# Pilot-scale anaerobic submerged membrane bioreactor (AnSMBR) treating municipal wastewater: the fouling phenomenon and long-term operation

D. Martinez-Sosa, B. Helmreich, T. Netter, S. Paris, F. Bischof and H. Horn

## ABSTRACT

An anaerobic submerged membrane bioreactor (AnSMBR) on pilot-scale treating a mixture composed of municipal wastewater and glucose under mesophilic temperature conditions was operated for 206 days. The performance of the AnSMBR was evaluated at different fluxes, biomass concentrations and gas sparging velocities (GSV). GSV was used to control fouling. In addition, the AnSMBR was operated in cycles that included relaxation and backwashing phases. The increase in the transmembrane pressure (fouling rate) was measured under different operational conditions and was used to evaluate the stability of the process. The fouling rate could be controlled for a long period of time at a flux of 7 l $m^{-2}$ $h^{-1}$ with a GSV of 62 m/h and an average biomass concentration of 14.8 g TSS/L. The membrane was physically cleaned after 156 days of operation. The cleaning efficiency was almost 100% indicating that no irreversible fouling was developed inside the pores of the membrane. The COD removal efficiency was close to 90%. As in anaerobic processes, nutrients were not exposed to degradation and almost no pathogens were found in the effluent, hence the effluent could be used for irrigation in agriculture.

**Key words** | anaerobic submerged membrane bioreactor, anaerobic treatment of municipal wastewater, critical and operational flux

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## INTRODUCTION

Municipal wastewater is commonly treated biologically by aerobic/anoxic processes. Despite some advantages, energy requirements and significant sludge production remain the biggest disadvantages of these processes. In anaerobic conditions, biogas is produced and can be used as a sustainable source of energy. Moreover, the production of wastewater sludge is significantly lower and inorganic nutrients (e.g. nitrogen and phosphorus) are not subjected to biological degradation. Hence, the liquid phase containing the nutrients could be used for irrigation purposes in agriculture.

On the other hand, the use of membranes to separate the biomass from the effluent has gained increasing interest in the last decade (Yang *et al*. 2006). Although the so-called Membrane Bioreactors (MBR) are normally more expensive than conventional processes (Judd 2006), they have the advantage that organic or particulate material is kept inside the reactor until it can be degraded (Harada *et al*. 1994; Fuchs *et al*. 2003). However, membrane fouling, and hence flux decline is without a doubt the main drawback of MBRs.

Membrane properties, operational conditions and suspension properties are the category of factors that affect the applicable flux (Jeison 2007). However, physiological characteristics of bulk biomass, such as concentration of mixed liquor suspended solids, particle size distribution and extra-polymer substances change according to the operational conditions. Thus, fouling is very unpredictable and difficult to control in MBRs (Le Clech *et al*. 2003).

High cross-flow velocities (CFV) resulting in high shear rates on the membrane surface can be used in MBRs with external membrane units to reduce membrane fouling. High CFV can result in higher fluxes. However, a poor anaerobic digestion performance can be induced by high CFVs (Brockmann & Seyfried 1996). Furthermore, high CFV can induce the decrease in particle size distribution,

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thereby increasing the chances for particle deposition (Choo & Lee 1996).

Gas sparging (GSV) is used as a cleaning method in anaerobic submerged membrane bioreactors (AnSMBR) since gas bubbles provide shear conditions on the membrane surface. Air sparging is widely used in aerobic MBRs, where it has a double function: providing oxygen transfer to the liquid phase, and promoting scouring of the membrane surface (Cui *et al*. 2003). In an AnSMBR, produced biogas can be circulated to generate shear close to the membrane surface. Therefore, AnSMBRs represent an interesting alternative to the conventional side stream process because this option can reduce energy costs and biomass stress associated with recirculation (Aquino *et al*. 2006).

