MUNICIPAL WASTEWATER TREATMENT IN A MEMBRANE BIOREACTOR

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ABSTRACT

A membrane bioreactor (MBR) with a submerged membrane was used for the treatment of municipal wastewater from the city of Zagreb, Croatia, in a continuous mode for 123 days. The MBR was very efficient in organic matter removal (92.3 and 98.5 % for COD and BOD, respectively) for the entire duration of the experiment. Nitrification was established after 20 days remaining stable and efficient with a low concentration of ammonia and nitrite in the effluent. On average, 87% of ammonia was converted to nitrate. Biomass concentration, measured as MLSS, was dependant on the organic loading rate (OLR) and food to microorganism ratio (F/M), and its growth could be stopped or its concentration reduced by setting OLR and F/M to appropriate values, thus reducing the excess sludge production. Throughout the range of hydraulic retention times from 2.6 to 5.9 h, the efficiencies of organic matter removal and nitrification were not affected.

KEYWORDS: membrane bioreactor, municipal wastewater, submerged membrane

INTRODUCTION

Membrane bioreactor (MBR) technology, which combines biological activated sludge process (ASP) and membrane filtration, have became more popular, abundant and accepted in recent years for treatment of many types of wastewater where conventional ASP cannot cope with either the composition of wastewater or the fluctuations of wastewater flow-rate. It is also used in cases where demand on the quality of effluent exceeds the capability of ASP [1, 2]. Although MBR capital and operational costs somewhat exceed the costs of a conventional process, it seems that an upgrade of a conventional process occurs even in cases when conventional treatment works well. It can be related with the increase in water price and the need for water reuse, as well as with more stringent regulations on effluent quality [3]. MBR technology has not only attracted interest in setting up new wastewater treatment systems but it has also great potential for upgrading the already existing conventional ASP treatment plants [4].

A need for the development of MBR technology arose mainly from the limiting factor in conventional treatment, namely, the separation of sludge from treated water through sedimentation. Without good sedimentation in the secondary settler, parts of the sludge end up in treated water, which leads to poor removal efficiency. Sludge with poor settling characteristics is often called bulking sludge and, in most cases, problems occur due to the growth of filamentous bacteria. The main reasons for bulking are low dissolved oxygen concentration, low food to microorganism ratio (F/M) and nutrient deficiency. While the necessary dissolved oxygen concentration can be provided by a proper aeration system, problems with variations in wastewater flow-rate and composition can seriously affect the ASP. If the design of the plant allows it, bulking can be mitigated by setting operational parameters, such as F/M ratio, high enough to enhance the growth of floc-forming organisms. By doing so, microorganisms in the activated sludge are kept in exponential growth phase in which they produce large amounts of excess biomass. To achieve high F/M, the MLSS in the aeration basin has to be kept low (around 3-5 g/L dry mass weight), while the concentration of organic matter in the feed water needs to be high. Those conditions are usually easy to achieve with municipal wastewater with small amounts of industrial wastewater and drainage water. In cases when drainage water dilutes the wastewater significantly or industrial wastewater adds its components into the influent, the ASP efficiency can be seriously lowered due to poor sedimentation of microbial flocs.

Effluents from ASP always contain significant microbiological contamination, since there is no physical barrier between activated sludge and treated water. A correlation has been reported between the occurrence of eye and ear infections in humans and their contact with ASP effluents during recreational use of such water [5]. This problem is even more pronounced if hospitals discharge their wastewater into the sewage without treatment when an increased number of pathogens may be found in raw sewage and effluent.

