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Treatment of primary settled municipal wastewater in a pilot scale MBR

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ABSTRACT

Membrane bioreactors (MBRs) technology shows many advantages that convert it into an attractive solution for upgrading existent wastewater treatment plants (WWTP). The aim of this study was to investigate the feasibility of applying an MBR for treating primary settled wastewater in large WWTPs. In the 400,000 inhabitants equivalent WWTP of Vigo (NW Spain), 174,000 m^3 d^{-1} of wastewater receives primary treatment, whereas only 130,000 m^3 d^{-1} receives secondary treatment. In this facility, land scarcity is an issue, thus, the conventional activated sludge system (CAS) used may be replaced by MBR to retrofit this WWTP. This study was carried out in an MBR pilot plant of 3.97 m^3 effective volume using a modified University of Cape Town (UCT) process with a Zenon ZW500d membrane module operating at low HRT (4–7 h). During the experimental stage, permeability values ranged from 90 to 125 l h^{-1} m^{-2} bar^{-1}, with fluxes between 20–23 l m^{-2} h^{-1}. Only three maintenance cleanings were applied during the 286 experimental days. Total COD values of the used wastewater were 50–350 mg l^{-1}. Good performance in COD and BOD_5 removal was achieved, being 15 ± 7 mg l^{-1} and 5 ± 3 mg l^{-1}, respectively. Nitrogen removal efficiency was limited (40–60%), due to the low COD/N ratio in the influent. Primary settling protects MBR against membrane clogging and gives robustness to this technology.

Keywords: Low-strength wastewater; Membrane bioreactor; Primary wastewater; Water reuse; Hollow fibre; WWTP upgrading

1. Introduction

MBRs are considered one of the most important wastewater treatment technologies developed in the last decade [1]. Compared with conventional sludge bioreactors, MBRs produce a better quality effluent in a lower surface area [2]. Generally, an MBR can be defined as a sludge bioreactor in which the secondary settlement stage is replaced by a filtration stage using microfiltration or ultrafiltration membranes with pore size between 0.01 and 0.5 μm, to produce an effluent free of suspended solids and microorganisms. Despite these advantages, MBR technology increases operational costs due to their high energy demand compared with activated sludge reactors [3] and the necessity of replacing membrane modules. Thus, the use of MBR technology is recommended in the following circumstances:

1) Use in areas with high environmental sensitivity, or in places where the legal requirements become more stringent in terms of low content in biological and chemical contaminants.
2) Use in areas with water scarcity, where it is necessary to reuse the reclaimed wastewater.

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3) Low land availability for upgrading or constructing a new WWTP using the Activated Sludge Process.
4) Treatment of complex industrial wastewaters where the use of other biological technology is neither effective nor reliable and also for the treatment of wastewater of seasonal industries.

Currently, most MBRs treat degritted municipal wastewater. This fact might be due to the relative novelty of the technology and its use only in small and medium sized WWTP. However, it is expected that in the near future very large MBR plants (>100,000 inhabitants equivalent) will be constructed, competing with the use of tertiary membrane filtration, in WWTPs where land availability is an issue [4]. In such cases, the use of primary settlement and anaerobic digestion of the sludge should be considered as in CAS bioreactors. Primary settling is used to remove readily settleable solids and therefore, particulate COD, reducing the COD load to the secondary biological stage [5], diminishing aeration requirements in the MBR and maximizing methane production in the anaerobic digester.

Degritted wastewater must be pretreated with a fine screening system before being fed to MBRs to avoid coarse solids affecting the performance of the membrane modules. Therefore, the selection of an appropriate screen is one of the key points regarding the implantation of MBR technology [6,7]. In this sense, primary settling would act as a redundant system for promoting the coarse solids removal and it could avoid the clogging of the fine screens, facilitating operational and maintenance tasks of these systems, at the cost of a larger plant footprint.

A Spanish WWTP of 400,000 inhabitants equivalent could be retrofitted in order to increase the secondary treatment capacity of the plant. Land availability of this facility is an issue. Thus, MBR was considered an alternative. However, information concerning the performance and reliability of MBRs treating primary wastewater is scarce. The objective of this paper was to assess the feasibility of the operation of an MBR pilot-plant treating primary settled municipal wastewater. The efficiency of the system, the stability of the operation and the fouling of the membrane module used were assessed in this research.

