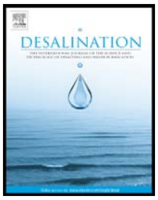
Desalination xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal



Immersed Membrane BioReactor (IMBR) for treatment of combined domestic and dairy wastewater in an isolated farm: An exploratory case study implementing the Facet Analysis (FA)

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ARTICLE INFO

Article history:
Accepted 28 June 2009
Available online xxxx

Keywords:
Dairy Wastewater
Facet Analysis
Management Modeling
Membrane BioReactor
Ultrafiltration

ABSTRACT

In many regions dairy farms and milk processing industries, discharge large quantities of their wastes to the surroundings which pose serious environmental risks. With the purpose of treating the combined dairy and domestic wastewater from a small dairy farm in the Negev Desert of Israel, the use of a recent emerging technology of Immersed Membrane BioReactor (IMBR) was evaluated over the course of 500 test hours, under a variety of wastewater feed quality conditions.

Field experiments were performed at the Kornmehl farm, an isolated dairy farm located 30 km south of Beer-Sheva, in the Negev Desert of Israel. The operating conditions for this experiment included constant product flow of 7 (L/h)], and the transmembrane pressure was increased smoothly during the experiment from 0.05 to 0.13 bar. Temperatures ranged between 30 °C and 37 °C, pH ranged between 4 and 9, TSS varied between 353 mg/L to 1000 mg/L and COD changed from 900 mg/L to 12,800 mg/L.

The overall performance of a pilot-scale Ultrafiltration (UF) IMBR process for a combined domestic and dairy wastewater was analyzed based on the Facet Analysis (FA) method. Preliminary results of the FA model indicate: (i) the Trans-Membrane Pressure (TMP); the pH and the temperature do not have an effect on the performance of the permeate normalized flux and on the specific normalized flux, and; (ii) the bioreactor is characterized by high concentration of organic matters and it can be estimated that the IMBR normalized flux decline is dependent on other variables (air blower performance, backwash procedure and chemical cleaning).

1. Introduction

The scarcity of water resources in arid and semi-arid areas of the world, especially in the Mediterranean Basin, has changed public attitude towards wastewater management. Adequate management of wastewater is now a necessity, not just an option.

Dairy industries and milk processing farms frequently discharge their wastes directly to the close surroundings, generating environmental nuisances. As result of the multiple activities carried out during the processing of dairy products (i.e. pasteurization, cleaning, and disinfection of the milking sheds and other facilities), dairy wastewater usually contains high concentrations of organic matter, solids, and nutrients, as well as some dissolved inorganic pollutants [1–3]. Consequently, dairy wastewater deserves special attention since its levels of potential contaminants typically exceed those levels considered hazardous for domestic wastewater [4–9] (Table 1).

Despite the large number of publications, membrane treatment of wastewater is not well understood due to the complexity of the interacting phenomena and the multitude of module and reactor configurations as well as wastewater and operating conditions [10,11]. In this current paper the facet analysis method is implemented to clarify membrane pilot that uses a combined domestic and dairy wastewater operation at a constant product flow.

2. Immersed Membrane Bioreactor (IMBR) performance

The advanced tested treatment method is based on the Immersed Membrane BioReactor (IMBR). In contrast to the traditional technologies (i.e. stabilization ponds, activated sludge, etc.), the IMBR is a compact

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doi:10.1016/j.desal.2009.06.035

Table 1
Typical composition of untreated domestic and dairy wastewater (mg/L).

Variable	Domestic Wastewater[a]	Dairy Wastewater[b]	Dairy Wastewater[c]
COD	1000	2038–4728	2000–10,000
BOD_5	400	1077–2805	1300–1500
TSS	350	438–1224	800–1000
Total P	15	17–29	4.1
NH_4^+–N	50	–	–
Grease	150	240–286	35
Cl^-	100	–	–
Alkalinity ($CaCO_3$)	200	–	1200

[a] Metcalf and Eddy [4]
[b] Typical composition of strong concentration untreated dairy wastewater Tawfik *et al.* [1]
[c] Koyuncu et al. [3]

system (small footprint) with a high capacity of treating varying quality wastes and efficient energy use [12–20].