To overcome the limitations of ASP, MBR technology can be successfully employed. In general, MBR is a combination of an aerated bioreactor and the membrane filtration, where the membrane process replaces the sedimentation of the ASP. Since MBR is no longer restricted to operation within a narrow range of SRT typically required by an ASP to insure the settling of the sludge, F/M ratio can be set much lower than with ASP, thus allowing operation on much higher MLSS concentrations, which consequently leads to higher volumetric efficiency of the process. Given the reduction in bioreactor volume, the elimination of secondary clarifiers, and the elimination of granular media filters, an MBR typically has a much smaller footprint relative to ASP while achieving the same discharge limits. Due to this footprint reduction, other concerns, such as aesthetics and odours, can be more easily addressed. Also, lower F/M ratio leads to lower production of excess sludge which then decreases the cost of sludge handling and disposal.

As water reuse and reclamation increases, MBR technology can make reclaimed water more accessible by achieving the reclaimed water treatment standards in nearly a single step, thus reducing the complexity of these systems. Using a membrane instead of the ASP's sludge settling, most of the pathogens of concern in the wastewater can be significantly removed from the effluent. In addition, the clarity of effluent produced by the MBR process is consistently below 0.1 NTU, which is comparable to drinking water standards. This low turbidity can result in an effluent highly amenable to final disinfection using ultraviolet light. Membrane filtration followed by UV results in a highly disinfected effluent.

MBR systems do not require significant operational attention or, in any case, much less than conventional ASP and they are a much better solution for small plants where ASP is not feasible due to its requirement for constant attention and monitoring.

This paper reports on long-term pilot testing of a submerged MBR for treatment of real municipal wastewater.

MATERIALS AND METHODS

Experiments were conducted on a pilot plant MBR with a hollow fibre membrane (Zenon ZeeWee^{TM}-10) vertically submerged directly in the 40-L (useful volume) rectangular-based (24x24x93 cm) bioreactor. Membrane properties are given in Table 1.

TABLE 1 - Membrane properties.

Dimensions	Fibre length 0.52 m
Filtration area	0.93 m^2
Nominal pore size	0.4 µm
Cross section area	94 cm^2
Resistance R_m	6.5×10^{11} m^{-1}

The pilot plant was located near the municipal wastewater collector of the city of Zagreb (South). The plant was situated outside under a roof, so that the ambient temperature governed the temperature in the bioreactor. Municipal wastewater (almost completely domestic) was used as the source of raw water. Water was pumped directly from the sewage with no pre-treatment save for coarse particles removal using a 5 mm screen. The effluent was collected as a composite 24-hour sample in a plastic container, and analyses were performed on a daily basis, 5 days a week. Testing was carried out through an experiment that lasted uninterruptedly for 123 day. The bioreactor was inoculated with activated sludge from the full-scale municipal wastewater treatment plant with the initial MLSS (mixed liquor suspended solids) concentration in the bioreactor of 8 g/L. No sludge has been wasted save for small volumes due to sampling. Flow-rates of both permeate and feed water were maintained by a laboratory pump and measured with a flowmeter, while the corresponding transmembrane pressure (TMP) was measured by a pressure gauge. Compressed air was supplied through a diffuser at the base of the membrane in order to create shear stress, thus mitigating the formation of cake layer on the membrane surface, and in order to obtain aerobic conditions for biological treatment. Aeration was set to 3.4 m^3/h (3.62 $m^3/h/m^2$ of membrane cross section area), which gave high oxygen concentration, always above 4 mg/L. The temperature in the bioreactor was governed by the outside temperature and it was 8 °C (from 3-15 °C) on average for the first 40 days of the experiment, and then it rose to 20 °C (from 16-26 °C) on average, and remained within that boundary until the end of the experiment. The membrane was backwashed with effluent for 10 seconds every 9.75 min with the backwash flow-rate 1.5 times higher than that of the permeate. The membrane was not chemically cleansed during the experiment.