The critical flux concept is a useful tool to assess fouling tendency. The weak definition of this concept states that there is one flux above which the fouling is significant, i.e. the relation between flux and transmembrane pressure (TMP) becomes non-linear (Wu *et al*. 1999). However, the critical flux concept cannot be used to predict long term fouling behavior (Le Clech *et al*. 2003). Therefore, more research should be carried out to assess the stability of anaerobic membrane bioreactors in the long term.

The aim of this project was to evaluate the overall performance of a pilot AnSMBR treating municipal wastewater under different operational conditions, evaluating the filtration process as well as the biochemical degradation of organic substances in the influent.

## MATERIALS AND METHODS

A pilot scale AnSMBR was used to carry out the research (Figure 1). A flat sheet polysulfone ultrafiltration membrane module with a mean pore size of 0.038 μm and with a total membrane surface of 3.5 $m^2$ (Microdyn-Nadir, Germany) was used to separate the solids from the effluent. The plant consists of two containers: one was used as reactor and the membrane was submerged in the other container (membrane chamber). Both containers were connected by an eccentric screw pump (Seepex, Germany). Sludge was circulated at 2 $m^3$/h. The reactor was operated under mesophilic temperature conditions. The temperature was controlled at $35 \pm 1\,^{\circ}C$ by two electric heaters controlled by a temperature sensor.

The reactor was operated in cycles of 4 steps each one. The steps were (1) filtration (2) pause/relaxation (3) backwashing and (4) feeding.

An eccentric screw pump (Netsch, Germany) was used to carry out the filtration and the backwashing. The backwashing was applied by reversing the direction of the permeate pump. The filtration phase was set to 10 min. A pause of 30 s was included in the cycles to relax the membrane. A part of the permeate was taken for the backwashing, which lasts 1 min. The flux applied during the backwashing phase was always equaled to that applied during the filtration phase. Since the feed pump had to compensate the net volume of permeate, the duration of the feeding phase mainly depended on the operational flux. Thus, the higher the flux, the longer the cycle lasts.

Produced biogas could flow out of the reactor during the feeding phase. After the feeding phase, a new cycle started. Approximately 110 cycles were carried out a day.

Produced biogas was circulated by a vacuum pump (KNF, Germany) to create shear close to the membrane surface, thereby controlling particle deposition on the membrane surface. A coarse diffuser was installed in the bottom of the membrane module to generate biogas bubbles with relative large sizes.

The permeate pressure, the pressure inside the reactor as well as permeate and backwashing flows were saved on line. A programmable logic controller (PLC) allowed operation of the reactor automatically. TMP was calculated as the difference between permeate pressure and the pressure inside the reactor considering the mean hydraulic head at the mid-point of the membrane module.

### Inoculum and feed wastewater

The reactor was seeded with anaerobic digested sludge from the WWTP Garching, Germany. The reactor was fed with municipal wastewater from the city of Garching, Germany. As the influent COD concentration was low, glucose was used as additional carbon source. Further details will be discussed below.

### Critical flux determination

The critical flux concept was used to select the operational flux on the start-up of the reactor. The critical flux in its weak definition was determined by the flux-step method (Le Clech *et al*. 2003). Flux step duration was set to 10 min. Flux steps were 2, 4, 5, 7, 8, 10 and 12 $l\,m^{-2}\,h^{-1}$. The critical flux was assumed to be exceeded when the fouling rate (dTMP/d$t$) increased faster than 2 mbar/min.