The average Trans-Membrane Pressure (TMP) is generally given for an IMBR by [21]:

$$P_{\rm tm} = 0.5(P_{\rm i} + P_{\rm o}) - P_{\rm p} \tag{1}$$

where $P_{\rm tm}$ is the Trans-Membrane Pressure (bar), $P_{\rm i}$ is the inlet pressure of the membrane module (bar), $P_{\rm o}$ is the pressure at the outlet of the membrane module (bar) and $P_{\rm p}$ is the permeate pressure (bar). Temperature corrections to 20 °C for permeate flux are made according to Eq. (2), which is based on the variation of water viscosity with temperature [22]:

$$J_n = (Q\,p_{uf} \cdot e^{-0.0239(T-20)}) \,/\, Auf \tag{2}$$

Where J_n is the normalized permeate flux (at 20 °C), L/(hour·m^2); $Q\,p_{\rm uf}$ is the permeate flow, L/hour; T is actual operating temperature, °C, and, A_{uf} is the membrane surface area, m^2. The specific normalized flux, [J_{ns}, L/(hour·m^2·bar)] at 20 °C is given by Eq. (3):

$$J_{ns} = J_n \,/\, TMP \tag{3}$$

Subject to the above following expressions it can be concluded: (i) the specific normalized flux depends primarily on TMP, and; (ii) there is probably a very low correlation between the normalized flux and the colloidal molecular weight of the suspended matter in the solution. These equations that describe the used cross-flow UF model have several drawbacks: (i) The quantitative expressions do not account for the effluent quality, membrane characteristics and fouling processes, and; (ii) there are limited explanations for the heavy metal removal by hybrid complexation and polymer-enhanced Ultrafiltration [23].

The purpose of the paper is to demonstrate the use of Facet Analysis (FA) for clear distinction of the cluster of variables [24–28] affecting the IMBR performance. The following objectives are expected to be achieved in the framework of this paper: (i) development of a conceptual approach enabling to present effluent quality interactions with membrane treatment processes; (ii) identifying interaction between state variables (effluent quality) and operational variables (TMP, normalized flux), and; (iii) to apply the FA to an IMBR system (for treatment of combined domestic and dairy wastewater).

3. Management modelling

3.1. General

Management modeling provides effective means of rapidly testing and evaluating different scenarios for a given system operated under diverse conditions. Well-defined models allow examination diverse hypothetical situations, which yield perceptive insight into the analyzed phenomena. The various aspects of IMBR can be viewed at the following levels: (i) the local level of the isolated process: economic, chemical, microbial and membrane performance criteria [15,16], and; (ii) at the regional level of water sources utilization, environmental control, including membrane technology issues [29,30]. At this level, IMBR performance is only one link in a multi-component system. Other phases to be considered in management modeling include environmental pollution, disposal of concentrates, public involvement regulatory and risk issues [31].

Management models provide effective means of rapidly testing and evaluating different water system scenarios for a given set of conditions [15]. Well-defined models allow examination of many hypothetical situations, which will yield perceptive insight [32]. Although models frequently deviate from real life situations; they provide preferences of optimal system selection and potential directions of processing. These directions can be consequently interpreted by the decision-makers for project evaluation and implementation [33–36].

Facet Analysis is a research approach which has been found to be effective in the depiction and analysis of complex systems, where a large number of mutual interacting variables are involved [37]. In this current paper the FA method is implemented to clarify IMBR system performance.

3.2. The Facet Analysis (FA)

According to FA, it is assumed that a matrix "A" can describe the performance of an IMBR system.

$$A = \alpha_{il},\; i = l, \ldots\ldots, N;\; l = l, \ldots., L \tag{4}$$

where i is a record index [in this case the points (i = 1,……,N) describe the date] and l denotes a variable index [in this case the points (l = 1,….,L) describe the IMBR performance] The similarity coefficient $\mu_{\rm lm}$ is defined by Eq. (5) [38]:

$$\mu_{lm} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}(a_{il}-a_{jl})(a_{im}-a_{jm})}{\sum_{i=1}^{N}\sum_{j=1}^{N}|a_{il}-a_{jl}|\,|a_{im}-a_{jm}|}, \quad i{\neq}j, l{\neq}m \tag{5}$$

where $\mu_{\rm lm}$ is the similarity coefficient of the lth and the mth variables and $a_{\rm il}$ is the value of the variable. The inter-correlation of the variables, which serve as the empirical measure of similarity coefficient between them, is expressed in the space by the distances between pairs of point. Therefore, two points of variables are closer together if the correlation between the corresponding variables is high. When the correlation between the two variables is poor, they are farther apart, and the geometric distance between the points is large.

