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# Wastewater treatment by MBR pilot plant: flat sheet and hollow fibre case studies

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ABSTRACT

The design and implementation of membrane bioreactor (MBR) pilot plant was performed in order to treat municipal wastewater derived from the Súria municipality (Catalonia, Spain) wastewater treatment plant. Two submerged membrane configurations (flat sheet and hollow fibre) in MBR pilot plant were used for this purpose. The influent and effluents were monitored and controlled in order to ensure the achievements of the highest quality determined by Spanish legislation for water reuse. The Remosa company interest was focused in pilot plants applications for the small urban areas. Taking into account that the level of control and maintenance of this small plant can be lower than recommended, the start-up was performed under less favourable conditions without any sludge seed. After 8-months of continuous operation, the physico-chemical and microbial parameters of both MBR configurations achieved the water quality specifications defined for urban service, agricultural and recreational uses. The flat sheet configuration reported easier operation and maintenance (chemical cleaning frequency) compared to the hollow fibre one.

*Keywords:* Membrane bioreactor; Wastewater; Flat sheet; Hollow fibre; COD; Water reuse

## 1. Introduction

The use of membrane bioreactors (MBRs) is a very interesting option for wastewater treatment and reclamation as they combine efficiently the biochemical oxygen demand (BOD), suspended solids (SS), nitrogen and phosphorus removal [1–4] and the removal of micro-organisms [5].

The MBR has emerged in the last few years as one the major treatment solutions for wastewater treatment [6]. In the last two decades, the MBR process has been widely applied to treat various types of wastewater such as industrial wastewater and, especially, domestic wastewater for reclamation and reuse [7–12]. The advantages of the MBR system over conventional biological treatment processes include a smaller footprint, reduced sludge production and a compact system with better solids removal and disinfection. [6,13–15]. The MBR treatment of municipal wastewater yields high-quality water with reported removal percentages of 95, 98 and 99% (or greater) for chemical oxygen demand (COD), BOD and SS, respectively [16]. On the other hand, the main limitations are the high capital investment as well as membrane fouling which reduces productivity and requires eventual membrane replacement [6].

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As it is well known, the main factors affecting the performance of the MBR are membrane property, membrane module structure, operation conditions and bioreactor parameters such as trans-membrane pressure (TMP), cross-flow velocity, hydraulic retention times (HRT) and others. When using certain membranes and membrane modules, the influence of operation conditions on membrane flux and MBR performance is significant [17]. Therefore, it is very important to optimize operation conditions based on the effluent quality [6].

The increased interest in the reuse of treated wastewater for irrigational, urban or industrial purposes has become a critical issue, due to the shortage of water resources and the need to preserve the primary source for drinking purposes [7]. In Spain, reclaimed water quality is regulated by the Royal Decree (1,620/2007) [18] which follows similar criteria than other international guidelines [19,20] and aim to minimize the potentially negative impact on public health.

There are, in the literature, a lot of papers related to MBR technology for wastewater treatment; however, most of these studies are obtained in lab-scale experiments and treating synthetic wastewaters, thus, few of them regard to the long-term performance considering the domestic wastewater treatment by MBR technology for the reclamation purpose.

The objective of this work is the design and implementation of two MBR polymeric membrane configurations (flat sheet (FS) and hollow fibre (HF) submerged modules) in small wastewater treatment plant (WWTP) (10–100 $m^3$/day). In this order of ideas, the pilot plant was fed with real wastewater and the treated effluents were evaluated in order to ensure the quality criteria defined by the Spanish Royal Decree for the wastewater reuse [18].

## 2. Methodology

### 2.1. Experimental set-up

The schematic diagram of both MBRr configurations is shown in Fig. 1. The treatment was designed to be performed in three stages. It should be pointing out that the two first stages were identical in both plants, while they differed in the third stage. In the first zone, the denitrification takes place under anoxic conditions when oxidation of the organic carbon takes place using the nitrate ion ($NO_3^-$), generating molecular nitrogen ($N_2$) as the primary end product; this process is favoured by means of the continuous agitation. The bioreactor is the second zone (aerobic conditions)

