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Pilot-scale study to investigate the impact of rotating belt filter upstream of a MBR for nitrogen removal

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ABSTRACT

The goal of this study was to investigate what kind of impact the removal of particulate organic matter with 33 μm rotating belt filter (RBF) (as a primary treatment) will have on the membrane bioreactor (MBR) performance. Two small MBR pilot plants were operated in parallel, where one train treated 2 mm screened municipal wastewater (Train A) and the other train treated wastewater that had passed through a RBF with a 33 μm filter cloth (Train B). The RBF was operated without a filter mat on the belt. About one third of the organic matter was removed by the fine mesh filter. The assessment of the overall performance showed that the two pilot plants achieved approximately the same removal efficiencies with regard to total suspended solids (TSS), chemical oxygen demand (COD), total phosphorus and total nitrogen. It was also observed that the system with 33 μm RBF as a primary treatment produced more sludge, which could be used for biogas production, and required about 30% less aeration downstream. Transmembrane pressure was significantly lower for the train receiving 33 μm primary treated wastewater compared to the control receiving 2 mm screened wastewater.

Key words | membrane bioreactor, nitrogen removal, organic matter, primary treatment, rotating belt filter

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INTRODUCTION

The use of membrane technology, combining conventional activated sludge with low pressure membrane filtration, has been proven to be a feasible and efficient method to achieve high effluent quality in biological wastewater treatment (WWT). However, membrane fouling remains a major drawback of the membrane bioreactor (MBR), as it significantly reduces the membrane performances and membrane lifespan, leading to an increase in maintenance and operating costs (Iorhemen *et al.* 2016). It is well accepted that removal of particulate and colloidal fractions will lead to considerable operational savings in the downstream aerobic biological processes while allowing the recovery of energy in the form of methane via anaerobic sludge treatment processes. Moreover, carbon management plays a very important role for biological nutrient removal processes where certain carbon fractions are preferred for optimal performance without the addition of external carbon source (Ho *et al.* 2017).

Newcombe *et al.* (2011) found through literature that 15–20 μm was the possible new particle size delineation for effective biological treatment, after evaluating in bench-scale studies the impact of primary treatment on the size distribution of particles prior to biological treatment. Based on the study by Razafimanantsoa *et al.* (2014a), no huge impact on the denitrification rates was observed with the anoxic batch tests fed with wastewater passed through filters from 150 μm to 1.2 μm openings. However, a clear particle size cut-off was determined with the laboratory scale SBRs (Razafimanantsoa *et al.* 2014b). The comparative studies showed that all SBRs had approximately the same pollutants removal efficiencies, except for the reactors fed with filtrate passed through filters below 33 μm, where a reduction of the nitrogen removal efficiencies were noticed. Thereby, the objective of this present study was to determine if the removal of particulate organic matter with a 33 μm filter would affect the nitrogen removal performance of the MBR. The specific objectives were to evaluate the impact of fine mesh filters for particle removal upstream of the MBR (i.e. removal efficiencies of total suspended solids (TSS), chemical oxygen demand (COD), nitrogen and phosphorus in the MBR);

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and further to determine the total sludge production and the oxygen demand for the aerobic process.

MATERIALS AND METHODS

Sampling and study location

The experiment was performed at Nordre Follo wastewater treatment plant (WWTP) (Akerhus, Norway). Influent wastewater was collected just after the coarse screens using a grinder pump, then passed through a 2 mm screen (Train A) or a fine mesh filter cloth of 33 μm (Train B) mounted on a commercial rotating belt filter (SF 1000 machine) (Salsnes Filter AS, Norway). Screened and filtered wastewater, respectively, were stored in tanks that were filled three times per week. The mixed liquor suspended solids (MLSS) used as seed activated sludge for the MBRs was collected from the return activated sludge line at Bekkelaget WWTP (Oslo, Norway).