A structured map can be characterized by the similarity coefficients:

$$d_{lm}(x) = f(\mu_{lm}) \tag{6}$$

where $d_{lm}(x)$ is a distance (an Euclidean distance) and f is a function (typically a weak descending monotone function or a linear function). If Eq. (6) does not hold, an optimal solution is searched that minimizes a coefficient of alienation (St) that is defined by Groenen [39]:

$$St = \sqrt{\frac{\sum_{l<m}[f(\mu_{lm}) - d_{lm}(x)]^2}{\sum_{l<m} d_{lm}^2(x)}} \tag{7}$$

The smaller the value of the coefficient of alienation—the better is the correlation of Eq. (6). Mapping the problem thus involves a composite optimization problem, however, there are algorithms that almost definitely find the best solution [40].

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4. Materials and methods

Field experiments were performed at the Kornmehl farm, an isolated dairy farm located 30 km south of Beer-Sheva, in the Negev Desert of Israel [16]. The products manufactured at Kornmehl are based on goat's milk. The raw feed source is dairy and domestic wastewaters are discharged and collected in a settling tank. The wastewater from the settling tank is filtered by a strainer and pumped into a storage tank located 2 m above the bioreactor, where further settling is maintained. An extra filter is used (0.130 mm pore diameter) to remove suspended solids and then wastewater is fed into the bioreactor. The characteristics of the raw wastewater generated in the farm are summed in Table 2. (Total of 28 samples). As observed, Kornmehl Farm wastewater contains high concentrations of organics, solids, and nutrients because of the multiple activities comprised during the cheese manufacture (i.e. spilled milk, cheese wastes, goat dung, domestic and cleaning activities, etc).

Zenon Environmental Systems Inc supplied the IMBR used in the experiments as well as its respective components. The IMBR is equipped with an Ultrafiltration ZeeWeed ZW-10 hollow fiber membrane module, with a surface area of 0.93 m^2 and a nominal pore size of 0.04 μm. Other main elements of the system include a 220 Liter process tank, a 20 Liter backpulse tank, a small control panel, a process pump, an permeate pump, and a blower.

The Zenon ZW-10 module was cleaned prior to the system start up of the whole experiment, at the beginning of each experiment, and when the permeability of the membrane during the experiments reached approximately 10–20% of the initial permeability. All chemical cleanings were performed using manufacturers' recommendations and protocols. For the system startup, the process tank was filled with potable water and sufficient NaOCl was added to produce a 200-mg/L solution. The module was soaked in this solution at 25 °C for 24 h. After this period, the process tank contents were replaced and the membrane was rinsed with potable water. The initial permeability was then measured.

For maintenance cleaning, the membrane module was soaked with a 200-mg/L solution of NaOCl for 5 h in a clean-up vessel with a volume of 25 L. During this period, aeration was injected to the module to enhance cleaning efficiency. After this, the solution in the tank was replaced with a clean solution and the membrane module was submerged for a second time, to apply a concentrated backwash of 1000-mg/L of NaOCl of the solution for a half hour. At the end of the backwash, the module was cleaned with tap water and the membrane permeability was measured.

Initial specific flux was determined one day prior to the start of the experiment with clean tap water after chemical cleaning of the membrane. The permeate flow rate was set to a constant value by means of potentiometers mounted in the control panel to regulate the process pump. Three samples, namely: influent, bioreactor (MLSS), and effluent were collected on each one of the sampling days to determine wastewater quality and evolution before, during, and after the IMBR system. Data was recorded manually on operational and water quality data sheets prepared specifically for this study. In order to maintain a stable product flow, the flow rate of the wastewater was controlled by an adjustable timer installed on the front of the control panel. Solid Retention Time variation was controlled manually by a drain valve and by altering the flow rate of excessive sludge discharge.

Table 2
Typical composition of constituent concentrations for Kornmehl Farm raw wastewater (mg/L).