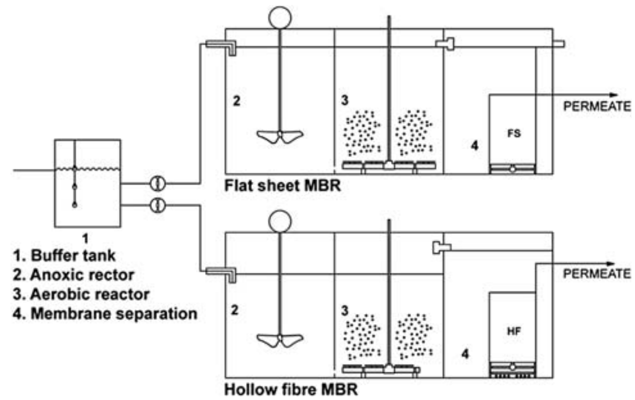


Fig. 1. MBR pilot plant scheme for both configurations.

and it is used to remove the organic compounds (BOD or COD) and to oxidize ammonia to nitrate. The last zone is the filtration stage; here, the effluent is filtered by means of FS or HF membrane configuration, respectively. The SS concentration was equilibrated between the bioreactor and the filtration zone throughout a recirculation system. Furthermore, the mixed liquor suspended solids (MLSS) overflowed back to the denitrification zone at a rate which is approximately four times the permeate flow rate.

The equipment was fabricated with fibre-reinforced plastic (FRP) and reached the maximum compactness and flexibility according to the design. In Table 1, the most important design parameters for both MBRs configuration are summarized. Both the HF and FS polymeric membrane modules employed in this comparative study were commercially available with mean pore diameters of 0.2 and 0.05 μm, respectively.

### 2.2. Physical and chemical membrane cleaning

In order to keep the TMP within the technical specifications, a chemical cleaning in place (CIP) was carried out periodically in both reactors following the recommendations of respective membrane manufacturers. In the case of FS module, when the TMP difference exceeded the TMP set-point, the membrane module was cleaned by soaking for few minutes with diluted NaClO solution under controlled flux conditions. Afterwards, the NaClO solution was kept into reactor for 2-h before returning to normal working procedure. On the other hand, in the case of HF modules, the chemical cleaning was performed at elapsed times, once per month, before the system reached the TMP set-point. The cleaning was performed in two steps at constant flux: an alkali-oxidative cleaning

Table 1
Design parameters for both MBR configurations

| Parameter | | MBR flat sheet | MBR hollow fibre |
|---|---|---|---|
| Volume ($m^3$) | Denitrification | 3.9 | 3.9 |
| | Bioreactor | 9.6 | 8.7 |
| | Membranes | 7.6 | 3.8 |
| Membrane surface area ($m^2$) | | 40 | 30 |
| Inflow rate ($m^3$/day) | | 19 | 7 |
| Outflow rate ($m^3$/day) | | 19 | 7 |
| Permeated flux (L/$m^2$ h) | | 25 | 20 |
| Backwashing flux (L/$m^2$ h) | | Not possible | 30 |
| Recirculation flow rate | | 400% inflow rate | 400% inflow rate |
| Operating conditions | | Permeated: 8 (min)<br>Relaxation: 2 (min) | Permeated: 4 (min)<br>Backwashing: 1 (min)<br>Aeration: 0.1 (min) |

with HClO at pH 12, followed by an acid cleaning with citric acid at pH 3. The overall cleaning time was much lower in the case of FS membranes. Moreover, the TMP set-point is 100 mbar higher in the case of FS compared with HF membranes. In both systems, complementary to chemical cleaning, the air diffusers were cleaned automatically to avoid clogging.

### 2.3. Analysis and control

The COD and total suspended solids (TSS) contents were determined according to the standard methods [21]. The $BOD_5$, conductivity (Crison GLP31–32), nitrogen Kjeldahl and P-total were measured by the procedures of the Spanish standard methods (UNE standards) [22,23] of water quality and nitrogen reported as total nitrogen (NKj BÜCHI K-355). Further, the pH and turbidity data were measured using a GLP-22, Crison pH metre and turbidity metre (HACH COMPANY 2100 N), respectively. The microbial parameters, Escherichia coli as well as the total and faecal coliforms were determined by standard methods [21]. Following the approval of Royal Decree 1,620/2007, the method for intestinal nematode eggs was updated. During the experimental test, the total nematodes were analysed by the method described by Ayres and Mara [24] on 1L of sample. The DO plus temperature, pressure gauge and flow rate were determined by means of OxyMax W COS 41 membrane-covered amperometric sensor Endress + Hauser, Cerabar T PMP 131 pressure transducer Endress + Hauser, and proline promag 50/53 W flow rate Endress + Hauser, respectively. Finally, the data collection and control process were performed by means of programmable logic controller (PLC) SE300 Siemens. Complementary to the study of physical–chemical parameters, during the start-up period, the characteristics and evolution of activated sludge was monitored by optical microscope observation (Zeiss, Axiostar plus).