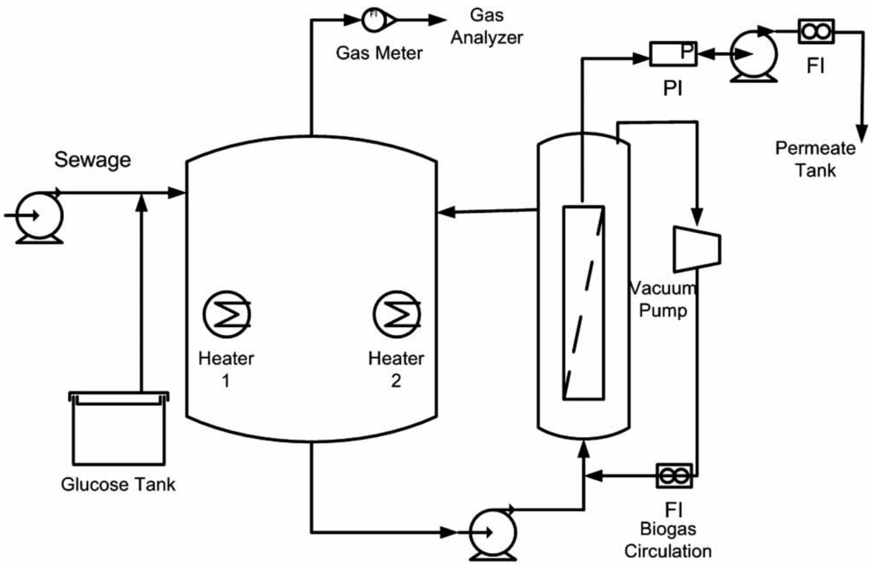


**Figure 1** | Schematic of the pilot AnSMBR.

## Resistance of the membrane

After 156 days of operation, the membrane was taken out of the reactor and submerged in tap water to assess fouling resistances according to Darcy's law, following Equation (1)

$$J = \mathrm{TMP}/(\eta R) \quad (1)$$

where $J$ is the permeate flux (m/s), TMP the transmembrane pressure (Pa), $\eta$ the dynamic viscosity of permeate (Pa s) (tap water) and $R$ the hydraulic resistance ($m^{-1}$).

## Experiments

In this work, the reactor was operated for 206 days under different operational conditions. Different fluxes, biomass concentrations and gas sparging velocities were tested. Firstly, three gas sparging velocities (GSV = 26, 44 and 62 m/h) and three different fluxes (7, 10 and 12 $l\,m^{-2}\,h^{-1}$) with a biomass concentration around 14 g TSS/L were tested. GSV were evaluated considering the free transversal area of the riser of the container, in which the membrane was submerged. Flow rates were 35, 25 and 15 LPM for the GSV of 62, 44 and 26 m/h, respectively.

Afterwards, three different biomass concentrations with three different fluxes (7, 10 and 12 $l\,m^{-2}\,h^{-1}$) keeping a GSV of 62 m/h were evaluated. Due to the fact that the biomass concentration was varied by reducing or increasing the active volume of the reactor, it varied from 350 to 800 L. Although the initial conditions of the membrane could not be controlled, it is worth mentioning that the reactor was stopped for 30 min and the membrane was backwashed for 5 min keeping a flux of 7 $l\,m^{-2}\,h^{-1}$, every time new operational conditions were imposed.

## Analysis

Total and soluble COD (sCOD), total and volatile solids (TSS and VSS) of the influent and effluent (permeate) were analyzed daily, sCOD after filtration (0.45 μm cellulose membrane filter). Particulate COD (pCOD) was calculated from the difference between total COD and sCOD. Ammonium-nitrogen ($NH_4$-N), total phosphorus (TP) and biochemical oxygen demand ($BOD_5$) were analyzed weekly for the same samples. Analyses were carried out according to the German Standard Methods for the examination of water, wastewater and sludge (DEV 1993).

Produced biogas was measured by a drum-type gas meter (Ritter Apparatebau, Germany). Biogas composition was analyzed online by a gas analyzer (Awite Bioenergy, Germany). $CH_4$ and $CO_2$ concentrations were determined using optical sensors of infrared absorption.

Fecal coliforms were used as pathogen indicators of hygienic permeate quality. The most probable number was obtained using the fluorocult lauryl sulfate system (Schindler 1991).

## RESULTS AND DISCUSSION

### Fouling behavior

Following the step-flux method (Le Clech *et al.* 2003), a critical flux of 7 $l\,m^{-2}\,h^{-1}$ was found at the beginning of this work. A biomass concentration of 14 g/L and a GSV of 62 m/h were used to find the critical flux. At the beginning, the reactor was operated under critical conditions. As mentioned above, the reactor was operated in cycles that included relaxation and backwashing phases.

