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Performance of commercial membranes in a side-stream and submerged membrane bioreactor for model textile wastewater treatment

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ABSTRACT

Membrane bioreactor (MBR) is one of the last techniques that allow a high quality of treated industrial effluents, which can be perfectly integrated into industrial processes, not only for the quasi-total reuse of water but also for the reduction of the manufacturing cost. The main objective of this work was to make a study, comparing the performance of commercial membranes in a side stream membrane bioreactor (SSMBR) and submerged membrane bioreactor (SMBR), at laboratory scale, for the treatment of the same Model Textile Dye Wastewater (MTDW). In order to reach the target, we kept the same operating conditions for both of the units SSMBR and SMBR, namely pH, temperature, conductivity, and MLSS, whereas the hydraulic retention time (HRT) was different. This is due to the reactors capacities and the membrane module surface being different (20 L/0.00856 m^2 and 57 L/0.33 m^2) for side-stream and submerged MBR, respectively. The COD removal efficiency was varied between 90 and 97%, respectively, and color rejection was found in the range of 20–40% for red dye and 50–90% for blue dye in both units. In order to improve the wastewater quality, a nanofiltration membrane (NF) was tested in the SSMBR unit and still has to be tested in the SMBR.

Keywords: Side-stream membrane bioreactor; Submerged membrane bioreactor; Model textile dye wastewater; Ultrafiltration; Nanofiltration

1. Introduction

Due to increasing water scarcity in many regions worldwide, water reuse is becoming more important. Therefore, the purpose of wastewater treatment is not only to remove pollutants that can harm the aquatic environment but also demands to comply with the required water quality standards for their reuse. Particularly in the MENA countries (Middle East North Africa), textile industry is an important and rapidly growing industrial sector [1]. Textile industry is a water-intensive sector and hence leaves a large water footprint on our planet [2]. The majority of water usage in the textile supply chain occurs in the raw materials and processing stages such as dyeing,

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preparation, and finishing [3]. The finishing of textiles alone can require up to 700 L of freshwater per 1 kg of textile [4]. Pollutants in wastewater from textile factories can vary greatly and are typically characterized by high amounts of persistent chemicals, for example, dyes. Hence, textile wastewater reflects a serious environmental and public health concern. Membrane technology is a very promising technology that offers the possibility to improve the quality of the wastewater. In particular, membrane bioreactor (MBR) technology has very good prospects. MBR is the combination of conventional activated sludge process with microfiltration and ultrafiltration membranes for solids separation. Complete solids removal, a significant physical disinfection capability, very high degree of carbon, nitrogen compounds, and color removal are the main advantages of MBR processes, which result in very high quality of treated water for further reuse [5,6].

Therefore, MBR technology is an attractive option for the treatment and reuse of industrial wastewaters from various industries including food processing, pulp and paper, chemical production, pharmaceuticals, mining and metal production, and textile.

The performance of MBR technology for treatment and reuse in textile industry has been studied in several research works.

Schoeberl et al. studied optimization of operational parameters for a submerged membrane bioreactor treating dye house wastewater [7]. The experimental study has been performed using a tubular membrane module (pore size 0.4 μm) immersed in a 60-L aerated activated sludge tank treating dye house wastewater. They optimized parameters such as suction pressure and back flush time, as well as aeration intensity in order to minimize fouling propensity. COD removal efficiency was between 89 and 94%, and the color removal was between 65 and 91%.

Brik et al. investigated its capability to achieve a water quality meeting reuse criteria with a laboratory-scale MBR which was fed with textile wastewater originating from a polyester finishing mill [8]. COD removal efficiency was found to vary between 60 and 95%. Color removal was above 87% for all wavelengths examined. However, in order to reuse MBR-treated wastewater, additional polishing steps have to be considered since the MBR permeate did not comply with the required water reuse standards [8]. In this regard, an NF membrane was suggested in order to further upgrade water quality.

Zheng and Liu tested a laboratory-scale membrane bioreactor (MBR) with a gravity drain for dyeing and printing wastewater treatment from a wool mill [9]. The MBR was operated with continuous permeate flow by gravity and without chemical cleaning for 135 d. The findings showed that excellent effluent quality could meet the reuse water standard in China. The average removal rates of COD, BOD_5, turbidity, and color were 80.3, 95.0, 99.3, and 58.7%, respectively [9].

Yigit et al. investigated the performance of a pilot-scale MBR with submerged hollow-fiber membranes for the treatment of a highly concentrated mixed wastewater from wet processes (dyeing, finishing, and sizing) of a denim producing textile industry [10]. The findings indicate that complex and highly polluted denim textile wastewaters could be treated very effectively by MBR systems [10]. Color values from as high as 8,100 Pt Co levels were significantly reduced to about 50 Pt Co levels indicating that MBR effluent could be reused in the production processes [10].

Huang et al. used a submerged hollow-fiber membrane bioreactor (MBR) with a capacity up to 400 L/d for treatment of dyeing wastewater from a printing and dyeing factory in Changzhou, China [11]. The pilot-scale MBR was operated continuously for 100 d, and the removal ratio of COD achieved was 90%. The removal efficiencies for NH_3-N and color were 90–95 and 60–75%, respectively. However, the color removal efficiency was not enough in order to directly reuse the MBR permeate, and hence, further treatment is necessary [11].