## 3. Results and discussion

### 3.1. Wastewater characterization

The influent wastewater for both MBR configurations was characterized during the experiment and the values indicated that the influent corresponded to the typical domestic wastewater with high variability as can be shown in Table 2 where main parameters are collected.

### 3.2. Pilot plant set-up

The equipment was installed in the Remosa facilities at the Súria municipality (Catalonia, Spain). The experiments started-up on August 2007 for both configurations. Both pilot plants were continuously fed with real municipal wastewater derived from the Súria WWTP pipeline collector. This water was pretreated by a screening unit (3 mm) in agreement with both membrane manufacturers and then pumped into the buffer tank from which both MBR configurations were fed. After the treatment the effluents were returned to the Súria WWTP pipeline collector. Both pilot plants were simultaneously operated for a period of 7 months controlling physico-chemical and biological parameters in influent (buffer tank) and the effluents from both configurations.

Due to the marketing objective of Remosa, the plants were tested under most unfavourable and extreme conditions which lead to easier

Table 2
Physico-chemical and microbial characterization of the influent wastewater for both MBR configurations

| Parameter | Range | Average | Standard deviation |
|---|---|---|---|
| pH | 7.3–8.4 | 8.1 | 0.21 |
| Conductivity (mS/cm) | 1,094–1,872 | 1,504 | 240 |
| Turbidity (NTU) | 99–1,164 | 237 | 260 |
| Temperature (°C) | 8.5–23.8 | 16.3 | 4.99 |
| $BOD_5$ (mg/L) | 75–370 | 269 | 88 |
| TSS (mg/L) | 42–456 | 304 | 108 |
| COD (mg/L) | 187–1,500 | 551 | 308 |
| P-total (mg/L) | 1.5–20 | 8.5 | 6.0 |
| N-total (mg/L) | 48–124 | 71.2 | 22.3 |
| Intestinal Nematode (eggs/10L) | 5–800 | 99 | 158 |
| *Escherichia coli* $Log_{10}$ (CFU/100 mL) | 5.6–8.7 | 7.2 | 0.7 |

implementation in remote or small urban areas in which robustness and absence of maintenance represent a significant benefit to the final user. For these reason, both pilot plants started-up without seed sludge and were directly fed with the inlet wastewater from the WWTP, despite the risk of permanent clogging of membrane pores. This problem did not occur in any configuration, but premature membrane chemical cleaning was needed to achieve continuous operation. The FS MBR configuration reached a steady state operation in a short period with physico-chemical and microbial parameters under the limits defined for wastewater reuse, while the start-up period of HF MBR was extended due to an inappropriate function of the reversible pump necessary for the backwashing procedure. Once the pump problem was solved, it was found that the operation of this pump still had a strong influence on MBR performance, mainly due to the time lost to achieve the flow rate following each direction change (permeate/backwashing). Due to this fact, the HF module never achieves the design regime, and hence the hydraulic parameters in both systems are so different. Finally, after 60 days, the HF MBR configuration reached stable conditions.

It is important to point out that sludge concentration in MBR was not regulated in order to simplify the operation control from the point of view of the potential final user of the MBR pilot plant; thus, the MLSS concentrations inside the MBR reactors showed an increase for three weeks after the start-up and then were ranged between 4–14 and 2–6 g/L for FS and HF configurations, respectively, as can been seen in Fig. 2.