2. Materials and methods

The pilot plant was located at the WWTP for the city of Vigo (NW Spain, 400,000 inhabitants equivalent) and it was operated with primary treated wastewater taken from one of the three circular sedimentation tanks of the facility. Primary treated wastewater was fed through a 1 mm fine rotary drum screen, which then accumulated in a 500 l buffer tank for feeding the MBR. The 3.97 m^3 MBR reactor had a configuration similar to the modified UCT process, but in this case the settler was replaced with a membrane filtration chamber. The internal recycle ratios are indicated in Table 1, and were set according to the recommendations for the UCT process [5]. The process diagram is depicted in Fig. 1. The reactor was divided into five different sections: an anaerobic chamber (11.9% total volume), two anoxic chambers (17.8% and 11.5% volume), an aerobic chamber (23.6% volume) and a filtration chamber (35.2% volume) connected in series. A submerged hollow fibre Zenon ZW-500 d module was used in the filtration chamber. The permeate was accumulated in a 250 l permeate tank for backwashing the membrane. Most of the elements of the plant were located in a lorry container, except for the screen and the membrane filtration chamber, which were located outside it (Fig. 2). The reactor was started up in December 2009 and operated for 286 experimental days in three different seasons (winter, spring, summer).

A blower was used for supplying oxygen to both the aerobic chamber and for the aeration to the filtration chamber. Dissolved oxygen (DO) was maintained between 0.5 and 2.0 mg l^{-1}, by using an on-off controller

Table 1
Main operational parameters of the pilot-plant

Operational parameter	Winter	Spring	Summer
HRT (h)	7.8 ± 1.6	6.4 ± 0.7	5.6 ± 0.4
SRT (d)	–	30	30
MBR flux (l m^{-2} h^{-1})	22.3 ± 1.1	19.7 ± 2.0	17.0 ± 3.0
Anoxic II recycle ratio to anaerobic chamber	1.5	1	1
Aerobic recycle ratio to anoxic chamber II	1.5	1	0
Membrane chamber recycle ratio to anoxic chamber I	2	1.5	1.5

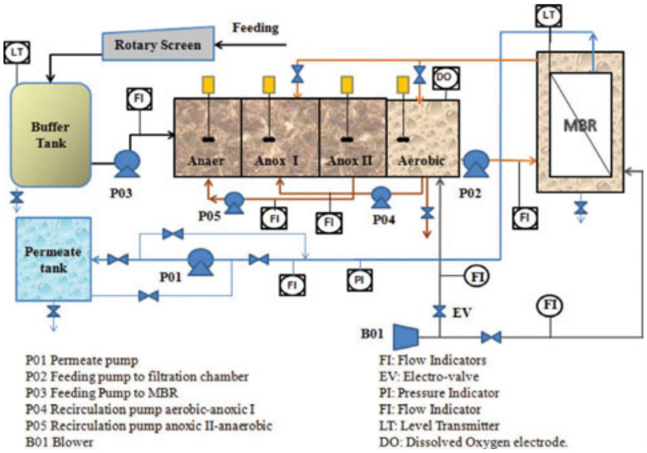

Fig. 1. Schematic diagram of the MBR pilot plant. Since operating day 101 the screening system was out of order.

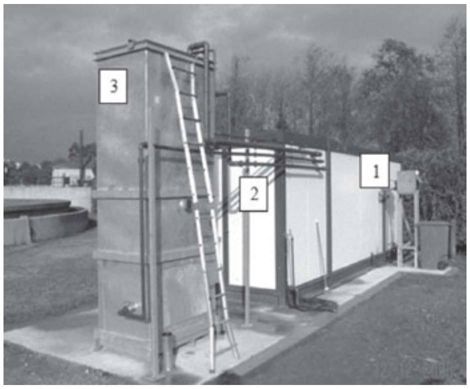

Fig. 2. View of the pilot-plant: (1) rotary fine screen, (2) lorry container in which four chambers of the MBR, the control panel, valves and pumps are located, and (3) external membrane filtration chamber.

that switched an air electro valve (Fig. 1). Pumps, blower and electrically actuated valves were controlled using a PLC. The permeate was suctioned from the MBR chamber by using cycles of 7 min of permeation and 30 s of backwashing.

