1988), the MBRs operated in this study achieved a reasonable average P removal rate of around 40-50%, while occasionally the removal exceeded 60%.No distinct trend of effect of influent P concentration, HRT and MLSS concentration on the P-removal could be detected (Fig. 4).

Disinfection

Reductions in bacteria and viruses of 4-8 log have been reported (Shang *et al*., 2005) in MBRs. Although in general the pathogen removal efficiencies of the MBRs were up to the mark, an interesting trend of slightly higher removal being associated with the reactor with the lower MLSS concentration was noticed (Table 6). In this study, the Fecal coliform removal efficiency, at times was as high as 99.92% and never plummeted below 99.20% (corresponding to a log removal of 3.1 and 2.1, respectively). A maximum 99.99991% (6 log) removal and a minimum 99.9993% (5 log) removal of total coliform were achieved during continuous operation of the MBRs with different MLSS concentration under different HRTs.

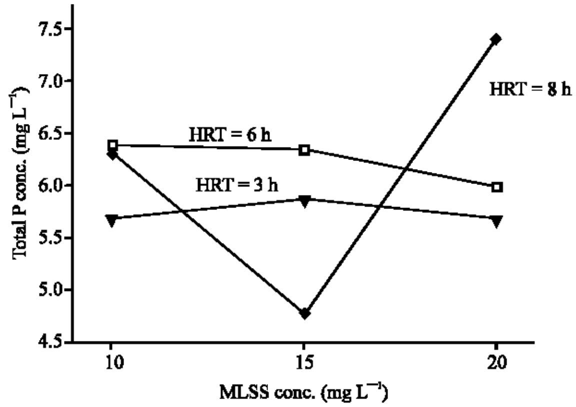

Fig. 4: Mean total P in permeates under different HRT and MLSS conc.

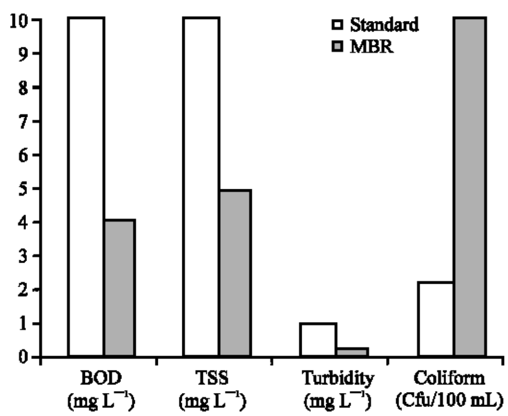

Fig. 5: Comparison of MBR permeate quality with reclaimed water standards in Saudi Arabia

Wastewater Reuse

An important aim of this study was to assess the suitability of MBR technology for accomplishing wastewater reuse. Hence a comparison of the quality of the permeate obtained during the experiment with the standards in Saudi Arabia was deemed essential. Figure 5 furnishes such a comparison. It is interesting to note that the permeate quality, in terms of all the studied parameters except one, convincingly conformed the quality requirements for reuse for irrigation purpose in Saudi Arabia

Membrane Fouling

Despite the inherent advantages of MBR, severe membrane fouling may necessitate frequent chemical cleaning and/or costly membrane replacement (Le-Clech *et al*., 2006). Hence assessment of the membrane fouling is an indispensable part of the overall feasibility study of MBR application at a particular site.

In addition to the permeate-backpulsing (15 sec/10 min), the requirements as specified by the membrane supplier for routine operation included sodium hypochlorite (NaOCl) backpulsing of the membrane corresponding to the rise of TMP to a value of 9.0 psig (62 kPa) and occasional off-site cleaning by soaking into NaOCl and/ or HCl solution. However, in the course of this study, a stable flux could be maintained without any chemical cleaning (Fig. 6). A stable pollutant removal performance concurrent with abatement of membrane fouling presents the proposed MBR system as a promising option for the treatment and reuse of the wastewater explored in this study.

Economic Feasibility and Environmental Impacts

Economic Feasibility

Membrane-based tertiary treatment options have been reported to be superior to conventional processes from technical and economic points of view (Al-Malack, 2003). Conversely, comparative cost assessment of two membrane-based wastewater reclamation options, namely, tertiary filtration of the effluent from a conventional activated sludge (CAS/UF) and an integrated membrane bioreactor (MBR) has also been performed by different researchers (Cote *et al*., 2004; Lesjean *et al*., 2004;). Although the specific conclusion tends to depend on the assumptions based on which the cost estimates are performed, in general, MBR has been shown to incur lower capital cost and a slightly higher or comparable operation and maintenance cost.