These values were higher than values recommended for large WWTP, which are enforced to operate at lower MLSS in order to optimize the oxygen coefficient transfer and hence, optimize the energy

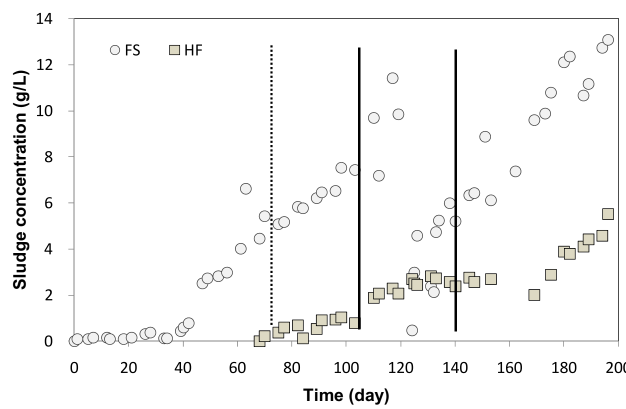


Fig. 2. Sludge concentration during the experiment for both membrane configurations. Solid lines: chemical cleaning for FS membrane module. Dotted line: non-periodical chemical cleaning of HF membrane module.

consumption [25], while in the present application, the robustness and ease of operation are more relevant parameters. As mentioned before, it is important to point out that that two MBR pilot plants were operated under quite different HRT, MLSS concentration and organic loading rate due to the operational difficulties observed during the test which leading to different operational conditions to reach the water quality objectives.

### 3.3. Membrane operation

The variation of permeate flux and the TMP is shown in Fig. 3. As mentioned before, the HF MBR configuration reached stable conditions after 60 days due to operational problems and this fact affected membrane operation as can be shown in Fig. 3. In this

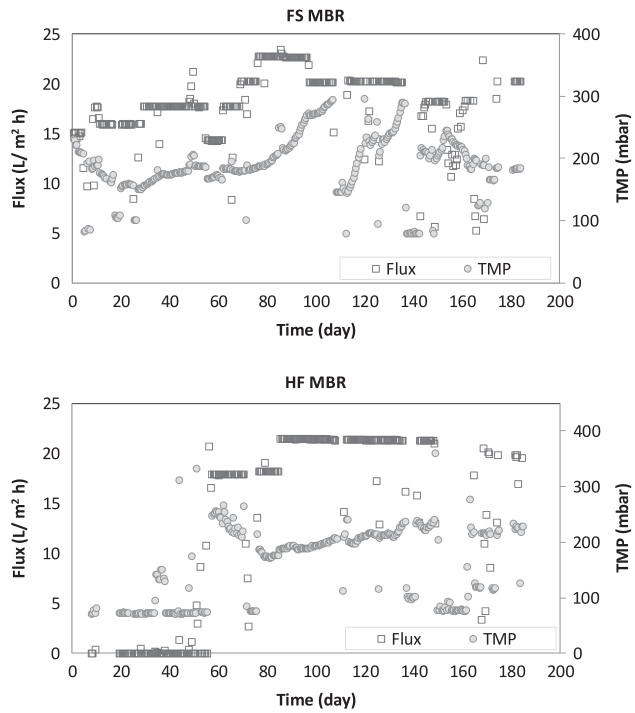


Fig. 3. TMP and flux variations during the experiment for both membrane configurations.

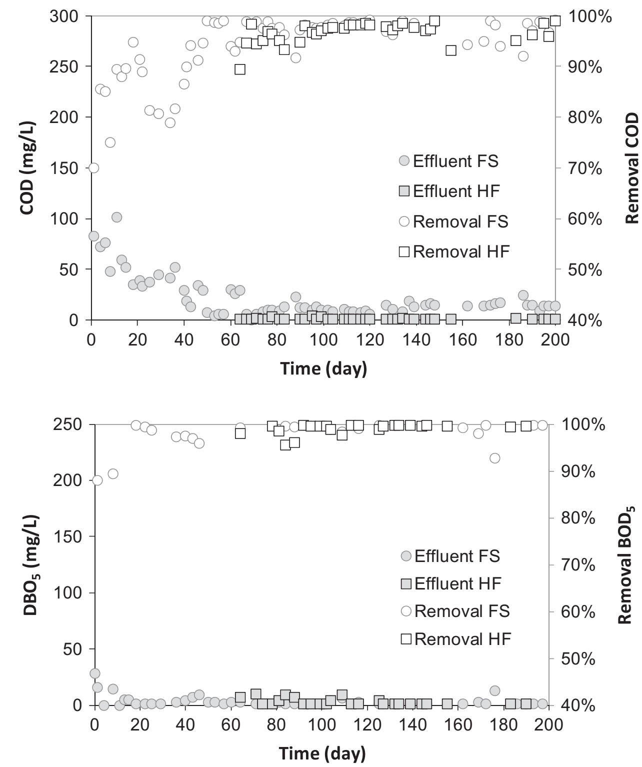


Fig. 4. COD and $BOD_5$ evolution and removal during the experiment.

study, when the FS TMP difference exceeded 300 mbar, the membrane modules were cleaned by procedure explained above in Section 2.2. As shown in Fig. 3, chemical cleaning was carried out twice during the experimental period of 200 days, after 107 and 140 days of operation for this configuration. In the case of HF, the chemical cleaning was performed once monthly as suggested by manufacturer, plus an additional CIP performed after 71 days of operation for this configuration. It is important to point out that no membrane changes (FS or HF) were performed during the experiment.

