



# Design and testing of a pilot-scale submerged membrane bioreactor (MBR) for textile wastewater treatment

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## Abstract

The objective of this paper is to deal with the design of a pilot-scale submerged membrane bioreactor (MBR) and a short-term functionality test to be performed with textile wastewater. The design calculations were done based on the design parameters analysed from local textile wastewater and typical values of activated sludge kinetic coefficients. Other process parameters like bioreactor volume (tank size), hydraulic residence time (HRT), biomass loading ( $F/M$  ratio), oxygen demand, etc., were calculated depending on the real textile wastewater characteristics. Taking the design basis into consideration, a pilot-scale MBR was constructed equipped with LabVIEW programme- and sensors-controlled computer system. Based on the theoretical calculations, the hydraulic volume of the MBR reactor was around 56.6 L with flat sheet membranes (3 sheets, with 25 cm × 25 cm dimensions of each sheet) with HRT of 16.9 h. Finally, performance tests for 6 weeks were carried out in a local (Darmstadt, Germany) laundry textile wastewater to test the functionality of MBR pilot plant. Under the operating conditions of 250 mbar suction pressure and 12 g/L of MLSS, the COD removal efficiency was around 90% for 800–3500 mg/L inlet COD fed to the membrane bioreactor.

**Keywords** MBR · Design · Wastewater · Test · Reuse

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## Introduction

Membrane bioreactor (MBR) technology is a combination of the conventional biological sludge process, a wastewater treatment process characterized by a suspended growth of biomass, with a micro- or ultrafiltration membrane system (Judd 2006, p. 55). The biological unit is responsible for the biodegradation of the waste compounds and the membrane module for the physical separation of the treated water from the mixed liquor. The pore diameter of the membranes is in the range between 0.01 and 0.1  $\mu\text{m}$  so that particulates and bacteria can be kept out of permeate and the membrane system replaces the traditional gravity sedimentation unit (clarifier) in the biological sludge process. Hence, the MBR offers the advantage of higher product water quality and low footprint. Due to its advantages, membrane bioreactor technology has great potential in wide ranging applications including municipal and industrial wastewater treatment (e.g. textile) and process water recycling.

Wastewater reclamation and reuse are effective tools for sustainable industrial development programmes. Increasingly stringent environmental legislation and generally

enhanced intensity, efficiency and diversity of treatment technologies have made the reuse of water more viable in many industrial processes. Membrane bioreactors (MBRs) technology will be an essential part of advancing such water sustainability because they encourage water reuse and open up opportunities for decentralized treatment. Moreover, membrane bioreactor (MBR) technology is recognized as a promising technology to provide water with reliable quality for reuse and is very attractive for industrial, e.g. textile wastewater treatment (Brik et al. 2006). But the performance of MBR technology depends on the proper design of the plant considering different factors required for optimum outcome (Yang et al. 2006). This paper deals with the design of a pilot-scale MBR to obtain optimum performance of this kind of technology, and the trial was done for 6 weeks using textile wastewater. The optimum design of the technology can prove the viability of the technology and open up a door of a reliable technology for industrial wastewater treatment and reuse.

## Materials and methods

The works carried out throughout this paper were divided into two sections as mentioned below:

**Table 1** Textile wastewater quality

Parameter	Unit	Value
Inlet COD	mg/L	3200
Soluble COD (sCOD)	mg/L	2336
BOD	mg/L	650
Soluble BOD (sBOD)	mg/L	474
Total suspended solids (TSS)	mg/L	400
Volatile suspended solids (VSS)	mg/L	240
TKN	mg/L	40
pH		7–9
Temperature	°C	20
Electrical conductivity	μS/cm	1900
AOX	mg/L	0.06
MLSS	g/L	12
Cu	mg/L	5

**Table 2** Activated sludge kinetic coefficients (Eswaramoorthi et al. 2008)

Parameter	Coefficient	Unit	Range	Typical value
Endogenous decay coefficient	$K_d$	g VSS/g VSS day	0.06–0.2	0.12
Fraction of cell mass remaining as cell debris	$f_d$	unit less	0.08–0.2	0.15
Biomass yield, mass of cell formed per mass of substrate consumed	$Y$	g VSS/g bCOD	0.3–0.5	0.4
Half-velocity constant	$K_s$	mg bCOD/L	5.0–40.0	20
Maximum specific growth rate	$\mu_m$	g VSS/g VSS day	3.0–13.2	6

- Design and construction of a pilot-scale MBR plant
- Performance tests of the developed pilot-scale MBR plant

## Design and construction of a pilot-scale MBR plant

### Wastewater quality

Some design parameters were calculated based on the wastewater quality (Table 1) of a local laundry textile wastewater. It was considered that the constructed MBR plant was supposed be tested in the same textile industry after its development.