The literature review showed that MBR in textile industry suffers from fouling like any other MBRs published [12]. In general, membrane fouling is regarded as the most important bottleneck for further development of MBR technology. It is the main limitation for faster development of this process particularly when it leads to flux losses that cleaning cannot restore [12]. Furthermore, state-of-the-art MBRs treating textile effluents in many cases cannot comply with water reuse standards mainly due to high color of the permeate. This can be attributed to the low-molecular weight of persistent dyes which can pass through MF and UF membranes.

The objective of this work is to compare the performance of commercial membranes, namely UF and NF in two laboratory-scale reactors a side-stream (SSMBR) and a submerged MBR (SMBR). In order to keep the feed water quality constant, a model water representing typical textile wastewater has been developed based on different publications. This work is considered as a preliminary step before testing novel membranes with an antifouling coating which have been developed at the Institute of Membrane Technology (ITM), Cosenza, Italy. The subsequent studies will be taking the findings of this work as benchmarking for further studies in pilot-scale submerged MBRs.

2. Materials and methods

2.1. Experimental rig

A brief description of the compact laboratory-scale bioreactors, side stream, and submerged unit, where the experiments were performed, is given below.

2.1.1. Side stream unit membrane bioreactor (SSMBR)

Commercial UF and NF membranes from company Microdyn-Nadir, Germany (see Table 4) have been tested in a sidestream flat-sheet filtration unit named "BIOSTAT® C-DCU" provided by the company Sartorius AG as shown in Fig. 1(a). The unit is composed of the following:

(1) A digital control unit (DCU) includes process measurements, calibration routines, and a standard set of control loops. The DCU is operated using a graphical interface on a flat panel touch screen.
(2) A jacketed stainless steel tank (1) (working volume up to 30 L) with mass flow controlled aeration (3) and an air inlet filter (4) on top were used to ensure that the air is free of dust and oil, an impeller for homogenous mixing of the sludge, a feed pump which is controlled by weight sensor. Air mass flow is controlled by a dissolved oxygen sensor (pO_2), and temperature is controlled by a thermostat, while a turbidity sensor determines the sludge density. Temperature (T), pH, and electrical conductivity (Cond) are measured as well.
(3) The cross-flow flat-sheet filtration unit (membrane area 0.00856 m^2) is fed by a frequency controlled recirculation pump. The permeate is drained, and the concentrate is returned into the tank from which flow rate can be adjusted. Due to failure of the permeate flow sensor, all permeate flow data were measured manually with a stopwatch and measuring cylinder. The transmembrane pressure (TMP) was calculated from feed (P_1), concentrate (P_2), and permeate pressure (P_3):

$$\mathrm{TMP} = (P_1 + P_2)/2 - P_3 \quad (1)$$

2.1.2. Submerged membrane bioreactor unit (SMBR)

A MBR pilot plant with a flat-sheet membrane module (see Table 4) from company Microdyn-Nadir, Germany, submerged in the reactor was used in this experiment. The active volume of the reactor was 57 L. Fig. 1(b) shows a schematic diagram of the MBR pilot plant. The module consists of 3 flat-sheet