Parameter	Mean	Min[a]	Max[b]	SD[c]	SE[d]
pH	6	4	9	1	0.25
EC (dS/m)	3.24	2.28	4.17	0.49	0.09
Alkalinity (as $CaCO_3$)	339	120	720	171	32
Cl^-	534	353	1000	152	29
TSS	702	172	2087	500	95
COD Tot[e]	5819	900	12,800	4099	775
COD Filt[f]	4530	770	9992	3198	604
BOD_5 Tot	2045	220	4350	1356	256
BOD_5 Filt	1668	150	3880	1152	218
NH_4^+–N	64	26	219	45	9
NO_2^-	0.83	0.00	6.74	1.46	0.28
PO_4^{3-} -P	196	48	334	83	16

[a] Min (minimum) concentrations or values recorded.
[b] Max (maximum) concentrations or values recorded.
[c] SD = Standard deviation.
[d] SE = Standard error.
[e] Tot represents the total organic matter in the sample prior to filtration.
[f] Filt represents the organic matter in the sample after filtration.

The first stage of the project recorded an operational period of 500 h. The maintenance procedure included a backwashing of 15 s every 5 min and chemical cleaning at following timing: 79, 160, 200, 275, 360 h. Temperatures ranged between 30 °C and 37 °C, with an average temperature of 33 ± 2 °C, typical for this period of the year in the Negev Desert. The operating conditions for this experiment include constant product flow [7 (L/h)], and the pilot was operated at a hydraulic retention time [reactor volume (L) divided by the volume of treated water per hours (L/h)] of 24 h. The transmembrane pressure always increased smoothly during the experiment from 0.05 to 0.13 bar and for 180 h, it was then increased from 0.13 bar to 0.33 bar in one day. The wastewater samples were analyzed according to accepted analytical procedures [41] and the data was analyzed by the FA model.

Twenty variables concerning the IMBR and the permeate performance were examined: quality variables [$PO_4\equiv$, NH_4^+–N, Electrical Conductivity (EC), pH, BOD_5, COD, TSS, Turbidity and Temperature], Ultrafiltration membrane performance [Trans-membrane Pressure (TMP), normalized flux and specific normalized flux].

5. Results and discussion

The measured turbidity in the bioreactor ranged between 310 and 8500 NTU during the entire experiment, the effluent turbidity varied between 0.3 and 3.9 NTU (Rejection is more than 98.8 percent), while the TSS varied between 0 and 48 mg/L (Rejection is more than 75%). Poor COD and BOD_5 rejection rates were obtained during the experiment: Average of 50.4% and 47.6% in the effluent were found. There was negligible NH_4^+ and $PO_4\equiv$ removal (less than 10%).

The results were analyzed by the FA algorithm that consists of the following phases [40]: (i) computing the similarity coefficient matrix (Table 3); (ii) matching points in a Euclidean space, and; (iii) performing iterations and representing variables on a map of distances.

Table 3 presents the matrix of the similarity coefficients for the observed variables calculated. The original coefficient were multiplied by 100 and rounded into integer numbers. Some of the correlation coefficients between the twenty variables are negative. The negative signs correspond to variables of different clusters.

According to the result of Table 3, the normalized flux and the specific normalized flux are not correlated with the bioreactor variables (COD, BOD_5, TSS, NTU). The results of a two-dimension facet analysis for the twenty variables (Table 3) are shown in Fig. 1.

Two elliptical curves (Fig. 2) divide the variables into three facets, each of them includes several variables: (i) the bioreactor wastewater quality variables (COD, BOD_5, TSS, NTU, $PO_4\equiv$, NH_4^+, EC); (ii) overall UF permeate performance (COD, BOD_5, TSS, NTU, $PO_4\equiv$, NH_4^+, EC), and; (iii) UF performance variables (normalized flux, specific normalized flux, TMP and external process variables such as the temperature and the pH.

Preliminary results of the FA model indicate the following (Fig. 2): (i) there are high correlations (small distances) between the constituent content in the bioreactor (BOD_5, COD, TSS and turbidity); (ii) concerning specific inorganic constituent (NH_4^+, Electrical conductivity, pH) there is high correlation (small distances) between the concentrations in the bioreactor and the permeate (implying a low

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Table 3
Similarity coefficient matrix for IMBR variables [Eq. (5)].