RESULTS AND DISCUSSION

The treated wastewater was the municipal wastewater from the city of Zagreb (South), with approximately 120.000 inhabitants. Wastewater was mostly of domestic origin with few industrial wastewater inflows. The composition of wastewater is given in Table 2. As can be seen, the used wastewater was not heavily polluted, with a composition and COD, total nitrogen and phosphorus ratio favorable for biological treatment. Fluctuations of pH were minimal and measured values also suitable for treatment. There was no

TABLE 2 - Composition of the wastewater

	Average	Minimum	Maximum	Standard deviation
COD (mg O_2/L)	290	72	507	95
BOD_5 (mg O_2/L)	102	36	267	40
Total N (mg/L)	38	24	54	6.7
Total P (mg/L)	7	3	9	1.7
pH	7.65	7.11	8.46	0.4
Fats and oils (mg/L)	21	10	66	16.6

dissolved oxygen in the wastewater due to its consumption by the bacteria within the sewer system.

The results of COD and BOD removal from the wastewater are presented in Figs. 1 and 2. It can be seen that removal efficiency for the organic matter was very high (92-94%) under all of the investigated experimental conditions.

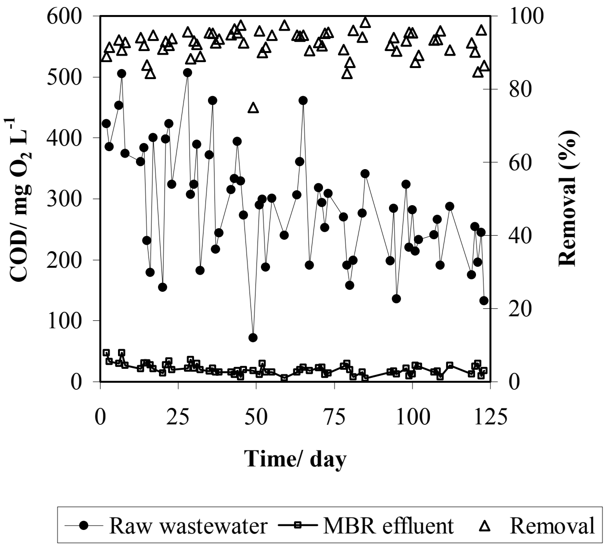

FIGURE 1 - COD in wastewater and MBR effluent.

High removal efficiency was enhanced by the high sludge retention time (SRT), i.e. sludge age and high sludge concentration, which together enhanced the volume efficiency of the process in the bioreactor. Membrane separation of sludge from the treated water achieved the retention of suspended matter within the bioreactor which prolonged the available time for its degradation by microbial culture. Membrane separation also enabled the adaptation and development of microorganisms capable of degradation of less biodegradable compounds in the wastewater. High removal efficiencies (always more than 90%) were reported in most of the papers concerning municipal wastewater treatment by MBR [1, 6, 7]. High removal efficiency is usually explained by good microbial activity and efficient removal of suspended solids by membrane filtration, Contribution of membrane filtration to this removal has been reported to be more than 70% [8], but it is generally considered that filtration itself contributed to overall removal by approximately 30% [6].

TABLE 3 - Treatment efficiency for the whole duration of the experiment.

	Removal efficiency [%]	Standard deviation	Minimum	Maximum
COD	92.3	3.9	75.0	98.3
BOD	98.5	1.2	93.5	99.9
Fats and oils	97.9	2.2	91.1	99.6
Total P	20			
Nitrification	87.3	12.6	26.9	72.2

The removal of BOD was, as expected, higher than the removal of COD (Table 3) and amounted to more than 98%. Since the effluent BOD values averaged about 2 mg O_2/L, this indicates the complete removal of biodegradable organic matter.

From the data in Fig. 2, it can be seen that all of the effluent BODs were consistently excellent. Ranges for all of the measured constituents of concern in the effluent are presented in Table 4. All the measured effluent samples were suitable for discharge into the natural water recipient according to Croatian legislation. In the near future, nitrogen removal through denitrification and advanced phosphorus removal will be necessary to meet the more stringent regulations for effluents from wastewater treatment plants.

TABLE 4 - Composition of the effluent.