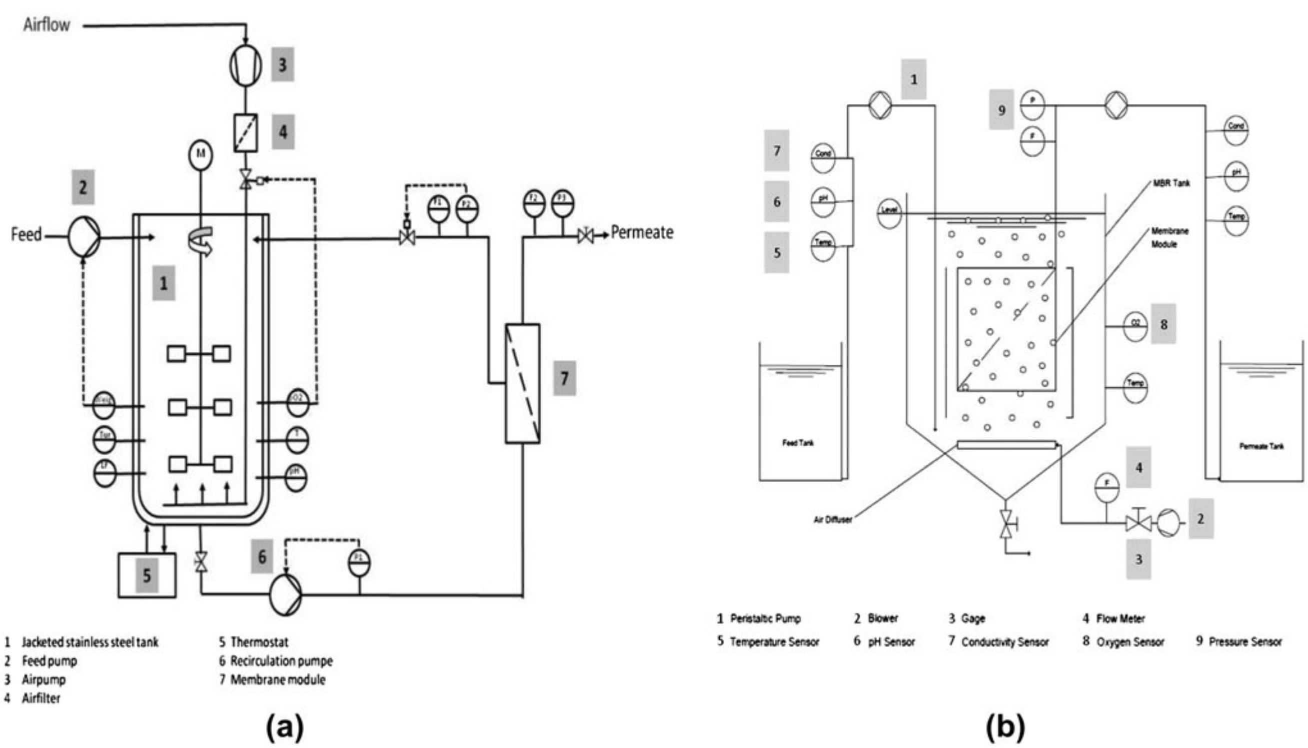

Fig. 1. Schematic representation of laboratory MBR (a) side-stream and (b) submerged.

membranes, each of these having $0.11\ m^2$ of area giving a total area of $0.33\ m^2$. The membrane module was equipped with a mechanical aerator at the bottom of the module cassette and a permeate suction channel in the middle of the cassette. Air was supplied by a compressor. Water level and foam were controlled by level and foam sensors, respectively, and transmembrane pressure (TMP) was recorded by a pressure sensor. Feed was supplied by a feed pump. Some other sensors were installed to measure pH, conductivity, temperature of feed and permeate. All the process parameters were monitored, and data were stored by LabVIEW program controlled computer system.

2.2. Model Textile Dye Wastewater

In order to keep the feed wastewater quality constant, a Model Textile Dye Wastewater (MTDW) was developed as test media because the composition of real textile dye wastewater changes over the time and season of the year (Table 1). The MTDW was developed by Deowan et al. [13], and it is mainly based on a blue antraquinone reactive dye (Remazol Brilliant Blue R) and on a red azo dye (Acid Red 4) which represent typical industrial dyes widely applied in textile industry (Figs. 2 and 3). Besides glucose added as C-source, a typical industrial detergent (Albatex DBC) was used along with the following salts: NaCl, $NaHCO_3$, and NH_4Cl (N-source). The chemical oxygen demand (COD) is one of the key parameters since it determines the wastewater strength. In this work, the chemical components were selected in such a way that the COD value remains close to 2,400 mg/L which is typical in textile factories [13]. Tables 1 and 2 below summarize the composition and the characteristics of the applied Model Textile Dye Wastewater (MTDW).

Different characteristics of the two dyes used in this MTDW, namely Acid Red 4 and Remazol Brilliant Blue R, are listed in Table 3. It is important to highlight that besides different chemical composition, the choice of these two dyes depends on the difference of their maximum absorbance wavelength in order to facilitate analysis by photospectrometer.

Table 1
Composition of Model Textile Dye Wastewater (MTDW)

No.	Dyestuff and chemicals	Concentration (mg/L)
1	Remazol Brilliant Blue R	50
2	Acid Red 4	50
3	NaCl	2,500
4	$NaHCO_3$	1,000
5	Glucose	2,000
6	Albatex DBC (detergent)	50
7	NH_4Cl	300

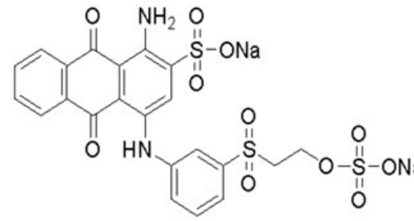

Fig. 2. Structure of Remazol Brilliant Blue R.

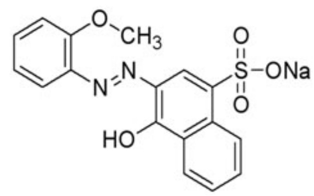

Fig. 3. Structure of Acid Red 4.

Table 2
Characteristics of Model Textile Dye Wastewater (MTDW)

Parameters	Measured values[a]
pH	7.5 ± 0.5
COD (mg/L)	2,367 ± 125
BOD_5 (mg/L)	731 ± 80
Total-N (mg/L)	78 ± 8
Conductivity (mS/cm)	6.6 ± 0.15

[a]Average values and standard deviation.

Table 3
Characteristics of Acid Red 4 and Remazol Brilliant Blue R

Characteristic	Acid Red 4	Remazol Brilliant Blue R
Maximum absorbance wavelength (nm)	505	595
Molecular weight (g/mol)	380.4	626.5
Empirical formula	$C_{17}H_{13}N_2NaO_5S$	$C_{22}H_{16}N_2Na_2O_{11}S_3$

2.3. Spectrophotometer method

The concentration of the red and the blue dyes, in the feed and the permeate solution, was analyzed by the use of spectrophotometer (Model: UV-1800) from Shimadzu (Japan). The wavelength of maximum absorbance for the red and the blue dyes was found as 505 and 595 nm, respectively (Table 3). A calibration routine based on Beer's Law was used to calculate the concentration from absorbance.