The experimental protocol to evaluate organic matter and nutrients removal was performed by sampling the influent and effluent twice per week. Analyses of pH, DO, temperature, conductivity, redox potential, turbidity, total and soluble COD, total and soluble BOD, total nitrogen, nitrates, nitrites, total phosphorus and phosphates were done accordingly to Ref. [8]. The following microbial indicators *Escheria Coli, Total Coliforms, Faecal Coliforms* and *Intestinal Enterococci* were analysed using membrane filtration methods. Data of transmembrane pressure (TMP), DO in the aerobic chamber and flow rates (influent, permeate and recirculation) were stored via a PLC. Membrane autopsy was carried out at the end of the experiment, using a Scanning Electron Microscope LEO-435VP with microanalysis Oxford 300 (SEM-EDX).

Critical flux can be defined as the highest value at which it is possible to operate without the variation of TMP with time (operating at constant flow rate). Critical flux experiments were performed according to the method described by de la Torre et al. [9], which uses successively increasing flow rates up to a maximum point before reducing it again until the initial value.

3. Results and discussion

The reactor was started up using approximately 1 g l^{-1} of biomass taken from the activated sludge plant at the WWTP. The biomass was previously filtered in order to avoid the ingress of sand or coarse solids. For the first 27 operating days, the bioreactor was fed with 500 l h^{-1} of primary treated wastewater. The HRT was set at 8 h. Energy consumption in the pilot-plant was relatively high (about 5 kWh m^{-3}) due to the use of oversized industrial equipment (pumps, blower and stirrers). It is important to highlight that the total specific energy requirement of modern, optimized large-scale MBR plants is reported as being in the range 0.6–1 kWh m^{-3} [10]. Table 1 summarises some of the main operational parameters during the three seasons in which the system was operated.

3.1. Pollutants removal

Table 2 summarises the average characteristics of the raw sewage, the primary effluent and the final permeate. The organic matter content of the fed primary treated wastewater was very low (Fig. 3); average total COD and soluble COD (sCOD) being 150 and 60 mg l^{-1}, respectively. Soluble COD accounted for 40% of the total COD. Average total BOD_5 and soluble BOD_5 ($sBOD_5$) were 81 and 37 mg l^{-1}, respectively. The average BOD_5/COD ratio was 0.54, within the 0.4–0.8 g g^{-1}, range typically found in municipal WWTP [5]. The observed average BOD_5 was 5 mg l^{-1} while TSS content was negligible,

Table 2
Characteristics of the raw sewage, the primary wastewater fed to the MBR system and the obtained permeate

Parameter	Raw sewage (average)	Primary treated, 0–125 d	Primary treated, 125–286 d	After MBR
pH	7.1	7.3 ± 0.4	7.3 ± 0.2	6.5 ± 0.6
SS (mg l^{-1})	200	34.2 ± 14.7	71.6 ± 33.7	1.1 ± 1.4
COD (mg l^{-1})	462.3	98 ± 44.6	190 ± 80	15.3 ± 7.4
BOD (mg l^{-1})	238.7	56.1 ± 26.7	98.5 ± 36.5	4.9 ± 3.2
TN (mg l^{-1})	36.6	21.5 ± 7.2	27.2 ± 9.3	14.9 ± 6.8
$N\text{-}NH_4^+$ (mg l^{-1})	21.4	15.0 ± 5.9	17.9 ± 7.5	1.3 ± 1.4
$N\text{-}NO_3^-$ (mg l^{-1})	7.5	0.9 ± 2.0	0.7 ± 0.6	12.9 ± 5.2
TP (mg l^{-1})	–	2.4 ± 0.8	4.4 ± 1.8	2.6 ± 1.0

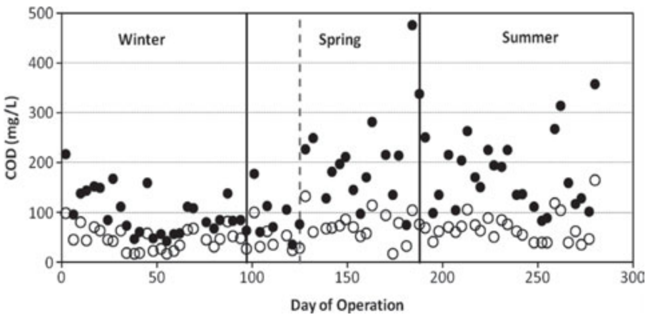

Fig. 3. Evolution of total COD (●) and soluble COD (○) in the influent. The dotted line indicates the moment from which two of the three primary settlers in the WWTP were out of operation.

around 1.2 mg l^{-1}. Such values were similar to those reported in Point Loma Wastewater Treatment Plant in San Diego [11].