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PO_4 Permeate 1	_	+62	+72	+79	+90	+81	−24	−26	−14	+36	−17	+60	+31	+42	+31	+39	+26	−52	−39	+54
PO_4 Bioreactor 2	+62	–	+35	+52	+73	+79	+8	+8	+56	+80	+24	+83	+41	+87	+38	+74	+4	+27	−48	−10
NH_4-N Permeate 3	+72	+35	–	+98	+68	+67	−25	−22	−36	+43	+6	+64	+54	+44	+42	+58	+3	−36	−17	+76
NH_4-N Bioreactor 4	+79	+52	+98	–	+79	+80	−24	−22	−22	+ +57	+9	+73	+54	+58	+39	+67	+3	−30	−27	+70
Electrical C. Permeate 5	+90	+73	+68	+79	–	+97	−41	−42	+7	+56	+5	+66	+22	+57	+13	+53	−2	−32	−30	+56
Electrical C. Bioreactor 6	+81	+79	+67	+80	+97	–	−36	−36	+17	+72	+16	+71	+24	+69	+9	+64	−7	−16	−34	+49
pH Permeate 7	−24	+8	−25	−24	−41	−36	–	+99	+42	−5	+39	−5	+10	−3	+25	−6	+70	+27	−66	−70
pH Bioreactor 8	−26	+8	−22	−22	−42	−36	+99	–	+44	−3	+45	−1	+15	+1	+30	+0	+65	+32	−63	−68
BOD_5 Permeate 9	−14	+56	−36	−22	+7	+17	+42	+44	–	+37	+70	+30	+1	+47	+11	+34	−3	+68	−32	−63
BOD_5 Bioreactor 10	+36	+80	+43	+57	+56	+72	−5	−3	+37	–	+22	+79	+51	+91	+12	+86	−19	+42	−32	+4
COD Permeate 11	−17	+24	+6	+9	+5	+16	+39	+45	+70	+22	–	+22	+3	+28	+15	+34	+0	+43	−28	−16
COD Bioreactor 12	+60	+83	+64	+73	+66	+71	−5	−1	+30	+79	+22	–	+81	+95	+63	+95	−20	+33	−18	+17
TSS Permeate 13	+31	+41	+54	+54	+22	+24	+10	+15	+1	+51	+3	+81	–	+70	+70	+80	−17	+35	+3	+11
TSS Bioreactor 14	+42	+87	+44	+58	+57	+69	−3	+1	+47	+91	+28	+95	+70	–	+46	+96	−29	+52	−18	−1
NTU Permeate 15	+31	+38	+42	+39	+13	+9	+25	+30	+11	+12	+15	+63	+70	+46	–	+50	−1	+22	−1	−5
NTU Bioreactor 16	+39	+74	+58	+67	+53	+64	−6	+0	+34	+86	+34	+95	+80	+96	+50	–	−34	+49	−9	+15
TMP 17	+26	+4	+3	+3	−2	−7	+70	+65	−3	−19	+0	−20	−17	−29	−1	−34	–	−47	−84	−22
Flux Permeate 18[a]	−52	+27	−36	−30	−32	−16	+27	+32	+68	+42	+43	+33	+35	+52	+22	+49	−47	–	+19	−62
Specific Flux Permeate 19[a]	−39	−48	−17	−27	−30	−34	−66	−63	−32	−32	−28	−18	+3	−18	−1	−9	−84	+19	–	+23
Temperature Bioreactor 20	+54	−10	+76	+70	+56	+49	−70	−68	−63	+4	−16	+17	+11	−1	−5	+15	−22	−62	−23	–

The original coefficient were multiplied by 100 and rounded into integer numbers.

[a] Normalized to 20 °C (Eq.((2))).

rejection); (iii) the pH and the temperature have a negligible effect on the performance of the immersed membrane normalized flux and on the specific normalized flux; (iv), the pH of the system can be considered as a state variable, and can be considered as an input effluent quality, and; (v) the bioreactor is characterized by high concentration of organic matters (Table 2) and it can be estimated that the IMBR normalized flux decline depends on other variables (air blower performance, backwash procedure and the frequency of chemical cleaning).

Concerning IMBR performance, the fouling remains the major issue and in order to reduce fouling, air and mixed liquor are introduced into the bottom of the membrane modules through an 'airlift effect'. The air bubbles blend with the mixed liquor and rise up into membrane fibers, providing an effective scouring action on the membrane's surface, and refreshing the surface to prevent solids concentration polarization.