Figure 2 shows typical operational cycles at different fluxes (7, 10 and 12 $l\,m^{-2}\,h^{-1}$) in the short term. It can be seen how the TMP increased during the filtration phase. The TMP was, however, lowered during the backwashing phases and achieved its initial value again. Therefore, it was supposed that the backwashing could remove most of the cake layer formed during the filtration phase, and thus the two fluxes higher than the critical one (10 and 12 $l\,m^{-2}\,h^{-1}$) were also evaluated in the long term. Since the filtration phase starts after the backwashing and feeding phases, the TMP increased at the beginning of the cycle and achieved a maximal value. Once this maximal value was achieved, further increases were negligible at the flux of 7 $l\,m^{-2}\,h^{-1}$, which is in accordance with the weak definition of the critical flux (Figure 2). In contrast, the TMP increased exponentially at the fluxes of 10 and 12 $l\,m^{-2}\,h^{-1}$. Besides the critical flux determination, this exponential increase also indicates that the critical flux was clearly exceeded. Furthermore, close observations show that the TMP at the end of cycle 1 was lower than the TMP at the end of cycle 2 and so on. This TMP increase (fouling rate) was calculated and used to evaluate the stability of the reactor in the long term.

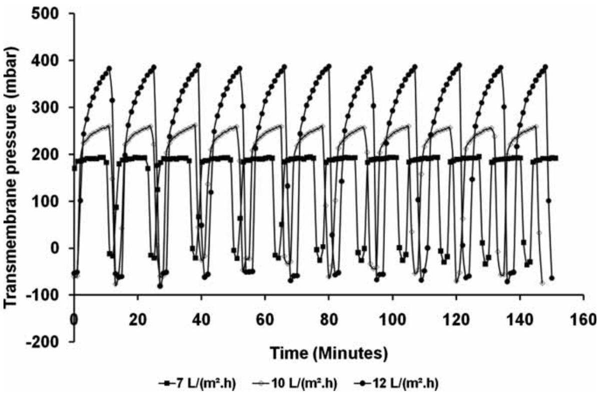


**Figure 2** | TMP profiles at different fluxes in the short term. GSV: 62 m/h. TSS: 14.9 ± 0.9 g/L.

### Gas sparging

During the first 44 days of operation, three different GSVs (26, 44 and 62 m/h) and three fluxes (7, 10 and 12 $l\,m^{-2}\,h^{-1}$) were tested. The biomass concentration was around 14 g TSS/L (Table 1). Since different fluxes were tested, the hydraulic retention time (HRT) varied from 1.4 to 0.8 days and the organic loading rate (OLR) from 0.2 to 0.5 g COD/L. In accordance with the number of variable combinations, nine experiments had to be carried out. However, three experiments were not possible because of the high values of the dTMP/d*t* (Figure 3).

The duration of each experiment strongly depended on the achieved TMP. The longest trial was carried out when the flux of 7 $l\,m^{-2}\,h^{-1}$ with the GSV of 26 m/h and the biomass concentration of 13.7 ± 0.7 g TSS/L were tested. This trial lasted 8 days. Since the fouling rate was not significant,

**Table 1** | Operational conditions during the GSV trials

| Period (days) | Flux ($l\,m^{-2}\,h^{-1}$) | GSV (m/h) | TSS (g/L) | VSS (g/L) | HRT (d) | OLR (g COD/L d) |
|---|---|---|---|---|---|---|
| 0 to 7 | 7 | 62 | 14.9 ± 0.9 | 9.0 ± 0.4 | 1.4 | 0.2 |
| 8 to 14 | 7 | 44 | 13.6 ± 1.4 | 8.5 ± 1.2 | 1.4 | 0.3 |
| 15 to 23 | 7 | 26 | 13.7 ± 0.6 | 8.8 ± 0.5 | 1.4 | 0.4 |
| 24 to 28 | 10 | 44 | 14.5 ± 0.5 | 9.7 ± 0.4 | 1.0 | 0.4 |
| 29 to 33 | 10 | 62 | 13.7 ± 0.7 | 9.1 ± 1.4 | 1.0 | 0.5 |
| 34 to 36 | 12 | 62 | 13.9[a] | 9.0[a] | 0.8 | 0.5 |
| 36 to 44[b] | 7 | 62 | NA | NA | NA | NA |

[a]Measured only one time.
[b]This trial was done to increase the active volume of the reactor.