	Average	Min.	Max.	St. dev.	Requirement[a]
COD (mg O_2/L)	20.7	5.8	47.0	8.7	max. 125
BOD_5 (mg O_2/L)	1.4	0.1	6.0	1.1	max. 25
Total N (mg/L)	34.6	20.6	47.5	6.7	No limit (15[b])
Total P (mg/L)	3.4	2.8	5.2	0.7	No limit (2[b])
Fats and oils (mg/L)	0.33	0.08	1.27	0.29	No limit

[a] According to Croatian law requirements for biologically treated municipal wastewater; [b] Limit for sensitive areas

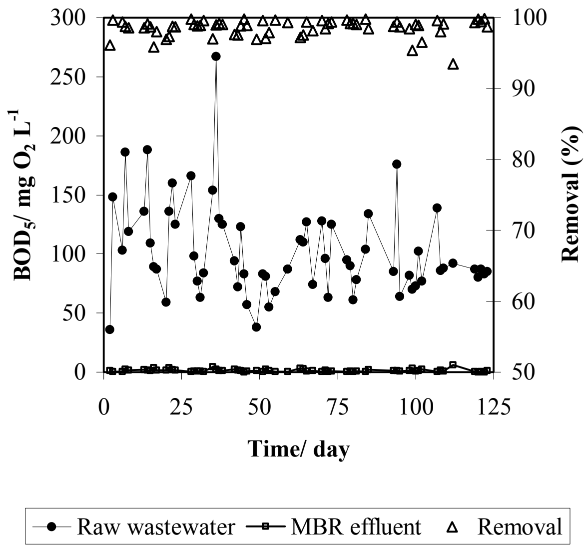

FIGURE 2 - BOD in wastewater and MBR effluent flow-rate.

Even when the feed flow-rate was increased from the usual value of 6.8 L/h in four steps, each lasting a week, to 16 L/h, the organic matter removal was undisturbed (Table 5). At the highest applied flow-rate, when the hydraulic retention time (HRT) was 2.6 h, the standard deviation and mean value of BOD concentration in the effluent were the same as at the lowest flow-rate.

HRT of 2.6 h is rather low compared to the operating conditions of most MBRs reported in literature. In the work

TABLE 5
COD removal efficiency and nitrification efficiency for various wastewater flow-rates.

Flow [L h^{-1}]	HRT [h]	OLR [g COD L^{-1} day^{-1}]	COD removal [%]	Nitrification [%]
6.8	5.9	1.29	92.1	93.1
9.0	4.4	1.75	94.6	74.3
10.3	3.9	2.02	94.9	93.3
13.5	3.0	2.44	93.9	79.3
15.6	2.6	2.36	91.9	81.8

work of Ren et al. [9], the effects of HRT (1–3 h) on removal efficiency were investigated. The influence of HRT was clearly observed when this parameter changed from 2 to 1 h. Trussell et al. [10] observed no disturbance of effluent quality over the range of food to microorganism ratio (F/M) of 0.34 to 1.41 g COD/g VSS d), while investigating membrane fouling. Working at low HRT certainly increases the volume efficiency of the bioreactor, thus making it smaller. However, Yoon et al. [11] calculated the cost for excess sludge handling and the aeration cost, which were primarily a function of MLSS and HRT. They proposed best economical operational conditions: HRT of 16 h and MLSS of 11,000 mg/L, when the aeration for biodegradation was 13.3 m^3 air/min, in order to treat 1000 m^3 of wastewater per day. They also concluded that the sludge treatment cost surpasses the aeration cost for reasonable ranges of HRT and MLSS.