For the first 125 operating days the average total COD was only 98 ± 44.6 mg l^{-1}. Thereafter, the COD value increased up to 189.8 ± 80.2 mg l^{-1}. The average organic loading rate (OLR) in the two periods changed from 0.33 kg CODm^{-3} d^{-1} to 0.82 kg COD m^{-3} d^{-1}. The reason for this increase was related to the fact that two of the three primary settlers of the WWTP were put out of service. Nevertheless, this fact did not cause a raise in the COD concentration in the permeate (Fig. 4), as was also found by other authors [12].

One of the objectives of the experimental work was the treatment of diluted sewage at low HRT, in order to minimize the problems that may appear when treating wastewater at low OLR. The HRT during most of the operational period was between 5 and 8 h while the maximum OLR treated was 1.06 kg COD m^{-3} d^{-1}. It was estimated that all the wastewater could receive secondary treatment in the WWTP of Vigo if one of the two CAS of the plant were converted into an MBR operating at an HRT of approximately 5 h. Large MBR plants installed in Europe that work with degritted sewage operate at low HRT. For instance, the MBR in the WWTP of Brescia (Italy) operates at an HRT of 7–8 h, treating more than 42,000 m^3 d^{-1}, while the WWTP at Nordkanal (Germany), that treats sewage for 80,000 inhabitant equivalent, operates with an HRT average value of 5 h and an OLR of 1 kg COD m^{-3} d [1,13]. In this sense, this research confirms that it is possible to treat primary wastewater with a similar OLR to those for large facilities treating degritted wastewater.

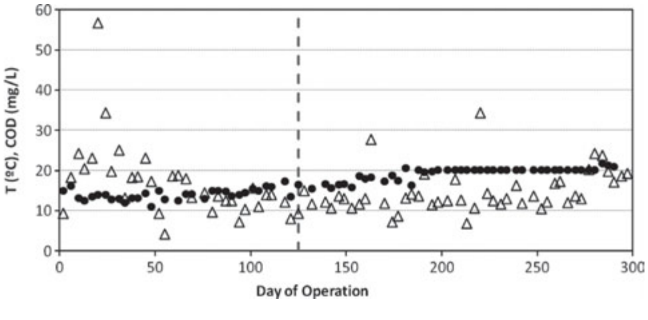

Fig. 4. Evolution of COD in permeate (Δ) and temperature of the MBR process (●) with time. The moment from which two of the three primary settlers in the WWTP were out of operation is depicted (—).

In the 400,000 inhabitants equivalent WWTP of Vigo (NW Spain), an average of 174,000 m^3 d^{-1} of wastewater receives primary treatment, whereas only 130,000 m^3 d^{-1}, receives secondary treatment. Hence, the Spanish water board administration considered, among other options, a possible upgrading by implementing MBR technology. Finally, at the end of 2010 submerged biofilters followed by tertiary UV treatment were selected, in order to reduce pathogens in the treated water, rather than upgrading the plant. In fact, the introduction of MBR technology was ruled out, given the lack of references for very large MBR plants (higher than 100,000 inhabitants equivalent) in Spain or Europe at that time.

The UCT process was chosen because it minimizes the effect of nitrate in weak wastewaters, as used, entering the anaerobic contact chamber [5]. However, nutrient removal was difficult to achieve due to the low organic matter content of the wastewater. Ammonia was fully nitrified during the whole experimental period. Concentration of total nitrogen ranged from 12 to 40 mg l^{-1} while total phosphorous content was between 2–6 mg l^{-1}, giving values for the total nitrogen content in the effluent between 5.5–23 mg l^{-1} and total phosphorous concentration between 1–3 mg l^{-1}.

The increase in COD concentration after operating day 125, caused by the discontinuation of the operation of two of the three primary settlers in the WWTP, affected nutrient removal. Two different periods with regard to nutrients removal may thus be distinguished. For the first 125 operating days the average COD/N and COD/P ratios were 4.8 g g^{-1} and 41.4 g g^{-1}, respectively. Thereafter, these ratios increased to 7.3 g g^{-1} and 45.3 g g^{-1}. The observed increases in COD/N and COD/P ratios favoured nutrients removal efficiency (Fig. 5). Nitrogen removal increased from 26.8 ± 16.2 % to 49.7 ± 21.0 %. Phosphorus removal improved from 13.4 ± 11.2% to 41.7 ± 19.8%.