2.4. COD measurement

All COD values were analyzed with COD cell tests (Method 1.14541) from Merck KGaA (Germany), where the range of measurement is 25–1,500 mg/L of COD. According to the COD product brochure, the coefficient of variation (% standard deviation) is supposed to be ±0.68% [14].

2.5. N-compounds

For all the samples collected from the side stream and the submerged unit, the N-compounds measurement has been realized as described below:

Total-N

The total-N has been determined by TOC-L CHP/CPN analyser (Shimadzu, Japan).

NH_4^+-N

All NH_4^+-N analyses have been conducted with cell tests (Method: 1.14558) from Merck KGaA (Germany). The measuring range of this method is 0.2–8 mg/L. The product brochure indicates a standard deviation of ±1.0% [14].

NO_3^--N

All NO_3^--N analyses have been conducted with cell tests (Method: 1.14542) from Merck KGaA (Germany). The measuring range of this method was 0.5–18 mg/L, with a standard deviation of ±1.5% indicated on the product brochure [14].

2.6. Membranes

The aim of this study was to compare the performance of commercial membranes (UF and NF from the company MICRODYN-NADIR GmbH) [15] while tested in two different MBR units, side stream and submerged. Table 4 shows the technical data of the commercial membranes. It has to be mentioned that in this work, the NF membrane has been tested only in the SSMBR unit, since a three-envelope module is not available from the Microdyn-Nadir Company.

Table 4
Technical data of UF and NF membranes from the company Microdyn-Nadir [15]

Technical data	UF membrane	NF membrane
Active layer	PES	PES
Support layer	PET	PES
MWCO (kDa)	150 kDa	1 kDa
Pore size (μm)	0.04	–
Water permeability (L/(m^2 h bar))	>280	>5

3. Experimental results

The MBR experiments were started only after having the microorganisms acclimated with the feed conditions (1 month). Subsequently, tests were carried out continuously investigating a variety of parameters mainly COD, TOC, pH, TMP, MLSS, HRT, flux, color rejection, conductivity, dissolved oxygen, and N-compounds. The operating conditions are summarized in Table 5.

The test duration for each membrane in the side stream unit was on average 15–30 d which can be considered a short period with respect to usual test periods in MBRs. However, the reason is that this work is considered as a first step for future research using novel membranes (with antifouling coating) in order to select the best membrane in terms of permeability, COD, and color rejection, so as to subsequently test them in the long-term, with a laboratory-scale submerged MBR unit. These trials were carried out at the Karlsruhe University of Applied Sciences within another study [13,16].

As shown in Table 5, the hydraulic retention time (HRT) for all experiments carried out in the side

Table 5
Operating conditions of MBR

Parameter	Side stream	Submerged
Temperature (°C)	20 ± 2	20 ± 2
TMP (bar)	0.3–0.5	0.03–0.05
pH feed	7.5 ± 0.5	7.5 ± 0.5
pH effluent	8 ± 0.5	8 ± 0.5
Permeate flux (L/(m^2 h))	5–15	2–4
HRT (h)	145–400	40–90
F/M ratio (g COD/g MLSS d)	0.02–0.06	0.05–0.1
MLSS (g/L)	6–8	8–12

stream unit is higher compared to the HRT within the submerged unit. This was due to the difference in membrane area of filtration with respect to the bioreactor tank volume (0.00856 m^2 for the side stream beside 0.33 m^2 for the submerged MBR). Also, the objective of this work lies in maintaining comparable conditions in order to select the best membranes, so that they can be subsequently studied under more practical conditions with a submerged MBR unit.

In order to consider any potential changes with the activated sludge, the same commercial UF membranes have been tested repeatedly throughout the experimental series (named as UF1, UF2, and UF3). For the nanofiltration membrane, the tests have been conducted only with one membrane in the side stream MBR unit.

Only permeability, COD, color rejection, N-compounds, OLR, and F/M ratio will be presented in this study.

3.1. Permeability

Permeability in L/(m^2 h bar) can be defined as the flux divided by the respective applied transmembrane pressure (TMP) under the operating conditions (Table 5). The permeability of the commercial UF membranes tested in the side stream unit was in the range of ca. 20–28 L/(m^2 h bar), except the UF1 that shows some fluctuations due to the acclimation period, whereas it was lower around 18 L/(m^2 h bar) for the NF membrane, due to the denser structure of the active layer of NF membrane in comparison to the UF (Figs. 4a). It can be seen from Fig. 4a that the UF membranes typically show a transient phase in which the permeability is reduced and subsequently achieving constant values. This reduction might be due to the pore swelling of the UF membrane, whereas the commercial UF membranes tested in the submerged MBR showed a permeability average of around 60–80 L/(m^2 h bar) with several cleanings and the membrane has been replaced twice, as shown in Fig. 4b. In order to study the effect of the aeration rate on the permeability, the airflow was reduced after day 33 from 1 to 0.5 m^3/h which did affect the permeability rate. However, from day 53 after having reduced the aeration down to 0.25 m^3/h, the permeability dropped to 20 L/(m^2 h bar). From day 70, the aeration rate was readjusted to 1 m^3/h, and consequently, the previous permeability rate was regained.