### Design conditions and assumptions

The design of the MBR plant was done based on the following conditions and assumptions:

- Mechanical aerator with oxygen transfer efficiency,  $O_{2,eff.} = 28\%$
- Liquid depth for aeration basin = 54 cm
- Dissolved oxygen (DO) in the aeration basin = 3 mg/L (normal range of DO is 2–4 mg/L; for better functionality of microorganisms, the DO of 3 mg/L has been assumed)
- Site (Karlsruhe, Germany) elevation above sea level = 115 m
- Oxygen transfer correction factor,  $\alpha = 0.6$
- Salinity–surface tension correction factor,  $\beta = 0.95$
- Fouling factor  $F$ , which accounts for membrane fouling = 0.77
- Activated sludge kinetic coefficients are given in Table 2.
- Sludge retention time (SRT) = 12 days
- Design MLSS = 12 g/L
- Ratio of VSS to TSS (VSS/TSS) = 0.601

### Design parameters

The design parameters shown in Table 3 were considered for design calculations. Some of the parameters were obtained by the analysis of the effluent (permeate), while others were determined using applicable equations.

**Table 3** Design parameters

Parameter	Notation	Unit	Value	Comment
Soluble COD	sCOD	mg/L	2336	Analysed by effluent
Soluble BOD	sBOD	mg/L	474	Analysed by effluent
Influent wastewater TSS concentration	TSS	mg/L	400	Analysed by influent wastewater
Influent wastewater VSS concentration	VSS	mg/L	240	Calculated based on VSS/TSS ratio
Influent of wastewater	$Q$	L/day	80	Measured
Solid retention time	SRT	D	12	Measured
Mixed liquor suspended solid	MLSS	g/L	12	Analysed
Biodegradable COD	bCOD	mg/L	1200	Calculated based on bCOD/BOD ratio (Eswaramoorthi et al. 2008)
Non-biodegradable COD	nbCOD	mg/L	2160	Calculated
Effluent soluble COD	sCOD <sub>e</sub>	mg/L	1576.6	Calculated
Non-biodegradable VSS	nbVSS	mg/L	162	Calculated
Endogenous decay coefficient	$K_d$	g VSS/g VSS day	0.12	Typical value used
Fraction of cell mass remaining as cell debris	$f_d$	unit less	0.15	Typical value used
Biomass yield, mass of cell formed per mass of substrate consumed	$Y$	g VSS/g bCOD	0.4	Typical value used
Half-velocity constant	$K_s$	mg bCOD/L	20	Typical value used
Maximum specific growth rate	$\mu_m$	g VSS/g VSS day	6	Typical value used
Biomass as VSS wasted per day	$P_{X,bio}$	g/day	19.1	Calculated
Effluent substrate concentration	$S$	mg bCOD/L	0.702	Calculated
Cylindrical volume of the reactor	$V_{cyl}$	L	51.9	Calculated
Conical volume of the reactor	$V_{con}$	L	4.8	Calculated
Aeration tank volume	$V$	L	56.7	Adding $V_{cyl}$ and $V_{con}$ .
Hydraulic residence time	HRT	H	~ 17	Calculated
Mixed liquor volatile suspended solid	MLVSS	g/L	6.65	Calculated
Food-to-biomass ratio	$F/M$		0.38	Calculated
Observed yield based on TSS	$Y_{obs,TSS}$	g TSS/g BOD	0.37	Calculated
Observed yield based on VSS	$Y_{obs,VSS}$	g VSS/g BOD	0.22	Calculated
Oxygen demand	$m_O$	g/h	0.65	Calculated
Air flow rate needed to transfer the required oxygen	$V_{air}$	m <sup>3</sup> /h	0.03	Calculated
Net waste activated sludge produced each day, measured in terms of total suspended solids	$P_{X,TSS}$	g/day	56.6	Calculated
Equivalent to bCOD	$S_O$	mg/L	1200	Calculated
Oxygen saturation concentration in clean water at temperature T and altitude H	$C_{S,T,H}$	mg/L	8.94	Calculated at 20 °C and at altitude of Karlsruhe (115 m above sea level)
Operating oxygen concentration	$C_L$	mg/L	3	Assumed from typical value 0f (2-4 mg/L)
Dissolved oxygen saturation concentration in clean water at 20 °C and 1 atm	$C_{S,20}$	mg/L	9.02	Calculated (US EPA 1989)
Temperature	$T$	°C	20	Assumed
Standard oxygen transfer rate	SOTR	g/h	2.3	Calculated
Density of air in Karlsruhe (above 115 m of sea level)	$\rho_{air}$	kg/m <sup>3</sup>	1.188	Calculated
Oxygen concentration in air	$O_{2,conc.}$	(%)	21	Assumed
Air flow rate needed to supply the required oxygen rate	$V_{air}$	m <sup>3</sup> /h	0.033	Calculated