Varela [14], performed analogous studies with a pilot-scale MBR working also with primary sewage with HRT around 5 h in summer and 7 h in winter. In this case, the organic matter content was higher, total COD ranged from 250 to 500 mg l^{-1}. COD/TN ratio 7–8 and COD/P was between 45–50, reaching then, total nitrogen levels and total phosphorous below 10 mg l^{-1} and under 1 mg l^{-1}, respectively. This fact highlights the importance of an adequate organic matter concentration,

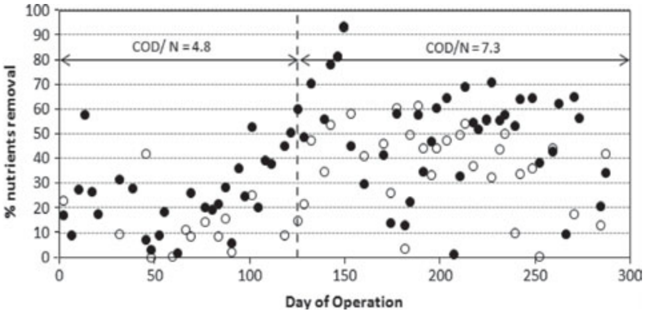

Fig. 5. Evolution of total nitrogen (●) and total phosphorus (o) removal percentage.

thus avoiding limitations in the biological processes of nitrification, denitrification and phosphorous assimilation. For diluted wastewaters, such as the current case study, it would be important to add an external source of carbon if the aim were to reduce nutrient concentrations, or a metallic salt to reduce phosphorous content in the effluent [6,15]. Biological nutrient removal in MBRs is also affected by the COD/N/P ratio of the wastewater, as referred to in [16,17] that used a wastewater with a COD/N/P ratio of 100/11/0.8. Phosphorus removal is also affected by the SRT because this process requires a lower SRT than the nitrogen removal process. The SRT used in this system after day 62 was 30 d.

The first MBR plants implemented within a WWTP operated with a high biomass concentration, above 20 g VSS l^{-1} [18,19]. However, recently membrane suppliers have recommended operation at lower concentrations of 8–12 g VSS l^{-1}. In the present research, the TSS in the MBR was lower than 3 g l^{-1} for the first 80 operation days and progressively increased, reaching 8 g l^{-1} at the end of the experimental period. Thus, lower biomass content did not affect organic matter removal or apparently membrane fouling. Therefore, operation with low biomass concentration could be interesting; especially considering that oxygen transfer in the aerobic chamber is affected by the biomass concentration [20–22]. In this sense, low TSS increases oxygen transfer efficiency [23] and reduces the operating costs for the plant. Biomass yield was 0.38 kg MLSS kg^{-1} COD, lower than the values observed in MBR plants treating degritted wastewater, which were in the range of 0.48 to 0.61 g MLSS g^{-1} COD [7].

The WWTP at Vigo is located in a high sensitivity zone, close to bathing and shellfish culture areas. MBR technology produces high quality reclaimed water [24]. The presence of microbial indicators in the permeate was much lower than those indicated by the new Spanish Water Reuse Directive (Royal Decree 1620/2007), the European Bathing Water Directive 2006/7/CE, or the European Shellfish Directive 2006/113/CE. The quality of the obtained treated wastewater was measured by analyzing the suspended solids, turbidity and microbial indicator content in permeate. TSS concentration in the permeate was almost negligible, around 1 mg l^{-1}, while turbidity levels in the permeate were lower than 0.5 NTU. Microbial indicators were absent in the permeate in terms of *Escheria Coli, Total Coliforms, Faecal Coliforms* or *Intestinal Enterococci.* It can be claimed then, that MBR technology fulfils not only the reuse standards, but also those relevant to the quality of water in high sensitivity environments.

3.2. Membrane module efficiency

The net average flux in the start-up period was 13 l m^{-2} h^{-1} and 21 l m^{-2} h^{-1} for most of the operational period, reaching 24 l m^{-2} h during 17 d of operation. These values are similar or slightly lower than those observed in different full scale MBR plants fed with degritted wastewater and operating with hollow fibre membranes: Beberwijk (The Netherlands), Point Loma (San Diego), Kloten/Opfikon (Switzerland) and Nordkanal with average net fluxes 27.5 l m^{-2} h^{-1}, 37.2 l m^{-2} h^{-1}, 19.5 l m^{-2} h^{-1} and 25 l m^{-2} h^{-1}, respectively [1].