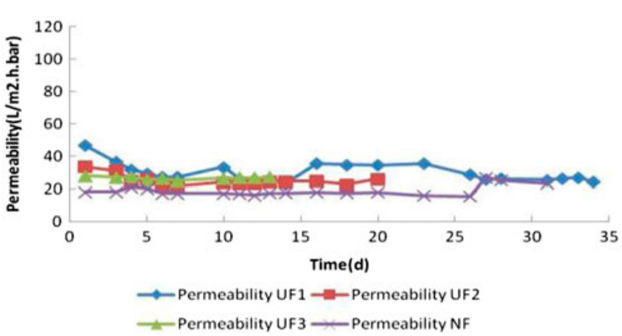

Fig. 4a. Water permeability of commercial membranes in the SSMBR unit.

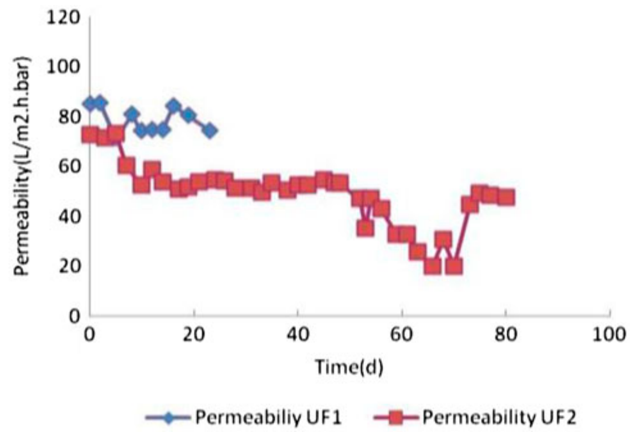

Fig. 4b. Water permeability of commercial membranes in the SMBR unit.

The water permeability obtained from this experiment is in line with the water permeabilities reported in different publications. Yigit et al. obtained a permeability of 55–70 L/(m^2 h bar) at a TMP of 0.14—0.56 bar in a submerged hollow-fiber UF (0.04 μm) MBR module (ZW®—10) treating denim producing textile wastewater in a no extra sludge removal operation system [10]. As it is reported by Huang et al., it also obtained a permeability of 40–80 L/(m^2 h bar) at TMP of 0.05—0.1 bar with a submerged hollow-fiber MF (0.2 μm) MBR module treating dyeing wastewater [11]. The NF membrane of this work was tested only in the side stream unit. However, is planned for future work in the submerged MBR unit.

3.2. COD removal

COD is considered as one of the main parameters to define the performance of an MBR system in terms of biodegradability. Regarding COD removal efficiency got within the side stream MBR, no significant difference could be noticed between all the commercial UF (UF1, UF2, and UF3) membranes. After the initial period, COD removal efficiency fluctuates typically between 93 and 95% (Fig. 5a). However, the NF membrane shows the highest removal efficiency up to 97% which can be explained by the denser structure of this membrane compared to UF membranes. It is known that performance of a MBR reactor is actually an interplay between rejection of the membrane and biodegradation by the activated sludge system.

Moving to the commercial membranes tested in the submerged MBR unit as shown in Fig. 5b, the COD removal efficiency was around 92–95%, except for some fluctuations during the final phase caused by the lower aeration rate applied starting from day 53 until day 70 of the experiments, that causes stress for the biological culture, proving that bacteria have been struggling from low aeration. Consequently, there was no significant difference between the COD removal efficiency of the side stream and the submerged MBR unit.

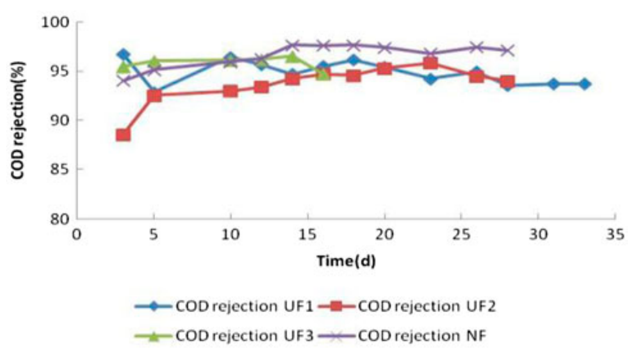

Fig. 5a. COD removal efficiency of commercial membranes in the SSMBR unit.

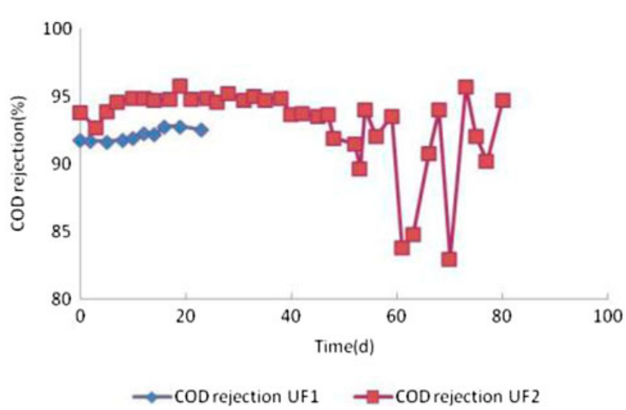

Fig. 5b. COD removal efficiency of commercial membranes in the SMBR unit.