According to the literature, air sparging, backflushing and high cross flow velocity are the main anti-fouling strategies [42,43] and an elevated rate of aeration can reduce the probability of sludge attaching to the membrane surface during filtration, and enhances the removal of the dynamic sludge layer during the backwashing and idle-cleaning phase [44]. The steady aeration intensity can be theoretically calculated from the boundary layer model and the actual value according to experiments it is nearly 20% higher [45].

Low aeration cannot remove the membrane foulants from the membrane surface effectively and too high aeration can induce a severe breakage of sludge flocs [46,47]. It is very important to find the

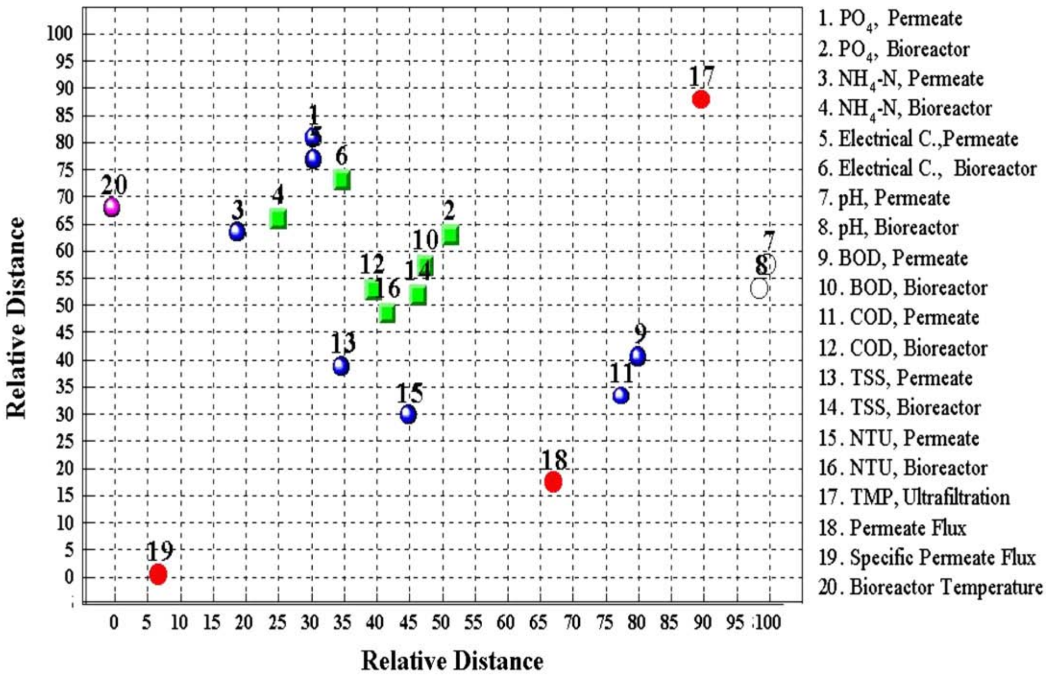

Fig. 1. Properties mapping of Immersed Membrane BioReactor performance [permeate flux and specific permeate flux are normalized to 20 °C (Eq. (2)); Coefficient of alienation (Eq. (7)) equals 0.178).

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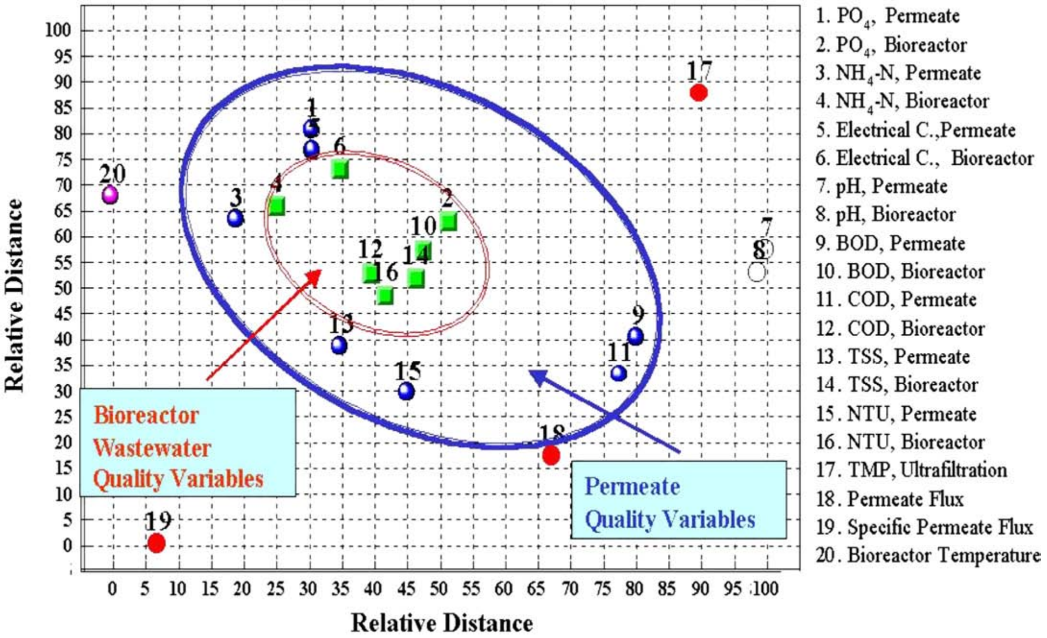