The comparison made by Côté *et al.* (2004), as presented in Fig. 7-10 and Table 7, is of special relevance to this study as the same membrane systems were used in both the studies. MBR plants are much smaller than CAS/UF plants. For all plant sizes considered, MBR plants are less expensive than CAS plants. This is because the savings associated with eliminating secondary

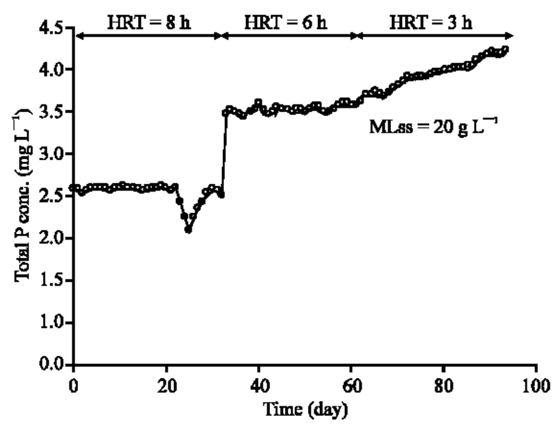

Fig. 6: Variation of transmembrane pressure (TMP) under different HRTs

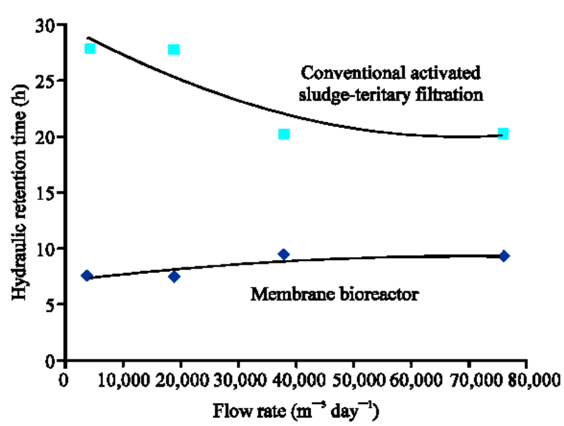

Fig. 7: Comparative hydraulic retention time (adapted from Cote *et al*., 2004)

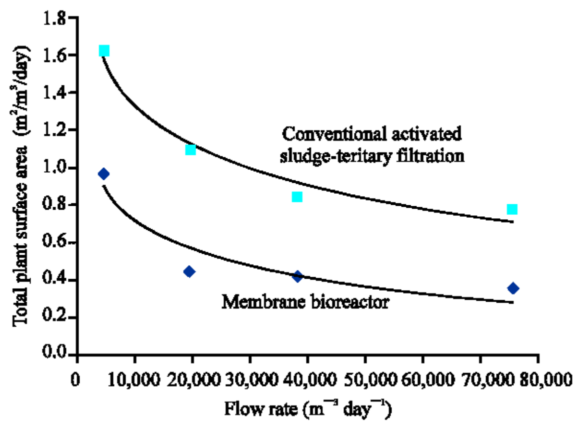

Fig. 8: Comparative total plant surface area (adapted from Cote *et al*., 2004)

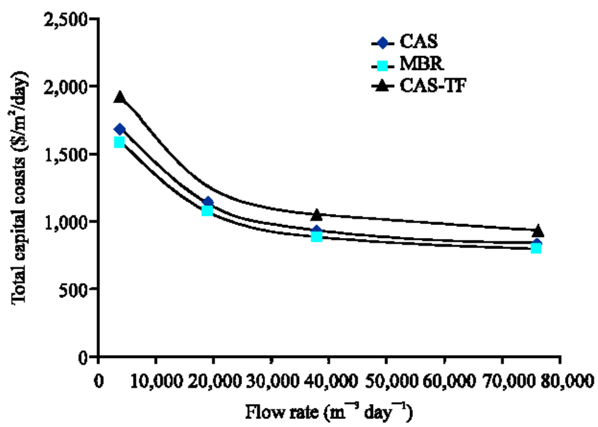

Fig. 9: Comparative total capital costs (adapted from Cote *et al*., 2004)

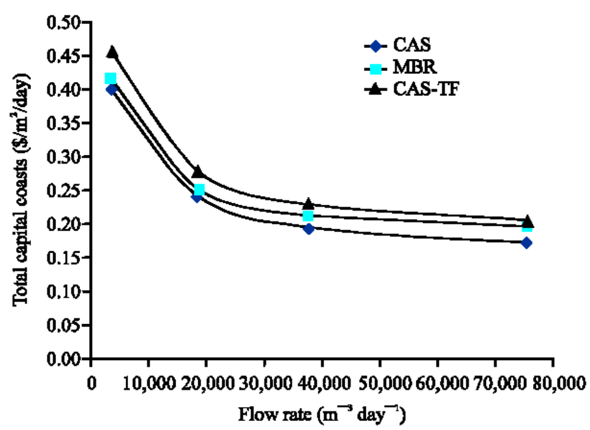

Fig. 10: Comparative total life cycle costs (adapted from Cote *et al*., 2004)

Table 7: Comparative costs[a] associated with MBR and CAS/UF technologies (Adapted from Cote *et al*., 2004)

	MBR	CAS/UF
Total capital cost ($/m^3/day)	1600	1900
Total operation and maintenance cost ($ m^{-3})	0.28	0.27
Total life cycle cost ($ m^{-3})	0.42	0.46

[a]For 1 MGD (3800 m^3 day^{-1}) plant

Table 8: Comparative assessment of the negative impacts of MBR and CAS/UF technologies on selected parameters

		MBR		CAS/UF	
Impact	Weightage	Impact value	Magnitude of impact	Impact value	Magnitude of impact
Economic/Demographic	5	-4	-20	-3	-15
Sludge disposal	4	-1	-4	-4	-16
Landscape (land use)	4	-1	-4	-5	-20
Landscape (visual)	3	-2	-6	-5	-15
Odor and noise	3	-1	-3	-5	-15
Spread of worms/insects	3	-1	-3	-4	-12
Impact on flora and fauna	2	-1	-2	-3	-6
Overflow of wastewater	1	-4	-4	-2	-2
Cumulative magnitude of impact		-46		-101	

clarifiers, reducing the size of the aeration tanks and reducing footprint are larger than the added costs for the membrane system and the fine screen. The total life cycle cost of MBR is also lower than that for CAS/UF.