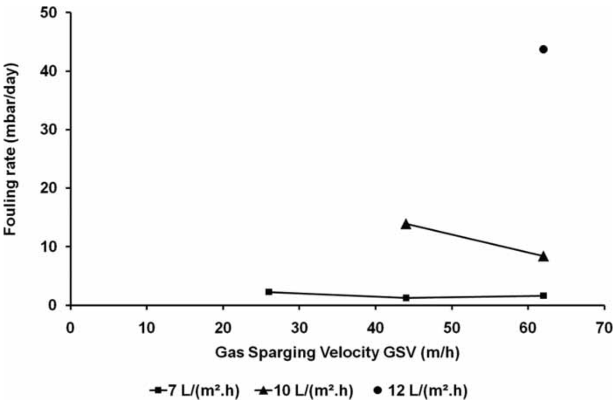


**Figure 3** | Effect of the gas sparging velocity on the fouling rate. TSS: 14 g/L.

the experiment was stopped and another flux was tested. The shortest experiment lasted 2 days (Table 1).

To our understanding, the magnitude of the GSV did not play a very important role in the cake layer formation when the critical flux was not exceeded. At the flux of $7\,\mathrm{l\,m^{-2}\,h^{-1}}$, no big differences in the fouling rate were observed. In fact, the lowest GSV (26 m/h) was also able to control the TMP increase (Figure 3). However, as soon as the critical flux was exceeded (supra-critical conditions), the GSV became more important. A GSV of 62 m/h controls better the TMP increase than the one of 44 m/h at the flux of $10\,\mathrm{l\,m^{-2}\,h^{-1}}$. By increasing the GSV to 62 m/h the fouling rate dropped from 14 to 8.4 mbar/day. When the flux of $12\,\mathrm{l\,m^{-2}\,h^{-1}}$ was tested, the TMP increase could not be controlled even at the maximal GSV. Nevertheless the trial continued for 2 days of operation.

## Biomass concentration

In the second part of this work, from day 74 onwards, the effect of the biomass concentration on the fouling rate was tested. All the experiments were carried out using a GSV of 62 m/h. Three different biomass concentrations (10.7, 14.8 and 21.7 g TSS/L) as well as three fluxes (7, 10 and $12\,\mathrm{l\,m^{-2}\,h^{-1}}$) were tested (Table 2). Because the TMP achieved high values during some trials, two experiments were not carried out (Figure 4). The HRT varied from 2.0 to 0.8 days and the OLR from 0.3 to 0.9 g COD/L (Table 2) depending on the operational fluxes and the active volume of the reactor.

Although a backwashing phase was applied after the filtration phase to lower the TMP, the fouling rate could not be controlled at 10 and $12\,\mathrm{l\,m^{-2}\,h^{-1}}$ (Figure 4). Therefore, a stable operation could not be assured in the long term under such flux conditions. Nevertheless, a trial should be excluded. Using the lowest biomass concentration tested in this work (10.7 g TSS/L), a fouling rate of 2.8 mbar/day was achieved with a flux of $10\,\mathrm{l\,m^{-2}\,h^{-1}}$ and a GSV of 62 m/h and could lead to a stable operation.

This low fouling rate can be explained considering that the critical flux is directly associated with the biomass concentration (Jeison & van Lier 2006). Thus, the critical flux under these conditions must have been close to $10\,\mathrm{l\,m^{-2}\,h^{-1}}$.