**Design of MBR reactor (aeration tank)**

**Determination of reactor (aeration tank) volume** The volume of the reactor was calculated from Eq. 1 (Eswaramoorthi et al. 2008):

$$V = (P_{X,TSS} * SRT) / X_{TSS}, \tag{1}$$

where  $P_{X,TSS}$  is the net waste activated sludge produced each day, measured in terms of total suspended solids,  $X_{TSS}$  is equivalent to MLSS, and  $V$  is the volume which needs to be calculated.

$P_{X,TSS}$  was calculated using Eq. (2):

$$P_{X,TSS} = P_{X,bio,VSS} + Q nbVSS + Q(TSS - VSS). \tag{2}$$

Since  $VSS/TSS = 0.601$ , the Eq. 2 can be rewritten as (Eswaramoorthi et al. 2008):

$$P_{X,TSS} = P_{X,bio}/0.601 + QnbVSS + Q(TSS - VSS). \quad (3)$$

The value of  $P_{X,TSS}$  depends on  $P_{X,bio}$  which can be calculated using Eq. (4):

$$P_{X,bio} = \frac{QY(S_O - S)}{1 + K_d * SRT} + \frac{f_d K_d QY(S_O - S) * SRT}{1 + K_d * SRT}. \quad (4)$$

Effluent substrate concentration ( $S$ ) is calculated using Eq. (5):

$$S = \frac{K_s(1 + K_d * SRT)}{SRT(\mu_m - K_d) - 1}. \quad (5)$$

Calculating the values of  $S$ ,  $P_{X,bio}$ ,  $P_{X,TSS}$  from Eqs. (5), (4) and (3), respectively, and putting them in Eq. (1), the volume of reactor was calculated. The correspondent values are presented in Table 3.

**Determination of aeration tank size** From Eq. (1), the calculated reactor volume was 56.6 L. To ease the availability of the tank size, commercially available plastic tank with diameter of 35 cm was selected. The tank had conical shape which was used as excess sludge disposal exit area. The cylindrical volume,  $V_{cyl}$ , calculated using Eq. (6) was in line with the expected volume:

$$V_{cyl} = \pi R^2 L, \quad (6)$$

where  $R$  is the radius of the tank (17.5 cm) and  $L$  is the vertical length. The conical volume  $V_{con}$  (Alexander and Koeberlein 2014) of the reactor was calculated from Eq. (7):

$$V_{con} = \frac{1}{3} BH, \quad (7)$$

where

$$B = \pi R^2 \quad (8)$$

and  $H$  is the height (the perpendicular distance from the base to the apex).

Considering  $H = 15$  cm, the conical volume was found around 4.8 L. The length of the available cylindrical tank was 66 cm. Taking  $L = 54$  cm, cylindrical volume from Eq. (6) was found around 51.9 L. The summation of cylindrical volume and conical volume resulted in total volume of the reactor which was equal to 56.7 L (closed to the calculated volume). Figure 1 outlines the MBR reactor size.

**Calculation of hydraulic residence time (HRT)** Hydraulic residence time (HRT) was calculated based on Eq. (9):

$$HRT = \frac{V}{Q}, \quad (9)$$

where  $V$  is the volume of the reactor and  $Q$  is the permeate flow. In this case, permeate flow and feed flow were equal since hydraulic level in the reactor was maintained constant by level sensor. The value of HRT is given in Table 3.