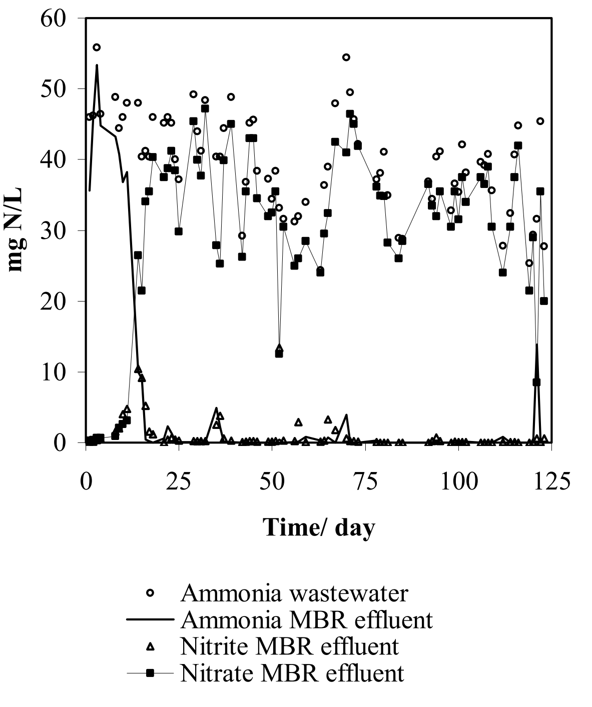

FIGURE 3 - Nitrification in MBR

The ability of MBRs to operate at higher biomass concentrations and provide better retention of slow growing microorganisms enhances biological nitrification, since nitrifiers are a slow growing autotrophic species. In this work, SRT can be estimated at around 6 months, since the minute amounts taken for sludge sampling represented the only sludge that was wasted. As it can be seen from Fig. 3, the initial sludge with a low number of nitrifiers started to show nitrification activity after the initial adaptation phase, which lasted about 20 days. Nitrite concentration sharply rose at the onset of nitrification, but then it fell to less than 0.2 mg/L and remained below that boundary until the end of the experiment, with only a few exceptions when its concentration rose to several mg/L (never more than 5 mg/L). The same can be observed with the concentration of ammonia in the effluent, which was high before the start of nitrification and, with few exceptions, remained low until the end. Usually, the disturbances in nitrification were correlated with the pumping problems of feed wastewater, which led to drops in mixed liquor volume in the bioreactor and, consequently, to a lower dissolved oxygen concentration. Also, in such cases, the bioreactor was being filled to the working volume of 40 L with wastewater, thus sharply increasing the organic and nitrogen load to the bioreactor. Obviously, nitrification was stable and efficient, but more susceptible to such disturbances in the process than organic matter removal. Overall efficiency of nitrification was rather high and stable throughout the treatment experiment, even at high nitrogen loads to the bioreactor, as can be seen in Table 5. Nitrification efficiency expressed as ratio of nitrate mass in the effluent divided by nitrogen mass loaded into the bioreactor was always higher than 0.74, reaching to over 0.9. With a low ammonia concentration in the effluent, the reason for lower nitrification efficiency during the increased nitrogen load into the bioreactor was biomass growth and assimilation of nitrogen in the newly formed bacterial biomass. Also, there might have existed some anoxic zones at the bottom of the bioreactor, or in the centre of the bacterial flocs, where some denitrification might have occurred and possibly some nitrogen left the bioreactor as a gaseous product of denitrification.

Several other studies reported high nitrification efficiency in MBR operating at a long SRT [7, 12]. Cicek et al. [13] showed that nitrification ability of the activated sludge is seriously affected when SRT is lower than 5 days while Huang et al. [14] achieved good nitrification with SRTs varying from 5-40. A number of other authors have researched the efficiency and rate of nitrification in MBR [15-17]. During treatment of municipal wastewater in an MBR, Witzig et al. [18] observed the absence of usual nitrifying organisms *Nitrobacter* and *Nitrosomonas* within the microbial community with good nitrifying ability. Tan et al. [19] also found the relative presence of different nitrifiers within the microbial community to be influenced by the SRT.

Here, most of the ammonia from the wastewater was converted to nitrite (more than 87% after the start of nitrification), which shows that microbial cells were not assimilating much nitrogen into the biomass. That observation implies slow growth of the biomass, which was the case for most of the experiment duration (Fig. 4).