### 3.4. MBR pilot plant performance

The effluents evolution and removal of COD during the experimental period are presented in Fig. 4. The influent COD fluctuated from 500 to 1,500 mg/L (data not showed) and removal of COD for FS membranes varied between 80 and 99%. The lower value was observed at initial time of the experiment and then after 50 days the COD removal efficiency reached values over 92%. On the other hand, no significant variability was reported by the HF membranes, once stable operation was reached, obtaining removals over 90%. The average COD removals were 94 and 97% for FS and HF membranes, respectively.

On the other hand, the $BOD_5$ average values reported at the effluents were 2.8 and 3.2 mg/L for the FS and HF membranes, respectively. Soon after 5 days, 90% of $BOD_5$ removal was achieved. The lower $BOD_5$ initial removals were due to the systems that had not been inoculated with active sludge prior to start the tests as it was explained before. Further, the removal kept increasing and resulted in up to 98% for both configurations as can be seen in Fig. 4. The removal performance was remarkably stable, in spite of the variability of this parameter during the experiment (269 mg/L of average influent concentration).

During the wastewater treatment with both MBR configurations, pollutants were removed considering the limits determined by the Spanish Royal Decree 1,620/2007 for wastewater reuse. In the case of TSS, 10 and 20 mg/L (for wastewater effluents) are the values determined by the Spanish Royal Decree for residential and urban use, respectively. The average TSS concentration during the experiment and for both configurations were around 1 mg/L with an influent concentration over 300 mg/L and then, an average removal of 99% was achieved confirming a significant TSS removal for both membrane configurations.

Turbidity was also controlled considering the water quality criteria for wastewater reuse. Here, the limits defined for Spanish Royal Decree are 2 and 10 NTU for residential and urban use, respectively. The turbidity in effluents was 0.4 and 0.7 NTU for the FS and HF membranes, respectively. As can be expected considering the higher TSS removal, the turbidity effluents were one order of magnitude lower than the limits defined for wastewater reuse.

The microbial parameters were also monitored in order to define if the effluents from both MBR configurations were under the limits defined for wastewater reuse. The influent and effluent average concentration of Escherichia Coli, total and faecal coliform ($\log_{10}$ CFU 100 $mL^{-1}$) as well as the limit defined by the Spanish Royal Decree is shown in Fig. 5. It is observed that both MBR effluents were 2 $\log_{10}$ units lower than the limit defined for urban service, agricultural and recreational uses and most of the days, the concentration on the effluents was below the detection limit of the technique (<5 CFU 100 $mL^{-1}$) fulfilling the limit of wastewater regenerated for residential use.

The total and faecal coliforms, which are generally used as indicators to determine the degree of disinfection [26], were also monitored during the experiment. The influent concentration was around 7 $\log_{10}$CFU 100 $mL^{-1}$, while the effluents of both membrane configurations were lower than 1 $\log_{10}$CFU 100 $mL^{-1}$. Other microbial parameter measured was the nematode eggs, in this case, the average concentrations were 99, 2 and 2 eggs $L^{-1}$ for influent and effluents FS and HF, respectively. As it is explained in previous section, these values do not correspond necessarily with intestinal nematodes.