To determine critical flux, successive steps of increasing the flow rates up to a maximum point and diminishing it again until reaching the initial value are needed. Critical flux was 32.3 l m^{-2}.h, higher than the maximum value used during the operating period. Furthermore, taking into account that even at low fluxes an increase of TMP with time takes place, it is necessary, in addition, to introduce the concept of "sustainable flux" as the flux at which the decrease in permeability is operationally acceptable [25]. A sustainable flux of around 24 l h^{-1}.m^{2} was reached for around a fortnight without any cleaning performance needed (Fig. 6).

Permeability values obtained during the operational period of the pilot-plant were between 80–130 l m^{-2}.h.bar, with a stable average value of around 100 l m^{-2}.h.bar. The permeability was lower than other values obtained in full-scale MBRs operated with Zenon ZW500d modules: an average value of 144 l m^{-2} h .bar

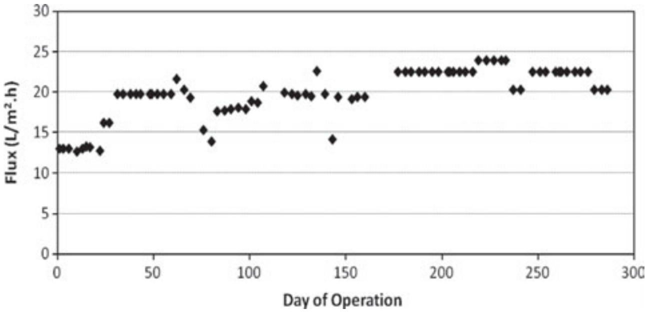

Fig. 6. Evolution of the applied flux in the membrane module.

at the WWTP in Brescia and 150–200 l m^{-2} h bar at the WWTP in Nordkanal [1].

Fouling of the membranes is one of the main problems of this technology; reducing the efficiency of the system, strongly influencing the operation costs and reducing module permeability. This issue is a complex aspect in MBR operation as there is no single universal fouling indicator and a combination of several parameters must be taken into account [26]. There are different strategies to control fouling: physical cleaning or chemical cleaning [18]. Nowadays, two different chemical cleaning strategies are being used: Maintenance cleaning or cleaning in place (CIP) and cleaning out of place (COP). On the one hand, CIP is an intermediate chemically enhanced backwashing that uses a low chemical dosage at ambient temperature. Up to 1000 ppm of sodium hypochlorite and citric acid in a second step may be used to remove inorganic fouling. On the other hand, COP implies soaking the module with higher concentration of chemicals in clean water over longer periods of around 24 h [7].

It is recommended [27,28] to perform a CIP every 1–2 wk and a COP every 6–12 mo. Throughout the 286 operating days of this study, three CIP were performed when permeability was below 100 l $(m^2 \text{ h bar})^{-1}$: This was done on operating days 43, 90 and 237, using between 250–500 mg l^{-1} of sodium hypochlorite solution. At the end of the experiment (day 286), a physical cleaning and COP were performed in series. Initially, the membrane tank was emptied and both the membrane and the tank were cleaned and flushed using tap water. Secondly, the membrane was soaked using a 1000 mg l^{-1} sodium hypochlorite solution in tap water. Thirdly, a 2000 mg l^{-1} citric acid solution was added. The objective was to investigate the evolution of inorganic fouling compounds adhered on/into the membrane after each cleaning procedure. An autopsy of the membrane was performed to assess the efficacy of the COP. Three samples of three different fibres were examined via SEM-EDX, after each cleaning step. The following exogenous chemical elements adhering to the membrane were detected: Na, Mg, Al, Si, P, Cl, Ca, Fe. This was observed especially in the sample taken after performing the water flushing step. The application of sodium hypochlorite cleaning removed a large fraction of all of them. The last step, citric acid cleaning, removed completely the presence of these exogenous elements.

Fouling is not the only parameter affecting the performance of membrane modules. Another aspect which has been less studied in MBR technology is membrane clogging. This term referred to the deposition and formation of large clusters of biomass and suspended solids in the internal spaces of the membrane modules. Among other parameters, clogging is caused by an inappropriate pre-treatment of the fed wastewater. For degritted wastewater, it is important that the influent fed to the MBR should be treated using appropriate fine screen systems [6,7]. The entrance of coarse solids can cause or exacerbate this problem. For instance, an internal break down of the modules in three Erftverband MBRs was observed due to an insufficient pre-treatment which caused the accumulation of hairs and fibrous materials [7].