The critical flux was also determined using a solid concentration of 21.7 g TSS/L. Despite the fact that the biomass concentration was higher, the critical flux was also close to

**Table 2** | Operational conditions during the TSS trials

| Period (days) | Flux ($\mathrm{l\,m^{-2}\,h^{-1}}$) | GSV (m/h) | TSS (g/L) | VSS (g/L) | HRT (d) | OLR (g COD/L d) |
|---|---|---|---|---|---|---|
| 74 to 75 | 7 | 62 | 10.7 ± 1.1 | 7.5 ± 1 1.7 | 2.0 | 0.3 |
| 76 to 83 | 12 | 62 | 10.7 ± 1.1 | 7.5 ± 1 1.7 | 1.3 | 0.4 |
| 84 to 86 | 10 | 62 | 10.7 ± 1.1 | 7.5 ± 1 1.7 | 1.5 | 0.4 |
| 89 to 102 | 7 | 62 | 14.8 ± 1.2 | 9.6 ± 0.9 | 1.4 | 0.4 |
| 128 to 135 | 10 | 62 | 14.8 ± 1.2 | 9.6 ± 0.9 | 1.0 | 0.5 ± 0.1 |
| 137 to 140 | 12 | 62 | 14.8 ± 1.2 | 9.6 ± 0.9 | 0.8 | 0.6 |
| 141 to 155 | 7 | 62 | 14.8 ± 1.2 | 9.6 ± 0.9 | 1.4 | 0.4 |
| 157 to 163 | 10 | 62 | 14.8 ± 1.2 | 9.6 ± 0.9 | 1.0 | 0.6 ± 0.1 |
| 167 to 172 | 7 | 62 | 14.8 ± 1.2 | 9.6 ± 0.9 | 1.4 | 0.6 ± 0.3 |
| 173 to 185[a] | 7 | 62 | NA | NA | NA | NA |
| 186 to 206[b] | 7 | 62 | 21.7 ± 2.3 | 12.7 ± 1.3 | 0.8 | 0.9 ± 0.1 |

[a]This trial was carried out to reduce the active volume of the reactor. NA: Not available.
[b]TMP Jump.

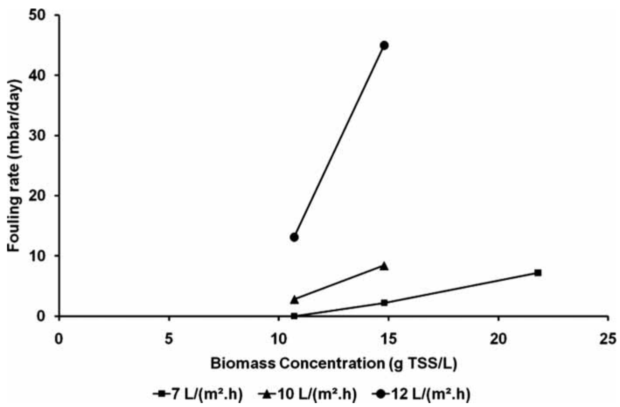


**Figure 4** | Effect of the biomass concentration on the fouling rate. GSV: 62 m/h.

$7\,l\,m^{-2}\,h^{-1}$. At the critical flux ($7\,l\,m^{-2}\,h^{-1}$), the fouling rate could be controlled using a maximal biomass concentration of 14.8 ± 1.2 g TSS/L. Above this value, the fouling rate was significantly high (7.2 mbar/day) and after 14 days of operation the fouling rate became non-linear (i.e. the TMP showed the so-called TMP jump) at the end of this work. It should be emphasized that the fouling rates presented in this work did not take into account, if it occurred, the sudden increase in the TMP. Only the slow linear increase in TMP was considered.

Although 21.7 g TSS/L is considered a normal or even a low concentration in anaerobic systems, the operation of the AnSMBR was instable at this concentration and $7\,l\,m^{-2}\,h^{-1}$. The instability of the process shows the strong influence of the biomass concentration on the applicable flux and suggests that the critical flux is not an appropriate tool to predict how long a MBR can be operated. In addition, results show that the biomass concentration played a more important role than the GSV in the stability of the AnSMBR. In MBRs, the applicable flux depends on several parameters, which, in addition, strongly depend on each other. Nevertheless, it should be emphasized that MBRs can be operated over extended periods at a fixed flux if this flux is substantially below the nominal critical flux (Cho & Fane 2002). In our study, the AnSMBR was not operated under sub-critical flux conditions but under critical.