**Determination of oxygen demand** Oxygen demand was calculated applying Eq. (10) (Metcalf and Eddy 2003):

$$m_O = Q(S_O - S) - 1.42P_{X,bio} + 4.33Q(NO_X) - 2.83Q(NO_X), \quad (10)$$

where  $S_O$  is equivalent to COD. The first term in Eq. (10) refers to substrate oxidation, the second refers to biomass respiration, the third refers to nitrification, and the final term refers to denitrification (Judd 2006). Without considering nitrification and/or denitrification, the Eq. (10) can be written as

$$m_O = Q(S_O - S) - 1.42P_{X,bio}. \quad (11)$$

The calculated value of  $m_O$  is given in Table 3.

**Calculation of standard oxygen transfer rate (SOTR)** For the calculation of standard oxygen transfer rate (SOTR), Eq. (12) is used (Metcalf and Eddy 2003):

$$AOTR = SOTR \left( \frac{\beta C_{S,T,H} - C_L}{C_{S,20}} \right) \times (1.024^{T-20})(\alpha)(F), \quad (12)$$

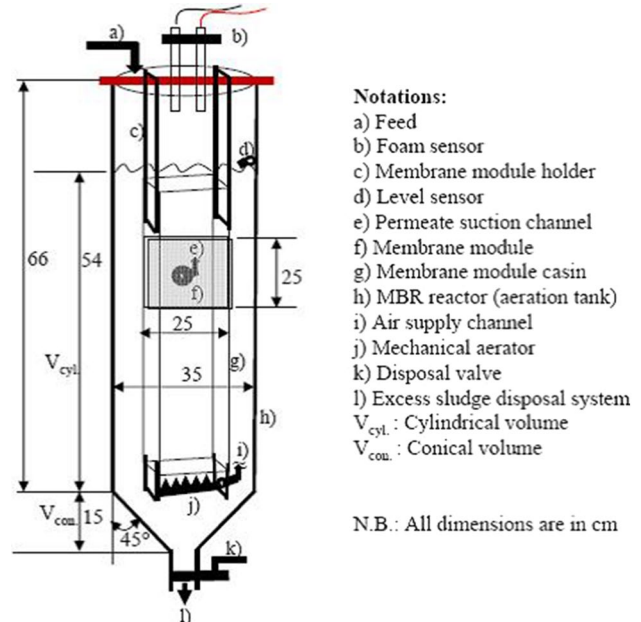


Fig. 1 MBR reactor

where AOTR = actual oxygen transfer rate (g/h) equivalent to  $m_O$ ; SOTR = standard oxygen transfer rate (g/h).

The terms in Eq. 12 are given in Table 3.

For surface aerator  $C_{S,T,H} = C_{S,T,H}$ .

Therefore,

$$SOTR = \frac{AOTR}{\left(\frac{\beta C_{S,T,H} - C_L}{C_{S,20}}\right)(1.024^{T-20})(\alpha)(F)} \tag{13}$$

The calculated value of SOTR is given in Table 3.

**Calculation of air flow rate needed to meet the required SOTR** The air flow rate needed to meet the required SOTR was calculated using Eq. (14):

$$\rho_{air} = \frac{M_{air}}{V_{air}}, \tag{14}$$

where  $V_{air}$  is the volume of air and  $M_{air}$  is the mass of air which is related to SOTR as it can be correlated as shown in Eq. (15):

$$SOTR = M_{air} * O_{2,conc.} * O_{2,eff.} \tag{15}$$

To calculate the required air, Eq. (14) is rewritten as follows:

$$V_{air} = \frac{SOTR}{(O_{2,conc.} * O_{2,eff.} * \rho_{air})} \tag{16}$$

The calculated value of  $V_{air}$  is given in Table 3.

**Construction and implementation of MBR pilot plant**

Since around 60% of the operation cost of MBR technology comes from the air supply which is needed for microorganisms for their functionality, the main objective of this paper was to design and calculate how much air is needed for the MBR operation which can be shown by Eq. 16 along with other design parameters. The suction pressure or transmembrane pressure is an associated parameter which is normally in the range of around 500 mbar and requires less energy, that’s why suction pressure has been excluded in the model.