According to the results obtained here primary settling can protect membranes in case of screening breakdowns. Primary settling removes most of the settleable suspended solids and floating materials. Throughout the current study, a very small amount of suspended solids was separated with the 1 mm rotary screen system (primarily ear sticks and other small plastic materials). On operating day 101, the fine screening system broke down. Even considering that the pilot-plant then operated without screening during 185 d, clogging was barely observed in the membrane module. It should be stressed that after operating day 125, the hydraulic loading rate for primary settling increased from 33 to 98 m^3 m^{-2} d^{-1}, much higher than recommended [5]. This high loading rate did not cause any problem in the MBR system even considering that it was working without screening. Fig. 7 shows the aspect of the bottom part of the module at the end of the operations. Only small black patches of "anaerobic biomass" were observed. This fact highlights that in MBRs working with primary treated wastewater, the effect of a screening failure has much lower impact on the operation of the membranes modules, as occurs with MBRs fed with degritted wastewater [6,7]. Therefore, primary treatment should give a measure of robustness to WWTPs using an MBR system and might be an effective pretreatment system in order to avoid membrane clogging due to the ingress of

Fig. 7. Bottom part of the membrane module, taken at the end of the operational period.

coarse solids with the fed wastewater. With regard to the observed small patches of anaerobic biomass, these were probably originated from the presence of a scum layer in the MBR system. A small fraction of the top layer of the scum tended to dry out and form small pieces of dried biomass that could be entrapped at the bottom of the membrane module.

4. Conclusions

The operation of an MBR system treating primary settled sewage with an OLR of 0.7–1.0 kg COD m^{-3} d^{-1} was found to be feasible. Neither effluent quality nor the membrane stability were affected by the temperature or operational parameters at low HRT value (4–7 h). Permeability was steady around 100 l h^{-1} m^2.bar for the almost 10 months of operation, during which only three chemical maintenance cleanings were performed. The average flow rates were roughly 21 l m^{-2} h^{-1} during most of the operational period.

The system showed excellent organic matter removal, with COD and BOD in the effluent being 15 ± 7 mg l^{-1} and 5 ± 3 mg l^{-1}, respectively. Full ammonia oxidation was observed after the first two weeks of operation. Nutrient removal was affected by the COD/N or COD/P ratios. For example, nitrogen removal increased from 26.8% to 49.7% when the COD/N ratio increased from 4.8 to 7.3 g g^{-1}.

The quality of the permeate, in terms of turbidity, suspended solids content and microbial indicators, was very high and the level of such contaminants in the permeate were much lower than the requirements of the Spanish reuse standards or the European bathing water quality directive.

Results indicated that the treatment of primary settled wastewater with an MBR is feasible under similar operating conditions to those for MBRs working with pre-treated municipal wastewater. Moreover, in an MBR working with primary treated wastewater, the effect of the failure of any screening system has a much lower impact on the operation of the membrane modules. At the end of the operational period, clogging of the membrane module was almost negligible, despite that the fine screening system broke down during the first few months. In this sense, primary treatment gives significant robustness to a WWTP using an MBR system.