3.3. Color rejection

The color concentration was measured via spectrophotometer and calculated based on Beer's law by calibration curves (see Section 2.3). As shown in Figs. 6a and 6b, the average reduction rate of the red was between 20 and 50% for both MBR units. Among the tested membranes, the NF has the highest rejection. The red rejection obtained from the UF1 is more or less fluctuating and cannot be considered, since UF1 is the 1st membrane used during acclimation period, where the sludge concentration was still lower than the one in the feed. Since the molecular weight of the red dye is only 380 g/mol (see Table 3), it is not expected to be rejected neither by the UF nor by the NF membrane (MWCO: 1 kDa, see Table 4). However, previous experimental studies with the same MTDW which have been done in a flat-sheet cross-flow cell showed a red dye rejection of about 25%. This might be attributed to a charge exclusion effect since the PES membrane surface is negatively charged and the red dye also has negative charge (Fig. 3). Since we lowered the aeration rate up from day 53 within the submerged unit, the red rejection increased. The reason is that the red dye is an azo dye and is better decomposed under anoxic than aerobic conditions (Fig. 6b).

Regarding blue dye removal, the rejection rate was generally higher than the red dye (Figs. 7a and 7b). Rejection averaged 50–60% for the UF. Among the tested membranes, rejection for the NF is outstandingly high achieving almost 90%. This can be attributed to the dense nature of the membrane (MWCO: 1 kDa) compared to the UF membranes and the molecular weight of the blue dye (627 g/mol) being significantly higher than the red dye. Experiments carried out in a flat-sheet cross-flow cell with MTDW showed blue dye rejection of approximately 45%. As for the red dye, this could be also attributed to the

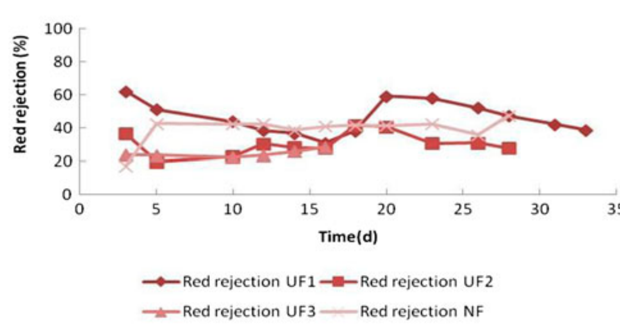

Fig. 6a. Red dye rejection of commercial membranes, in the SSMBR unit.

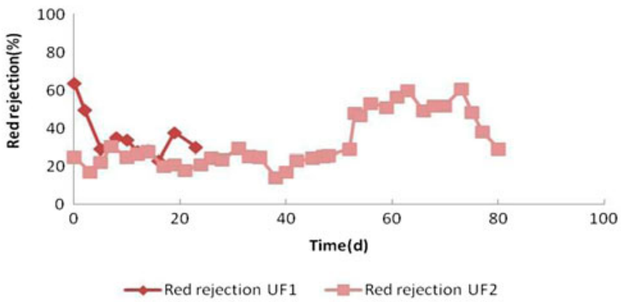

Fig. 6b. Red dye rejection of commercial membranes, in the SMBR unit.

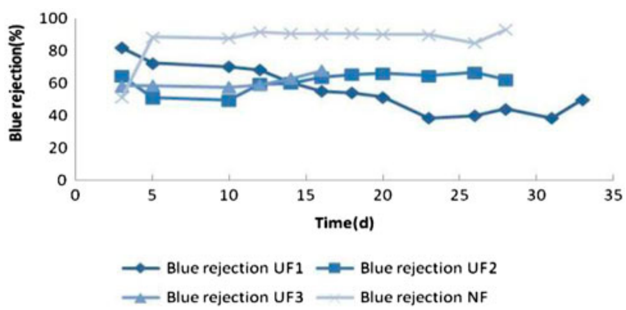

Fig. 7a. Blue dye rejection of commercial membranes in the SSMBR unit.

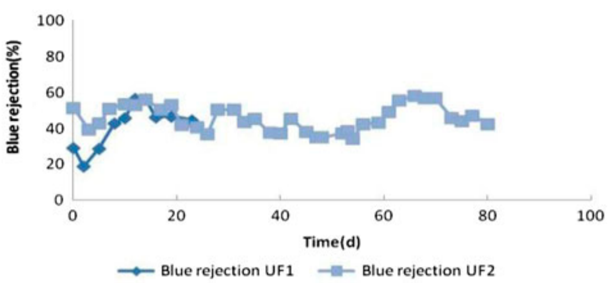

Fig. 7b. Blue dye rejection of commercial membranes in the SMBR unit.

charge exclusion effect since the blue dye molecule is also negatively charged (Fig. 2).

3.4. N-compounds

To obtain the nitrogen (N) balance, the nitrogen content in permeate in terms of Total-N, NH_4^+-N, and NO_3^--N was analyzed. The main sources of nitrogen (N) were mainly NH_4Cl as well as to smaller extend the red and blue dyes used in MTDW.