Experimental setup

Two pilot-scale MBRs were operated in parallel during the experiment. As illustrated in Figure 1, each MBR Train was composed of two anoxic reactors of 10 L (R1 and R2), equipped with a mechanical mixer rotating at about 220 rpm, one aerobic reactor of 25 L (R3), and a submerged hollow fiber membrane ZeeWeed-10 (ZW10, Zenon Environmental Systems Inc., Oakville, ON, Canada) with a 40 nm nominal pore size. Nitrified activated sludge was recycled from R3 to R1 at twice the flow of the influent wastewater (Figure 1). The membrane ZW10 was operated at normal flow for about 9.5 min and backwashed for about 0.5 min. All pumps (feed, recycle and permeate)

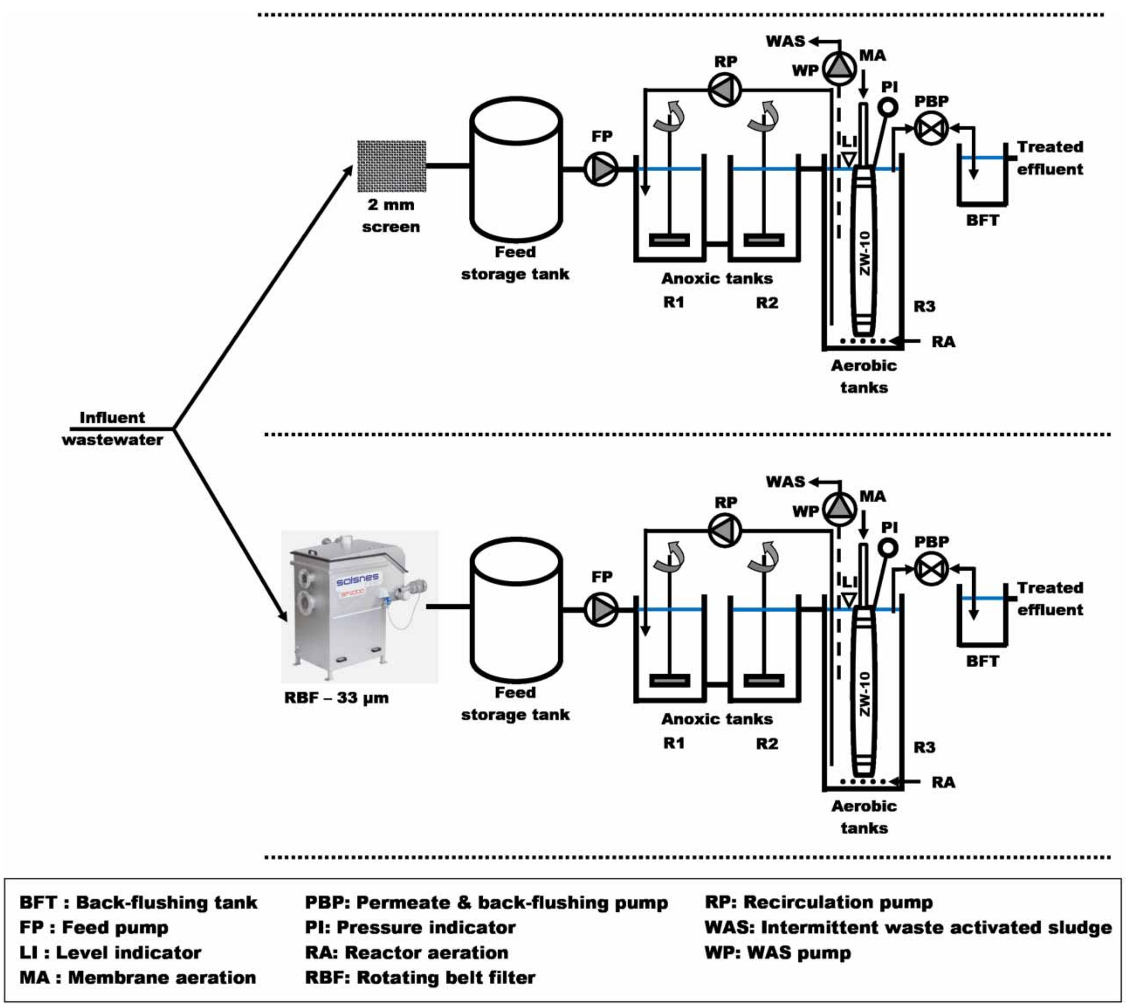

Figure 1 | Simplified flowsheet of the pilot-scale MBRs.