In the context of the prevailing situation in the water sector of Saudi Arabia it is also important to note that the incremental life cycle cost to treat sewage to indirect potable water reuse standards (i.e. by ultrafiltration and reverse osmosis) is only 39% of the cost of seawater desalination (Cote *et al*., 2004). Taking all the above mentioned information in to account, MBR technology appears to be a feasible option for wastewater reclamation in Saudi Arabia.

Environmental Impact Assessment

Table 8 furnishes a comparative assessment of the negative impacts of MBR and CAS/UF technologies on selected environmental parameters. The estimated impacts have been plotted in Fig. 11.

In the EIA, MBR received better ratings than its counterpart in case of all the selected environmental parameters except two, namely, ‘economic and demographic’ and ‘overflow of wastewater’. At the present stage of development MBR may involve a cost slightly higher than or comparable to that associated with CAS/UF technology and in case of accidental overflow of wastewater from reactor, MBR may induce severer impact since it usually maintains higher sludge concentration (in the order of tens of thousands of mg L^{-1}) within bioreactor. On the other hand, an MBR plant, by virtue of de-coupling HRT and SRT and maintenance of high MLSS concentration, requires much smaller plant size and, hence, imposes lesser effect on landscape (‘land use’ as well as ‘visual’). Compact footprint of MBR plant allows it to be completely covered, which, in turn, minimizes the chance of odor and noise pollution and spread of worms and insects. MBR minimizes excess sludge production in the biological unit due to operation under lower F/M ratio and this technology may realize better organic and nutrient removal as compared to CAS/UF due to the fact that membrane here works in synergy with the biological agents.

The EIA conducted in accordance with the above discussion revealed that MBR poses lesser negative impacts on environment as compared to the CAS/UF option (magnitude of negative impact being 46 and 101, respectively).

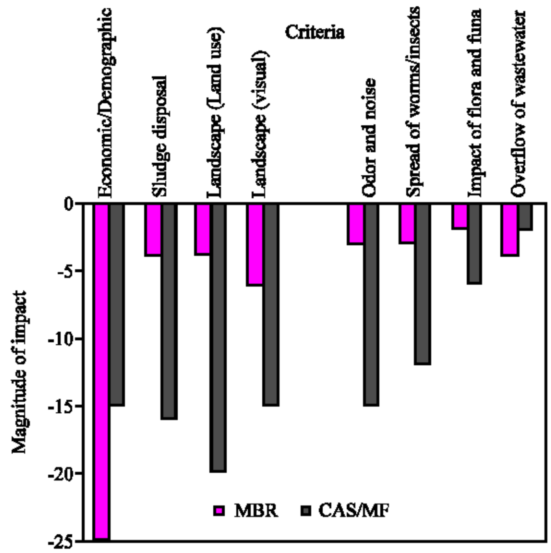

Fig. 11: Magnitude of negative impacts imposed by MBR and CAS/MF

Social Impacts Specific to Saudi Arabia

Besides the social impacts of wastewater treatment plants in general , the issue of reuse of treated wastewater entail an additional impact in a Muslim community. The question as to the suitability of the reclaimed water for the religious activities like ablution and bathing (Ghusl) may certainly arise. So an official decree (fatwa) from scholars (Ulama) should be obtained on whether reclaimed wastewater can be used or not. Notwithstanding such decree, there remain doubts on whether the people will accept reclaimed wastewater even for uses like toilet flushing, irrigation, landscaping and hence, this issue need to be properly dealt with.

CONCLUSIONS

MBR technology is a very attractive means for achieving tertiary effluent owing to its inherent compactness and single-step pollutant removal capability. However, MBR technology is rather new in Saudi Arabia. This study aimed at the assessment of the suitability of the MBR technology in the kingdom. Treatment performance and economy as well as environmental aspects were taken into account. The pilot plant MBR units realized excellent organics, nutrients and pathogen removal performances irrespective of the applied MLSS concentrations and HRTs. Membrane fouling—which impedes the widespread application of this technology, was rather minimal. Comprehensive literature review and analytical approaches also revealed the economic feasibility along with the eco-friendliness of the process. With progressive depletion of the limited water resources and increased demand of water, a serious pursue of alternative water resources, such as wastewater reclamation, is deemed imperative for the development and growth of the economy of Saudi Arabia. The present study is expected to serve to provide great momentum to this slowly progressing branch of research in the country.

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