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References

[1] S. Judd, The MBR Book, Principles and Applications of Membrane Bioreactors in Water and Wastewater Treatment, 2nd edition, Elsevier Press, London, 2011.
[2] A. Santos, W. Ma and S.J. Judd, Membrane bioreactors: Two decades of research and implementation, Desalination, 273(1) (2011) 148–154.
[3] J.A Gil, L. Túa, A. Rueda, B. Montaño, M. Rodríguez and D. Prats, Monitoring and analysis of the energy cost of an MBR, Desalination, 250(3) (2010) 997–1001.
[4] B. Lesjean, and E.H. Huisjes, Survey of the European MBR market: Trends and perspectives, Desalination, 231(1–3) (2008) 71–81.
[5] Metcalf and Eddy, Wastewater Engineering: Treatment and Reuse, 4th Edition, Mc Graw-Hill, New York, 2003.
[6] A.G.N. van Bentem, C.P. Petri, P.F.T. Schyns and H.F. Van der Roest, Membrane Bioreactors: Operation and Results of an MBR Wastewater Treatment Plant, IWA Publishing, London, 2007.
[7] C. Brepols, Operating Large Scale Membrane Bioreactors for Municipal Wastewater Treatment, IWA Publishing, London, 2011.
[8] Standard Methods for the Examination of Water and Wastewater, American Public Health Association/American Water Works Association/Water Environment Federation, 20th Edition, Washington, DC, 1998.
[9] T. de la Torre, B. Lesjean, A. Drews and M. Kraume, Monitoring of transparent exopolymer particles (TEP) in a membrane bioreactor (MBR) and correlation with other fouling indicators, Water Sci. Technol., 58(10) (2008) 1903–1909.
[10] B. Lesjean, V. Ferre, E. Vonghia and H. Moeslang, Market and design considerations of the 37 larger MBR plants in Europe, Desalin. Water Treat., 6 (2009) 227–233.
[11] Z.M. Hirani, J.F. DeCarolis, S.S. Adham and J.G. Jacangelo, Peak flux performance and microbial removal by selected membrane bioreactor systems, Water Res., 44(8) (2010) 2431–2440.
[12] E.H. Bouhabila, R. Ben Aim and H. Buisson, Fouling characterization in membrane bioreactors, Sep. Purif. Technol., 22&23(0) (2001) 123–132.
[13] N. Engelgardt and W. Lindner, Experiences with the World's Largest Municipal Waste Water Treatment Plant Using Membrane Technology, Water Practice and Technology, IWA Publishing, London, 2006.
[14] C. Varela, B. Casares, M. Caminos, L. Larrea and E. De la Paz Cobos, Eliminación de nitrógeno y fósforo en proceso BRM alimentado con agua decantada de EDAR de Valdebebas, Tecnología del Agua, 294 (2008) 38–45.
[15] A. Monti, E.R. Hall, F.A. Koch, R.N. Dawson, H. Husain and H.G. Kelly, Toward a high-rate enhanced biological phosphorous removal process in a membrane-assisted bioreactor, Water Environ. Res., 79(6) (2007) 675–686.
[16] H. Monclús, J. Sipma, G. Ferrero, J. Comas and I. Rodriguez-Roda, Optimization of biological nutrient removal in a pilot plant UCT-MBR treating municipal wastewater during start-up, Desalination, 250(2) (2010) 592–597.
[17] H. Monclús, J. Sipma, G. Ferrero, J. Comas and I. Rodriguez-Roda, Biological nutrient removal in an MBR treating municipal wastewater with special focus on biological phosphorus removal, Bioresource Technol., 101(11) (2010) 3984–3991.
[18] M.A. Garder, B. Jefferson and S.J. Judd, Membrane bioreactors for use in small wastewater treatment plants; membrane materials and effluent quality, Water Sci. Technol., 41(1) (2000) 205–211.
[19] B. Jefferson, A.L. Laine, S.J. Judd and T. Stephenson, Membrane bioreactor and their role in wastewater reuse, Water Sci. Technol., 41(1) (2000) 197–204.
[20] H.F. van der Roest, D.P. Lawrence and A.G.N. van Bentem, Membrane Bioreactors for Municipal Wastewater Treatment, IWA Publishing, London, 2002.

[21] P. Cornel and S. Krause, State of the Art on MBRs in Europe, Proceedings: Applications and Perspectives of MBR in Wastewater Treatment and Reuse, Cremona, Italy, 28–29 April 2003.

[22] P. Artiga, E. Ficara, V. Oyanedel, J.M. Garrido and R. Mendez, Treatment of two industrial wastewaters in a submerged membrane bioreactor, Desalination, 179(1–3) (2005) 161–169.

[23] L. Holakoo, G. Nakhla, A.S. Bassi and E.K. Yanful, Long term performance of MBR for biological nitrogen removal from synthetic municipal wastewater, Chemosphere, 66(5) (2007) 849–857.

[24] V. Lazarova, P. Sheilds and B. Levine, Production of High Quality Water for Reuse Purposes: The West Basin Experience, 3rd World Water Congress of the International-Water Association, Melbourne, Australia, 2003, 167–175.

[25] G. Guglielmi, D. Chiarani, S.J. Judd and G. Andreottola, Flux criticality and sustainability in a hollow fibre submerged membrane bioreactor for municipal wastewater treatment, J. Membr. Sci., 289(1&2) (2007) 241–248.

[26] T. de la Torre, V. Iversen, F. Meng, J. Stüber, A. Drews, B. Lesjean and M. Kraume, Searching for a universal fouling indicator for membrane bioreactors, Desalin. Water Treat., 18 (2010) 164–269.

[27] M. Kraume, D. Wedi, J. Schaller, V. Iversen and A. Drews, Fouling in MBR—what use are lab investigations for full scale operation Desalination, 236(1–3) (2009) 94–103.

[28] A. Drews, Membrane fouling in membrane bioreactors–characterization, contradictions, cause and cures, J. Membr. Sci., 363(1&2) (2010) 1–28.