were controlled by a programmable logic controller (PLC). A pressure transmitter and a dissolved oxygen probe were also connected to the PLC to record continuously the transmembrane pressure (TMP) and dissolved oxygen (DO) in the aerobic reactor.

Operating parameters

The MBRs were operated at an influent flow rate of about 5 L/h and a recycle flow rate of 10 L/h. The hydraulic retention time was 9 h for both trains. The MLSS in the anoxic reactors was around 5 g/L, while the MLSS in the aerobic reactors were 7 g/L. The temperature of the reactors varied from 16 to 21 °C due to the seasonal variation of wastewater temperature and the room temperature at the WWTP. The pH in the three biological reactors was neutral throughout the study period for both MBR trains and the DO in the aerobic reactors were about 4 mg/L. The operating parameters of the MBR systems are summarized in Table 1.

Table 1 | MBRs operating parameters

Parameter	Train A (2 mm)	Train B (33 μm)
Feed flow (L/h)	5.2 ± 0.2	5.2 ± 0.2
Recirculation flow (L/h)	10.3 ± 0.3	10.1 ± 0.4
Permeate flow (L/h)	5.9 ± 0.2	5.9 ± 0.2
Backflush flow (L/h)	~12	~12
MLSS – R1, 2 (mg MLSS/L)	5,165 ± 1,021	4,724 ± 935
MLVSS – R1, 2 (mg MLVSS/L)	4,063 ± 729	3,176 ± 521
MLSS – R3 (mg MLSS/L)	7,196 ± 1,263	6,862 ± 1,188
MLVSS – R3 (mg MLVSS/L)	5,487 ± 945	4,877 ± 837
SRT (d)	13.7 ± 2.7	16.8 ± 3.3
Aerobic SRT (d)	8.7 ± 1.7	10.8 ± 2.0
C/N ratio (g TCOD/g TN)	12.4 ± 2.8	9.4 ± 2.3
C/N ratio (g sCOD/g TN)[a]	4.0 ± 1.1	3.9 ± 1.2
Temperature R1 (°C)	18.7 ± 2.3	18.6 ± 2.3
Temperature R2 (°C)	18.7 ± 2.4	18.6 ± 2.3
Temperature R3 (°C)	18.8 ± 2.4	18.7 ± 2.3
pH – R1	7.3 ± 0.1	7.3 ± 0.2
pH – R2	7.3 ± 0.1	7.3 ± 0.1
pH – R3	7.1 ± 0.2	7.0 ± 0.3
DO – R1, 2 (mg/L)	<0.02	<0.02
DO – R3 (mg/L)	3.8 ± 1.4	4.1 ± 1.2
Mixer speed R1 (rpm)	216 ± 33	216 ± 46
Mixer speed R2 (rpm)	226 ± 44	219 ± 40

[a]sCOD = soluble COD, measured after filtration through a 1.2 μm filter.

Analytical methods

Influent wastewater, filtrate from 33 μm belt filter and effluent from the pilot-scale MBRs were analyzed four to six times per week for TSS according to *Standard Methods* (APHA 2005). COD, nitrogen and phosphorus compounds were analyzed using the Dr Lange cuvette test kits and a DR 2500 UV-Vis Spectrophotometer (Hach Lange, Germany). The same analyzes were done for the samples taken twice per week from each biological reactor. Whatman GF/C glass fiber filters, with an average pore size of 1.2 μm, were used for filtration of samples and measurement of TSS. Temperature, DO and pH were measured daily in all biological reactors using a calibrated WTW multi-parameter meter, model 3420 (Weilheim, Germany).