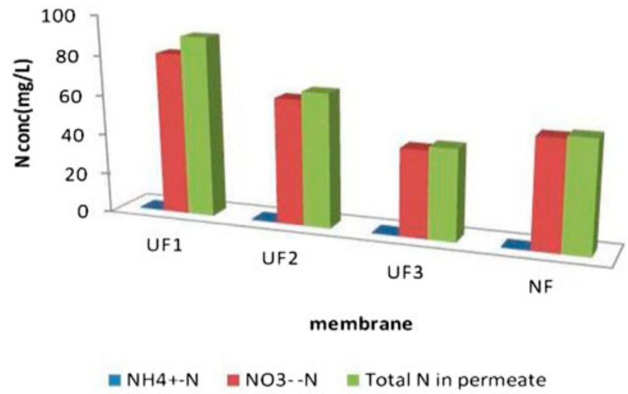

Fig. 8a. N-compounds in permeate for the SSMBR unit.

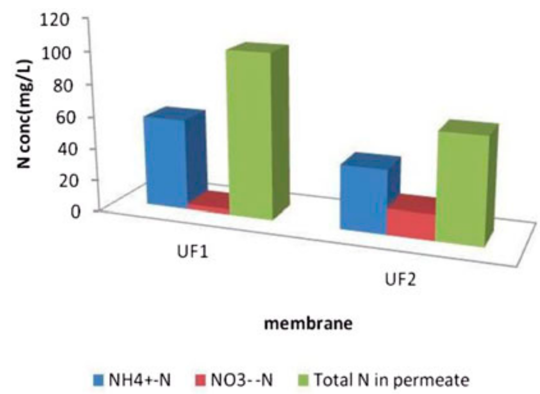

Fig. 8b. N-compounds in permeate for the SMBR unit.

A complete nitrification has been noticed during the whole experimental time for all the tested membranes in the side stream MBR unit as shown on Fig. 8a.

Regarding the N-balance for the samples from the submerged MBR unit, the Total-N contents in the feed (MTDW) were lower than the Total-N contents in the permeate as shown on Fig. 8b (also see Table 2). This can be explained by nitrogen (N) accumulation in the biological sludge during the conversion to NO_3^--N, or remaining from the previous phases and released during the final phase. In addition, only incomplete nitrification occurred for the submerged MBR trials. This could be explained by the inhibitation of nitrification bacteria which needs to be further studied.

3.5. Organic loading rate

Organic loading rate (OLR) is an important design and controlling parameter in biological wastewater treatment process. It is measured by the amount of food provided to a unit amount of biomass (or reactor volume) for a unit period of time. The OLR is also an important parameter which indicates how many kilograms of organic dry solids is loaded per m^3 of digester volume and unit of time [17]. The OLR is important for the plant components (especially mixer/agitator) and for the biocenosis, and if the OLR is too high (over 4.0 kg COD/m^3 d [17]), the overall performance of the system could be hampered due to the overload that stresses the bacteria, by too much feeding. Consequently, the digestion process may stop completely. The OLR for both units the SSMBR and the SMBR is similar and typically between 0.3 and 0.8 kg COD/m^3 d as shown on Figs. 9a and 9b. It is only lower than 0.3 kg COD/m^3 d due to lower flux. The flux was reduced for the NF membrane due to denser structure of the membrane and for the UF2 in the SMBR due to lower aeration rate.

3.6. Food to microorganism F/M ratio

Typically, MBR runs at lower F/M ratio than conventional-activated sludge (CAS) process in order to mitigate membrane fouling and maintain high oxygen transfer efficiency. The preferred F/M ratio range in MBR is approximately a third to a half of that in CAS. Food–to-microorganism (F/M) ratio is one of the most fundamental control parameters for the activated sludge process. This is the relationship between load of COD fed into the tank and the bacteria population in the tank and is given in (g COD/g MLSS d), as it is shown in Figs. 10a and 10b. The F/M ratio for the UF membranes applied in the SSMBR is typically between 0.04 and 0.06 (g COD/g MLSS d) with some fluctuations for UF1 attributed to the acclimation period, but it can be seen clearly that the UF2 and UF3 had the same F/M ratio since the conditions were more or less stable and the bacterial population got used to the system. The F/M ratio for the NF is significantly lower than the F/M ratio for the UF membrane due to lower water flux. The F/M ratio of the SMBR, showed an average of 0.05–0.09 (g COD/g MLSS d) exept for the period after day 56, when the F/M ratio dropped to 0.02 (g COD/g MLSS) due to lower flux. In general OLR values of this work are close to those obtained by Wu et al. [18] in a full-scale MBR operation treating TFT–LCD (thin film transistor–liquid crystal display) wastewater with high strength of organic.