Since the critical flux could never be increased for a long period of time, the hydraulic capacity of the process is still limited to the range of critical flux. Other configurations that can increase the shear rate close to the membrane surface should be therefore evaluated.

As the operational flux of $7\,l\,m^{-2}\,h^{-1}$, either with a biomass concentration of 10.7 or 14.8 g TSS/L, and the GSV of 62 m/h could assure a stable long-term operation, these conditions were often tested to operate the AnSMBR (Table 2). Compared to other works, the operational flux found in this research, is in agreement with values reported in the literature. For instance, Akram & Stuckey (2008) reported a flux range from 2 to $5\,l\,m^{-2}\,h^{-1}$. Under thermophilic conditions and depending on the feed water matrix, operational fluxes from 3 to $7\,l\,m^{-2}\,h^{-1}$ have also been reported (Jeison & van Lier 2007). Nevertheless, in the present research, backwashing was used every ten minutes and although it could remove part of the cake layer formed, it clearly reduces the hydraulic capacity of the reactor. Vallero *et al.* (2005) reported fluxes up to $17\,l\,m^{-2}\,h^{-1}$. However, the maximal biomass concentration used in their study was very low (1.75 g TSS/L).

## Physical cleaning

The membrane was physically cleaned on day 156. The resistance of the membrane was measured before and after the physical cleaning. The values were compared with the resistance of a new membrane (Table 3). The efficiency of the physical cleaning was nearly 100% indicating that no irreversible fouling was formed inside the membrane pores and the cake layer was easily detached by using physical cleaning. Jeison & van Lier (2006) reported reversible cake layer formation as the limiting factor in operational flux in MBRs. Jeison & van Lier (2007) also found low values of irreversible fouling in AnSMBR.

## Anaerobic treatment performance

Excluding the start-up period, COD removal efficiencies were always close to 90% and depended neither on the organic loading rate nor on the biomass concentration (Figure 5). However, it should be mentioned that the influent matrix had a fraction of easily biodegradable COD. As mentioned above, glucose was added to increase the COD concentration in the influent. The composition and flow rate of municipal wastewater depend among other things,

**Table 3** | Membrane resistances

| | Resistance ($m^{-1}$) |
|---|---|
| New membrane | $9.97/(10\times10^{11})$ |
| After 156 days of operation | $2.82/(10\times10^{12})$ |
| After physical cleaning | $9.99/(10\times10^{11})$ |

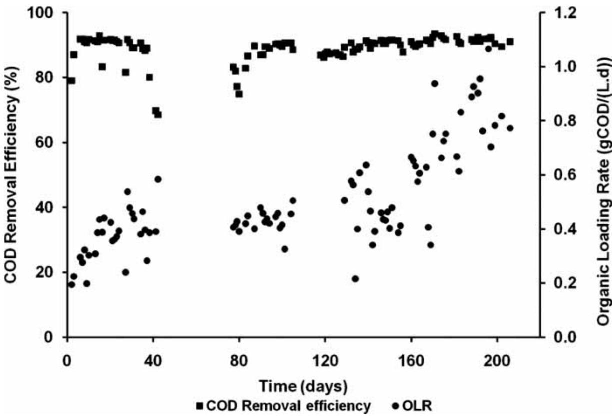


**Figure 5** | COD removal efficiency and organic loading rate in time.

on economic aspects, social behavior and climatic conditions (Seghezzo *et al.* 1998). Total COD concentrations from 267 to 800 mg/L have been reported in the literature (Seghezzo *et al.* 1998; Monroy *et al.* 2000). In our work, the average total COD concentration of the original wastewater, before adding glucose, was $402 \pm 73$ mg/L. The ratio glucose/municipal wastewater expressed in terms of COD was $0.87 \pm 0.18$. After the addition of glucose, the COD concentration of the feed wastewater was $750 \pm 90$ mg/L.