RESULTS AND DISCUSSION

Rotating belt filter (RBF) performance

The 33 μm RBF filter removed about 42% of TSS, 33% of COD, 12% of the total nitrogen (TN) and 14% of the total phosphorus (TP). Ruiken *et al.* (2013) has determined that most of the solids removed by RBF (350 μm) were paper fibers. The main factors that could affect the filter performance were the influent wastewater characteristics, especially the particle size distribution, the filter mesh size and the hydraulic flow through the filter cloth, referred to as the filter rate (Rusten *et al.* 2017). When comparing the present performance to literature data, it must be noted that the RBF in the present study was operated without a filter mat on the belt. Belt filters of 350 μm were typically used in various WWTPs and with the right operating conditions, the belt filters could achieve very good pollutants removals (Franchi & Santoro 2015; Rusten *et al.* 2017). At the beginning of the operation, the filter act as a sieve removing only solids smaller than the belt size, but as the operation progresses, solids start to build up on the surface of the RBF forming a so-called 'mat' reducing the filter nominal pore size. Wet sludge retained on the filter cloth will be blown off the belt by an airknife mounted on the back of the filter as the belt rotates. In addition, scrapers and intermittent water spray could also be used to clean the filter (Rusten *et al.* 2017).

Biological process

The effect of the biological process can be evaluated through the degree of pollutants removals (%). Table 2 shows the concentration of pollutants in the influent and effluent wastewater, as well as the removal efficiencies in the two MBR trains. The removal efficiencies were determined by mass balance: first by calculating the average daily value for a given pollutant and then calculating the pollutants removal efficiencies based on the average values. As expected, the two MBR systems produced high effluent quality, free of particles and without contribution of particulate phosphate and nitrogen from the suspended solids due to the use of membrane as final solid–liquid separation.

The assessment of the performance of the MBR trains revealed that the removal efficiencies for different pollutants were the same. The two trains removed 94% of the COD, 80% of the TP and more than 70% of the TN. The performance of MBR varies from plant to plant but excellent pollutants removals were observed in several papers related to the treatment of municipal wastewater: 95–98% for COD and 80–84% for TN (Jiang *et al.* 2004; Lobos *et al.* 2006; Bracklaw *et al.* 2007; Galil *et al.* 2009). The effectiveness of the MBR systems can be affected by several factors such as MLSS concentrations to which the membrane modules were exposed, the operating temperature, DO levels, pH and organic loading rates (Johir *et al.* 2012). During this study, even though the organic load was reduced with a 33 μm RBF filter (Train B), the overall performance of the MBR system was not affected, as observed in Table 2.

Nitrogen removal

Conventional biological nitrogen removal is accomplished via autotrophic nitrification and heterotrophic denitrification. During aerobic nitrification, ammonium is first oxidized to nitrite by ammonia-oxidizing bacteria (AOB), and then oxidized into nitrate by nitrite-oxidizing bacteria (NOB). In anoxic denitrification, nitrates are reduced into nitrogen gas by denitrifying bacteria. During this study, all rates were adjusted to a temperature of 20 °C using a temperature coefficient of $\theta = 1.103$ for nitrification (Urbini *et al.* 2015) and $\theta = 1.07$ for denitrification (Rusten *et al.* 1995).