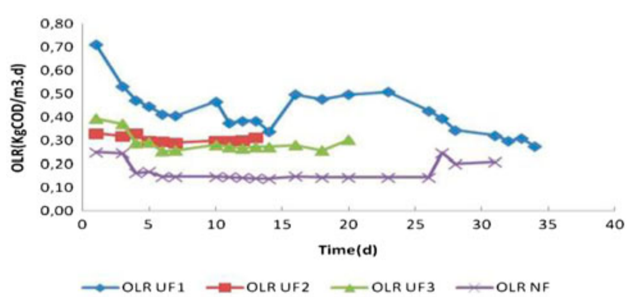

Fig. 9a. OLR for the SSMBR unit.

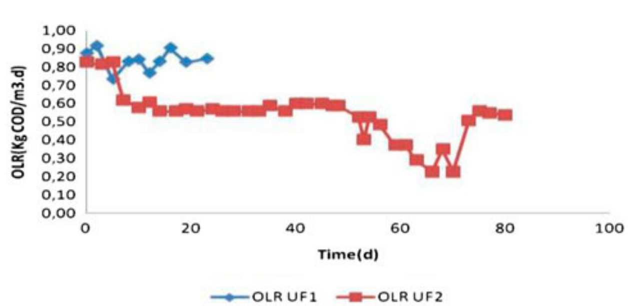

Fig. 9b. OLR for the SMBR unit.

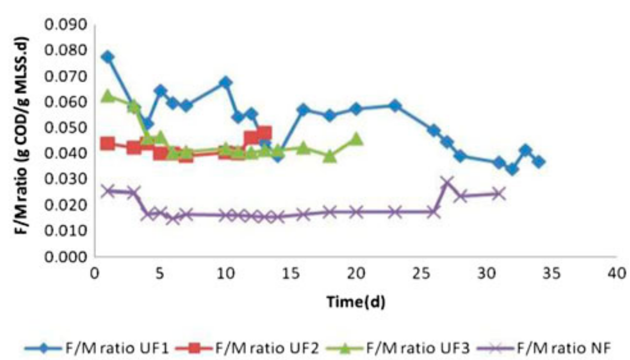

Fig. 10a. F/M ratio for the SSMBR unit.

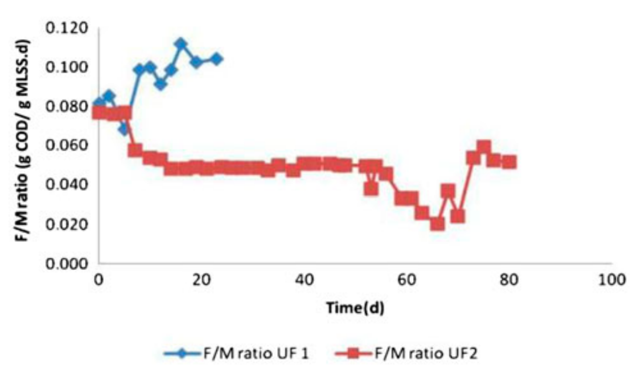

Fig. 10b. F/M ratio for the SMBR unit.

4. Conclusion

The comparison of the performance of the commercial UF, while tested in two different MBR units, showed constant water permeability for all tested membranes, with an average of 25 L/(m^2 h bar) and 80 L/(m^2 h bar) for side stream (SSMBR) and submerged MBR (SMBR), respectively. Only at the beginning phase, the water permeability was more or less fluctuating, due to the acclimation period. It is important to highlight that the NF membrane within the side stream unit showed lower permeability around 18 L/(m^2 h bar) due to the higher density of the active layer in comparison to the UF.

The experiments showed a very high and relatively constant COD removal efficiency under various operating parameters (90–97%). All commercial membranes showed a similar rejection of 20–40% for the red model dye; Acid Red 4. Rejection of the blue model dye (Remazol Brilliant Blue R) was generally higher (50–60%) whereas being significantly higher for the commercial NF (approximately 90%). The analysis of the N-balance results showed that a complete nitrification took place in the side stream unit, whereas in the submerged unit, the nitrification rate was significantly lower. Among the commercial membranes, the NF showed higher COD and color removal efficiency compared to the UF membranes, however, at the cost of lower water permeability. However performance of the NF membrane in the long term proved to be an interesting option since it offers higher removal efficiency for low-molecular weight compounds. In a later phase, similar experiments under anaerobic condition using the same membranes will be studied, where the overall aim is to realize a combined anaerobic/aerobic process for textile wastewater treatment.

Based on the previous experience using the commercial MBR Microdyn-Nadir membrane for the treatment of real industrial wastewater, the cost is estimated to be around €0.3/m^3 of treated water considering permeate flux 10–15 L/(m^2·h). This cost goes up when the volume of treated water is significantly less, for example, on laboratory-scale treatment. In this study, the treated wastewater volume compared to the real-field industrial scale treatment is significantly lower and the flux is lower as well especially for the submerged MBR (2–4 L/m^2 h) which might drive the treatment cost higher. Since the ultimate target of the experiment was to test different kind of membranes in submerged and side-stream MBR to select the best membrane for upcoming submerged MBR experiment, cost factor for submerged MBR has been emphasized. The flux of the submerged MBR in this study is roughly one third of that mentioned by membrane producer. So, the cost of treated water for the experiment can be considered 3 times higher which makes €0.9/m^3 of treated water. However, in order to get a more viable cost estimate for this process, larger pilot-scale trials applying these commercial membranes in MBR need to be conducted.

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