In MBRs, the flux is directly related to the organic loading rate (OLR), although it is not the only influencing factor. In the present work, due to the fouling, the major drawback of MBRs, the flux could not be further increased and the resulting OLR values were very low, varying from 0.2 to 0.6 g COD/(L d) during the first 160 days of operation (Figure 5). In this period of time, a slight increase in the OLR was possible when the higher fluxes (10 and 12 $l\,m^{-2}\,h^{-1}$) were tested. Due to technical problems the reactor was not operated from day 45 to 73 or from day 102 to 127. During both periods of time, the reactor was fed in batch mode. From day 173 onwards, the OLR could be increased when the active volume of the reactor was reduced to 350 L to test the highest biomass concentration (Table 2). The highest OLR value was close to 0.9 g COD/(L d).

Besides the different fluxes tested in this work, fluctuations in the influent COD concentration can also explain variations in the OLR. Concentrations of the total and particulate COD (pCOD), $NH_4$-N, total phosphorus, $BOD_5$ and fecal coliforms in the influent and effluent are summarized in Table 4. COD concentration in the effluent (permeate) was always lower than 70 mg COD/L. The pathogen indicator (fecal coliforms) was reduced by log 6. The pH was not controlled. It had a mean value of $6.8 \pm 0.1$. Although, the COD was increased by adding glucose, nitrogen and phosphorus concentrations in the influent were in the range of the typical concentrations for municipal wastewater reported in the literature (Seghezzo *et al.* 1998).

Sludge losses from the system were only due to sampling. Thus, the sludge retention time was not controlled.

As the OLR was low, the daily biogas production was also low. Nevertheless, methane yield was always close to the theoretical value of 0.35 L $CH_4$/g $COD_{removed}$ at 35 °C. The values obtained in the present work varied from 0.20 to 0.36 L $CH_4$/g $COD_{removed}$.

## CONCLUSIONS

A pilot-scale AnSMBR treating a wastewater mainly composed of municipal wastewater and glucose under mesophilic conditions was operated for 206 days. Different fluxes, biomass concentrations and gas sparging velocities were tested. The reactor was operated in cycles that included relaxation and backwashing phases. Despite this operational strategy, the critical flux could never be exceeded for a long period of time. Nevertheless, a long continuous operation could be achieved with a flux of 7 $l\,m^{-2}\,h^{-1}$, an average biomass concentration of 14.8 g TSS/L and a GSV of 62 m/h. The GSV does not play a central role in controlling fouling under critical conditions. Nevertheless, GSV becomes more important as soon as the critical flux is exceeded. No irreversible fouling was found after 156 days of operation. Thus, the physical cleaning efficiency of the membrane was almost 100%. COD

**Table 4** | Feed wastewater and permeate quality

| | COD (mg/L) | pCOD (mg/L) | $BOD_5$ (mg/L) | $NH_4$-N (mg/L) | Total phosphorus (mg/L) | Fecal coliforms (MPN/100 mL) |
|---|---|---|---|---|---|---|
| Influent | $750 \pm 90$ | $239 \pm 52$ | $483 \pm 35$ | $49 \pm 10$ | $7.4 \pm 1.2$ | $1.44 \times 10^7$ |
| Permeate | <70 | ND | <30 | $56 \pm 10$ | $6.7 \pm 1.3$ | 78 |

N.D.: No detectable.

removal efficiencies were always close to 90% and the hydraulic retention time was lower than 1 day at the end of this work. Permeate COD concentrations were always lower than 70 mg/L. Methane yield varied from 0.2 to 0.36 L $CH_4$/g $COD_{removed}$. The pathogen indicator (fecal coliforms) was reduced by log 6. Hence, permeate could be used for irrigation in agriculture. However, the produced permeate was used to backwash the membrane which clearly reduces the reactor efficiency. For this reason the operational strategy used in this work should be improved in further research.

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