Full nitrification was observed in both MBR Trains. The nitrification rates were in the range of 0.65–1.75 (average ~1.12) mg NH_4-N/g MLVSS-h in Train A and between 0.67–1.82 (average ~1.21) mg NH_4-N/g MLVSS-h in Train B. According to this result, the nitrification rates were slightly higher in the MBR Train B receiving filtered wastewater. The difference might be due to the lower MLVSS concentration in Train B which was 4.88 g MLVSS/L compared to 5.48 g MLVSS/L in Train A. The removal of particulate COD during the primary treatment reduces the organic loading, thus reducing the concentration of the MLVSS in Train B. Furthermore, the higher sludge retention time (SRT) (16.8 d) in Train B might contribute to the higher rates as well. In biological process, a longer SRT can result in a higher nitrifying bacteria concentration, thus improving

Table 2 | Concentrations and removal efficiencies of the two MBRs

	Train A (2 mm)			Train B (33 μm)		
Parameter	**Feed (mg/L)**	**Effluent (mg/L)**	**Rem. (%)**	**Out RBF (mg/L)**	**Effluent (mg/L)**	**Rem.[a] (%)**
Total COD	522 ± 134	32.4 ± 7.2	**93.8**	349 ± 88	32.1 ± 7.5	**93.8**
sCOD	168 ± 47	29.7 ± 7.3	**82.3**	145 ± 35	29.1 ± 7.7	**82.7**
TSS	275 ± 99	0.27 ± 1.46	**99.9**	161 ± 69	0.04 ± 0.21	**99.9**
VSS	216 ± 67	0.00 ± 0.00	**100**	128 ± 53	0.00 ± 0.00	**100**
Total N	43.2 ± 12.0	11.3 ± 3.5	**74.2**	38.7 ± 11.8	11.3 ± 2.5	**74.2**
NH_4-N	31.5 ± 10.5	0.24 ± 0.74	**99.3**	30.1 ± 9.9	0.32 ± 1.37	**99.0**
NO_3-N	0.41 ± 0.15	8.63 ± 3.0	–	0.40 ± 0.15	10.0 ± 3.2	–
NO_2-N	0.03 ± 0.01	0.14 ± 0.22	–	0.03 ± 0.05	0.13 ± 0.19	–
Total P	4.26 ± 1.51	0.82 ± 0.62	**80.8**	3.70 ± 1.25	0.74 ± 0.55	**82.7**
PO_4-P	1.51 ± 0.60	0.57 ± 0.44	**62.3**	1.09 ± 0.65	0.55 ± 0.52	**63.6**

[a]The removal efficiencies in Train B were calculated based on the screened influent concentrations as the results take into account the overall removal efficiencies (RBF + biological process).

the nitrification. Long SRT applied in the MBR prevents nitrifying bacteria from being washed out of the system and nitrifiers are less endangered by fast-growing heterotrophs, which are better competitors for the ammonia nitrogen (Rittman & McCarty 2001).

The specific denitrification rates varied from 0.63–1.82 (average ~1.27) mg NO_x-N/g MLVSS-h in Train A, whereas the rates were between 0.75 and 2.41 (average ~1.50) mg NO_x-N/g MLVSS-h in Train B. The values were within the range of the specific denitrification rates (SDNRs) with internal carbon source found in literature (at 20 °C, $\theta = 1.07$), which were between 1.26 and 6.5 NO_x-N/g MLVSS-h (Zhao & Ma 2002; Kim 2004). The denitrification rate was slightly higher in the MBR treating filtered wastewater. The difference might be explained by the lower MLVSS concentration in the anoxic reactors in Train B (3.1 g MLVSS/L) compared to Train A (4.1 g MLVSS/L). Moreover, the highest denitrification rate was observed in Train B with a C/N ratio of 9.6 g TCOD/g TN (data not shown). This result confirmed the finding during the laboratory-scale SBRs, where the optimum C/N ratio upfront a biological process was around 9 g TCOD/g TN (Razafimanantsoa et al. 2014b). The C/N ratio required for complete nitrate reduction to nitrogen gas by denitrifying bacteria depends on the nature of the carbon source. Carbon limitation may result in incomplete denitrification and a concomitant accumulation of intermediate products, such as NO_2 and N_2O. Conversely, an excess of carbon constitutes an extra cost and will promote dissimilatory nitrate reduction to ammonia and the presence of carbon in the denitrified effluent (Carrera et al. 2004). Therefore, the C/N ratio should be properly controlled to achieve good nitrogen removal efficiency as it directly effects on functional microorganism populations.