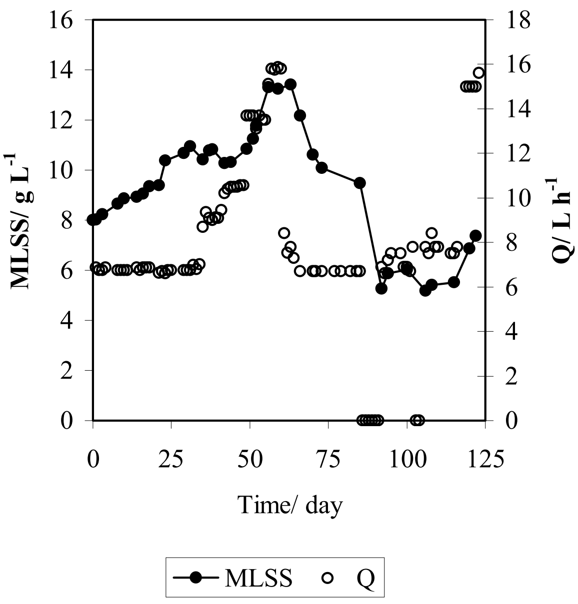

FIGURE 4 - MLSS concentration and feed water flow-rate

Until day 34 of the experiment, the wastewater inflow had been constant at 6.8 L/h, which resulted in a gradual increase of the MLSS up to 10-11 g/L, where the MLSS increase stopped. With a very low rate of sludge wasting, more biomass was accumulated inside the MBR than usually found in the ASP. Constant inflow of feed water with nearly constant COD concentration along with increase of MLSS resulted in a continuous decrease of the F/M ratio from initial 0.149 g COD g $MLSS^{-1}$ day^{-1} to 0.107 g COD g $MLSS^{-1}$ day^{-1} on day 31. Under these conditions, MBR was operated progressively in an endogenous respiration state of microorganisms rather than state of exponential growth, and so the resulting sludge production was minimized. After 34 days, the wastewater flow was gradually increased from 6.8 L/h to 15.6 L/h (Table 4), which increased the organic loading rate into the bioreactor and, as a consequence, biomass concentration also increased to the 13 g/L. This period was characterized by the F/M ratio of 0.15 to 0.22 g COD g $MLSS^{-1}$ day^{-1}. Along with the return of the feed flow-rate to its original value, a sharp decrease of MLSS can be seen, while after the complete break in the feed lasting 6 days (days 86-91), a serious decrease of MLSS concentration occurred. Feeding with wastewater commenced again on day 92, and the MLSS consecutively started to rise again. It is clearly obvious that biomass concentration in the bioreactor is primarily a function of the organic loading rate. The biomass concentration decrease between days 63 and 92 of the experiment did not influence the treatment efficiency, but the fate of the removed suspended solids needs explaining. Since there was no leakage of the suspended matter from the bioreactor, it is obvious that bacterial cell decomposition occurred and that decaying bacterial cells released their organic material into the dissolved phase of mixed liquor. There it became a substrate for other bacteria which transformed it to CO_2. Inert non-biodegradable matter, such as parts of the cell wall remained as particulate within the bioreactor. The nitrogen which had been also released during cell decomposition was converted to nitrate by the nitrifying bacteria, and left the bioreactor with the effluent. Due to the long period of biomass decrease, there was no significant increase of nitrate concentration in the effluent.