Fig. 2. Partitioning mapping of Immersed Membrane BioReactor performance variables [permeate flux and specific permeate flux are normalized to 20 °C (Eq. (2))].

relationship between sufficient aeration in order to minimize membrane fouling, while preventing formation of colloidal particles due to excessive share forces caused by the aeration. Effective distribution of the air over the whole bioreactor is particularly challenging in submerged membrane system [48].

The allocation of the membrane modules, as well as the distribution of the air-sparker are very important aspects that influence the bubble flow patterns, and on the effective aeration intensity. The filtration performance can be further improved as the membrane inclination is changed from the vertical position (90°) to an inclined position (160°) [49].

In general, the fouling problem does not appear to be avoidable for IMBRs. However, sludge cake deposition on the membrane can be minimized by decreasing the filtration flux and increasing the aeration rate and for a lower sludge concentration. But, sometimes it has a negative economic impact on wastewater treatment cost. Hence to choose the best combination between aeration, backwashing, chemical cleaning and flux it seems to be an important key for the process.

6. Conclusions

A management model was developed, defining clusters of similar Immersed Membrane BioReactor (IMBR) operational variables and their related ranges. The model provides a first approximation of UF membrane behavior by means of the Facet Analysis (FA). Membrane performance is discussed in terms of measured variables, permeate normalized flux, specific permeate normalized flux and permeate quality. The analysis provides the rational for a hypothesis concerning the interrelationships among components of bioreactor wastewater quality, permeate quality, and the membrane system operational characteristics.

From the results reported here, the following conclusions can be drawn:

- The normalized flux and the specific normalized flux are not correlated with the bioreactor variables (COD, BOD_5, TSS, NTU).
- There are high correlations between the constituent content in the bioreactor (BOD_5, COD, TSS and turbidity).Concerning specific inorganic constituent (NH_4^+–N, Electrical conductivity, pH) there is high correlation between the concentrations in the bioreactor and the permeate (implying a low rejection).
- The pH and the temperature have a negligible effect on the performance of the immersed membrane normalized flux and on the specific normalized flux. The pH of the system can be considered as a state variable, and can be considered as an input effluent quality.
- It can be estimated that the IMBR normalized flux decline depends on other variables (air blower performance, backwash procedure and the frequency of chemical cleaning).

Acknowledgments

This work was supported partially by the SMART (Sustainable Management of Available Water Resources with Innovative Technologies) project financed by the Ministry of Science of the German government [Projektantrag zum BMBF-Förderschwerpunkt, Integriertes Wasserressourcen-Management (IWRM)], by The Beracha Foundation, The Stephen and Nancy Grand Water Research Institute, The Technion, Haifa Israel, The Palestinian-Jordanian-Israeli Project (PJIP) (1996), on Membrane Technology for Secondary Effluent Polishing: From Raw Sewage to Valuable Waters and Other By-Products, and by The Levin Family Foundation, Dayton, Ohio, USA, on Membrane Use for Wastewater Reclamation Research Authority of Jerusalem College of Technology (JCT), Israel.

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Please cite this article as: A. Bick, et al., Immersed Membrane BioReactor (IMBR) for treatment of combined domestic and dairy wastewater in an isolated farm: An exploratory case study implementing the Facet Analysis (FA), Desalination (2009), doi:10.1016/j.desal.2009.06.035