Membrane performance

The performance of a membrane can be evaluated by monitoring the development of the TMP over time for a constant flux, which is in correlation with the fouling rate (Leiknes et al. 2006). The membrane ZeeWeed-10 was operated at constant flux. The permeate flux ranged from 5.8 to 7.0 LMH (~6.4 LMH) in Train A and between 5.7 and 6.6 LMH (~6.3 LMH) in Train B. Figure 2 shows the plot of the TMP against the influent TSS of both feeds. The average TMPs registered with the two membranes were 46 ± 9 mbar in Train A and 26 ± 7 mbar in Train B. It can be concluded that the fouling rate is higher during the treatment of coarse screened influent

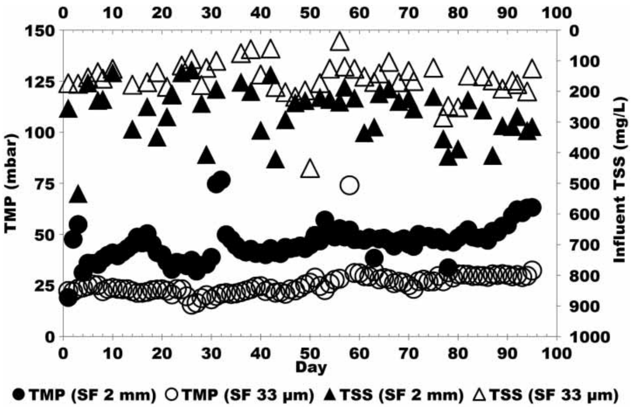

Figure 2 | Impact of suspended solids on TMP.

wastewater compared to the filtrate from 33 μm RBF. The latter removed about 40% of the influent TSS. Thus, reducing the organic load to the biological process will reduce the amount of new biomass produced, and consequently the amount of biological sludge produced. However, no chemical cleaning of the membrane was performed throughout the experiment as the TMPs were still well below 300 mbar, the maximum limit recommended by the membrane supplier.

Sludge production

In Train A, the overall sludge produced from the system was only composed of biosludge. It was about 21.3 g TSS/d. On the other hand, in Train B, the total sludge production is the combination of the sieve sludge and the biosludge. The biosludge production in Train B was only 16.4 g TSS/d. However, the total amount of sludge produced in Train B was about 46% higher compared to that of Train A because of the sludge removed with the RBF. The sludge yields were 0.36 g TSS/g COD and 0.43 g TSS/g COD in Train A and Train B, respectively. Both primary sludge and biological sludge could be used to produce methane (Appels et al. 2008). However, several studies showed that primary sludge contains higher biogas production potential (BMP) because its energy content has not yet been consumed. The biogas production could be increased up to three times depending on the primary separation methods (Ucisik & Henze 2008). Paulsrud et al. (2014) investigated the BMP of sludge from Salsnes Filter (sieve sludge) and sludge from conventional primary clarifier. The results showed that sieve sludge had higher volatile solids content and higher methane potential than primary sludge (345 NML CH_4/g VS versus 287 NML

CH_4/g VS). It has been observed in combined conventional activated sludge and anaerobic digestion (AD) processes that the nitrogen load increases when recycling the AD effluent back to the system. In such cases, one may consider removing less organic matter with the RBF during the primary treatment to have sufficient carbon source for the nitrogen removal. Tests done with laboratory-scale SBRs showed that similar nitrogen removal was observed in the reactors treating filtrates from sieve cloth openings of 33 μm and above (Razafimanantsoa *et al.* 2014b). Consequently, the right sieve cloth could be chosen depending on the AD effluent characteristics and the overall nitrogen load to achieve the optimal C/N ratio for nitrogen removal.