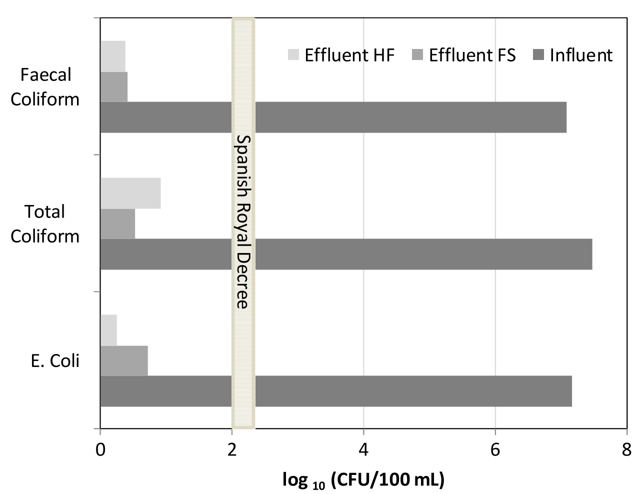


Fig. 5. Influent and effluents average microbial concentrations during the experiment for both configurations and quality criteria for reuse purpose (Spanish Royal Decree for urban, agricultural and recreational uses).

Finally, the removal of total nitrogen was 71 and 60% for FS and HF membranes, while phosphorous removal was 45 and 30% for FS and HF membranes, respectively.

### 3.5. Evolution of activated sludge

As a general statement, due to the lack of initial sludge feed; in both systems the activated sludge evolved and matured slowly. Periodically, 1L of solution was taken from bioreactor compartment in both systems for further microscopy analysis of activated sludge. Initially, in the case of FS configuration, only few flocks were observed and the presence of sludge was occasional. After 40 days, the flocks were well structured and the interflocular fluid was clear, so it can be concluded that the sludge was matured with a good quality. However, after 75 days, an increase of filamentous bacteria in interflocular fluid was observed, which was incorporated into flocks after 110 days. These accumulations of filamentous bacteria were derived in foaming problems, which were solved after partial replenishment of sludge in MBR. At the end of start-up period, after 7 months of evolution the quality of activated sludge was good (considering the structure and the number and diversity of microbial population), with slow sedimentation, while the flocks were poorly structured. Finally, the microbial activity was high and diverse (mainly zooflagelo, Spirochaeta (see Fig. 5 left) Aspidisca, Trachellophyllum, Vorticella and rotifers).

The sludge maturation of HF configuration was even slower than that of FS. No clear increase in the amount and size of flocks was observed during the first month. Moreover, after 57 days, a clear increase in the presence of filamentous bacteria was observed in both flocks and interflocular fluid, giving a significant reduction in the rate of sedimentation of the sludge. After 84 days, the quality of sludge was poor, and there is a potential bulking problem as there was foam on the surface of the sample. At the end of start-

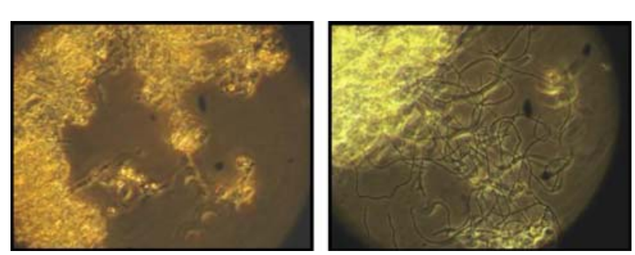

Fig. 6. Optical microscopic observation of activated sludge at 400x after days Left: FS (after 152 days) and right: HF (after 84 days).

up period, the amount of sludge was high, but of slow sedimentability. The microbial population was also low and was mainly due to zooflagelo and free ciliates. This fact also indicates the remarkable presence of filamentous bacteria in both interflocular fluid and flocks, which were still small (see Fig. 6 right). It can be concluded that the quality of sludge is poor in FS reactor taking into account both the number and the diversity of micro-organism observed by optical microscopy. This lower rate of maturation can be, at least partially, due to the operational problems observed during the start-up period.

However, independent of the evolution of sludge, the physical–chemical parameters described in the previous sections corroborate the adequate performance of both plants.

## 4. Conclusions

This study evaluates the design and implementation of the MBR technology for the wastewater treatment in small scale. The flexibility of both MBR configurations allowed to operate under not favourable conditions which represents a significant advantage for its implementation in remote or small urban areas in which robustness and absence of maintenance could be more relevant parameter than energy consumption optimization for the final user.

The results of this study indicate that both MBR configurations can achieve high removal efficiencies in municipal wastewater treatment and that MBR permeates are suitable for urban service, agricultural and recreational reuse according to the quality criteria defined by the Spanish Royal Decree for water reuse. The FS membrane configuration allows a better integration to MBR technology for water regeneration in small urban areas due to its compactness and flexibility. It can be explained by the easy installation, operation and maintenance compared to the HF configuration.

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