Low sludge production under low F/M ratio has been reported by several studies [7, 14, 20]. Usually, the biomass enters the steady state characterized by low or no growth when F/M ratio is set low by keeping the MLSS high. The most common explanation for the growth rate decrease is that in the conditions of scarce availability of substrate, and microbial cells utilize it to maintain themselves rather than to grow. According to the maintenance concept introduced by Pirt [21], part of the energy contained in the supplied substrate is used for maintenance functions which are independent of growth rate. When the energy supply into the bioreactor is lower than the maintenance energy, the biomass ceases to grow and utilize the substrate for maintenance. In that manner, the sludge production in the process is much lower or even absent. Another concept is based on assumption that the microbial growth rate is counteracted by the microbial death rate, which leads to a growth rate decrease or stoppage. Witzig et al. [18] measured the number of ribosomes in the biomass from an MBR under high SRT and in the absence of visible biomass growth. The observed biomass was not in the characteristic state for growth, which suggests that the maintenance concept, rather than the concept of equity of growth and death rate, is valid for the observed growth stoppage in MBR. Leara et al. [22] investigated the possible correlations between sludge retention time (SRT), biomass growth, biomass activity and membrane cleaning requirements in a submerged membrane bioreactor (MBR), and reported that TSS/VSS ratio remained above 75% for all SRTs used, suggesting low accumulation of inorganic substances in the bioreactor. They also observed stabilization of the MLSS over time in the case of complete retention of biomass and nearly infinite SRT at F/M ratio of 0.06 g COD $gVSS^{-1}$ d^{-1}. Very low sludge production in pilot MBR operations has been reported, but it is often impractical for full-scale operations to keep F/M too low, since a high MLSS concentration may promote membrane clogging and increase the energy consumption for oxygen transfer to aqueous phase through aeration. Nevertheless, due to a lower F/M ratio in the MBR, there is a significant decrease of sludge production in comparison to ASP, which decreases the cost of excess sludge handling.

The confirmation that the biomass was not in a state of over-saturation with the organic substrate in the wastewater can be seen in the linear dependence of the organic loading rate (OLR) and COD removal rate (Fig. 5). With the increase of OLR, COD removal increased, which shows that for the imposed operational parameters, the pollutants` decomposition rate was dictated by the feed flow and not by the MLSS concentration.

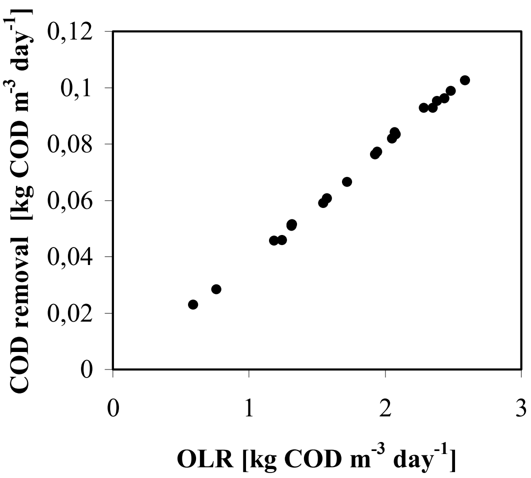

FIGURE 5 - COD removal for various organic loading rates (OLR)

During the experiment, the membrane was frequently backwashed, but it was not chemically cleaned. After the 123 days, it was cleaned with hypochlorite solution and its original permeability was restored. Permeate flux ranged between 7 and 15 L m^{-2} h^{-1} depending on the permeate flow-rate imposed by the pump, but it was on average 7.2 L m^{-2} h^{-1}. Transmembrane pressure varied over time depending on the imposed flux and the level of membrane fouling, and it was between 2.36 and 15.8 kPa. Estimated membrane permeability decreased from 417 L m^{-2} h^{-1} bar^{-1} to 55 L m^{-2} h^{-1} bar^{-1} in 123 days of experiment duration. The more detailed results of membrane fouling observation were published elsewhere [23].

CONCLUSION

MBR with a submerged membrane was capable of treating the municipal wastewater with high efficiency for COD and BOD removal. The nitrification was also very stable and efficient, but generally more susceptible to process disturbances than organic matter removal. The MLSS development was a function of the F/M ratio and, by its alteration, it was possible to achieve a complete stoppage of biomass growth or a decrease of its concentration. By setting the F/M ratio, it is possible to minimize the excess sludge production and cost of its handling.

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