Oxygen demand

Energy demand, related to sludge transfer, permeates production and most significantly aeration, is a key cost factor when considering MBR technology (Henkel *et al.* 2011). The oxygen required for biological treatment depends on the influent biodegradable organic matter and biologically oxidizable nitrogen. During this pilot study, the oxygen demand in each MBR system was calculated according to the German design guidelines (ATV 2000). The average values of SRTs were 13.5 days for Train A (2 mm) and 16.8 days for Train B (RBF 33 μm). Using a ratio of COD/$BOD_5 = 2$ (ATV 2000) and a temperature of 19 °C, the specific oxygen demand for the removal of organic matter was 0.610 g O_2/g COD for Train A and 0.625 g O_2/g COD for Train B. The standard values of 4.3 g O_2/g N nitrified and 2.9 g O_2/g N removed were used to determine the oxygen demand for nitrification and the oxygen credit for denitrification, respectively. Overall, the aerobic reactor in Train A required about 0.41 kg O_2 per m^3 treated wastewater, although that of Train B required only 0.29 kg O_2/m^3. More oxygen was required in the MBR fed with coarse screened wastewater when compared to the MBR treating filtrate from 33 μm RBF. The MBR in Train A, operated without fine mesh sieve as primary treatment required 40% more air than Train B (with 33 μm RBF); and it was mainly due to the partial removal of the influent organic matter with RBF. Ruiken *et al.* (2013) evaluated the net energy demand of wastewater treatment (including sludge treatment and incineration) and found that the system using RBF as a primary treatment required 40% less energy compared to the system without primary treatment. Therefore, efficient particle removal could lead to a reduction of the overall energy consumption.

CONCLUSIONS

During this experiment, an RBF with 33 μm filter cloth was used as a primary treatment to biological wastewater treatment and its impact on the downstream MBR system was evaluated. The 33 μm filter allowed the removal of 42% of the TSS, which corresponded to 33% of the organic matter (expressed as COD), 12% of the TN and 14% of the total phosphorus (TP).

The assessment of the performance of the MBRs revealed that the MBR fed with filtered wastewater had similar removal efficiencies as the MBR operated without primary treatment. The two trains removed 94% of the COD, 80% of the TP and 74% of the TN. The nitrification rates were slightly higher in the MBR receiving filtered wastewater (Train B), with an average value of 1.21 mg NH_4-N/g MLVSS-h compared to 1.12 mg NH_4-N/g MLVSS-h in MBR control (Train A). The difference might be due to the lower MLVSS concentration in Train B. Furthermore, the higher SRT in Train B might contribute to the higher rates as well. The specific denitrification rates varied from 0.63 to 1.82 mg NO_x-N/g MLVSS-h in Train A, whereas the rates were between 0.75 and 2.41 mg NO_x-N/g MLVSS-h in Train B. The average denitrification rate was slightly higher in the MBR treating filtered wastewater. The difference might be explained by the lower MLVSS concentration in the anoxic reactors in Train B (3.1 g MLVSS/L) compared to Train A (4.1 g MLVSS/L).

The result also showed that the fouling rate of the membrane, evaluated through the change of TMPs, was reduced to nearly half in the MBR fed with RBF 33 μm (Train B) compared to the system without fine mesh filter (Train A). The average TMPs registered with the two membranes were 46 ± 9 mbar in Train A and 26 ± 7 mbar in Train B. No cleaning of the membranes was required during the test.

The total amount of sludge produced in Train B was about 46% higher compared to that of Train A because of the sludge removed with the RBF filter. The biological sludge yields were 0.36 g TSS/g COD and 0.43 g TSS/g COD in Train A and Train B, respectively. Both primary sludge and biological sludge could be used to produce methane.

The aerobic reactor in Train A required about 0.41 kg O_2 per m^3 treated wastewater, although that of Train B required only 0.29 kg O_2 per m^3. More oxygen was required in the MBR fed with coarse screened wastewater when compared to the MBR treating filtrate from 33 μm RBF. The reduction was about 30% and it was mainly due to the partial removal of the influent organic matter with RBF. Overall, the use of RBF 33 μm as a primary treatment was beneficial for the downstream biological process.

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