**Construction of MBR reactor** Selecting the MBR reactor size as shown in Fig. 1, the flat sheet membrane module (UF membrane, PES, pore size 0.050  $\mu\text{m}$ , dimensions 25 cm  $\times$  25 cm) from company Microdyn-Nadir, Germany, was installed inside the reactor. The module consists of three flat sheets membrane each of having 0.11  $\text{m}^2$  of area giving total area of 0.33  $\text{m}^2$ . The membrane module was equipped with mechanical aerator at the bottom of the module and permeate suction channel in the middle of the module casin. Air was supplied by a compressor. To avoid any movement of the module, it was fixed with the head of the

MBR reactor with the help of module holder. It was taken care that the module was always submerged in the hydraulic volume ensured by level sensor. The permeate suction channel of the module was connected to a differential pressure sensor to measure the transmembrane pressure (TMP), and it was followed by a vacuum pump which created permeate flow. Feed was supplied by a feed pump. A foam sensor was incorporated at the top of the reactor to abate excess foam. Some other sensors were installed to ascertain pH, conductivity, temperature of feed and permeate. All the process parameters were monitored, and data were stored by LabVIEW programme-controlled computer system.

**Experiment**

**Start-up of the MBR pilot plant**

To check the functionality of the installed membrane bioreactor, some trials were done with water following the operation conditions as mentioned in Table 4. Firstly, the MBR plant was started with DI water for 1.5 h. All the equipment and instruments were checked if they were functioning properly.

After the first trial, the plant was tested with tap water of Karlsruhe (Germany) for almost 1.5 h and functionality of the plant was checked in the similar way. The results of the DI water test and tap water tests are shown in Fig. 2.

**Field tests of the developed pilot-scale MBR plant**

After running several trials of MBR with DI water and tap water with reproducible results, the plant was tested for 6 weeks with real laundry textile wastewater from where the data of water quality were the basis of MBR design. During this trial period, the industry was using different types of washing agents. So, MBR trial faced the variation of wastewater qualities and tests were carried out in different cycles.

Full duration of trials (6 weeks) was covered by 11 operating cycles depending on the wastewater quality of

**Table 4** Experimental operating conditions

Process parameters	Laboratory trial		Field trial
	DI water	Tap water	
Transmembrane pressure (mbar)	50	160	200
Temperature ( $^{\circ}$ C)	20 $\pm$ 1	22 $\pm$ 1	25 $\pm$ 1
pH	6.5 $\pm$ 0.2	7.0 $\pm$ 0.5	6.5 $\pm$ 0.5
Operation time (h/weeks)	1.5 h	1.5 h	6 weeks
Conductivity ( $\mu\text{S/cm}$ )	100 $\pm$ 5	460 $\pm$ 5	1200 $\pm$ 5
COD (mg/L)	–	–	800–3500

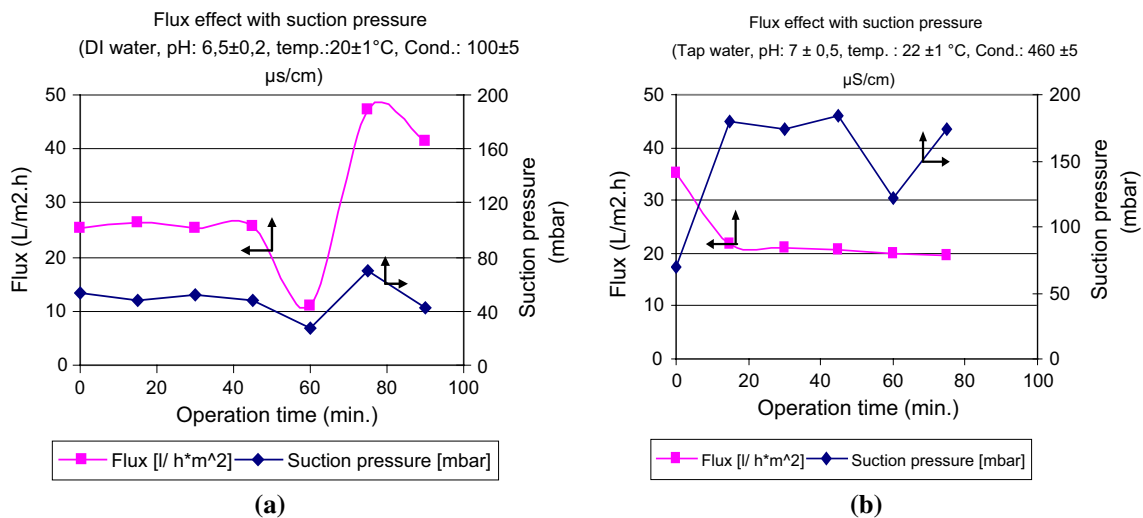


Fig. 2 Start-up results of MBR with a DI water and b tap water

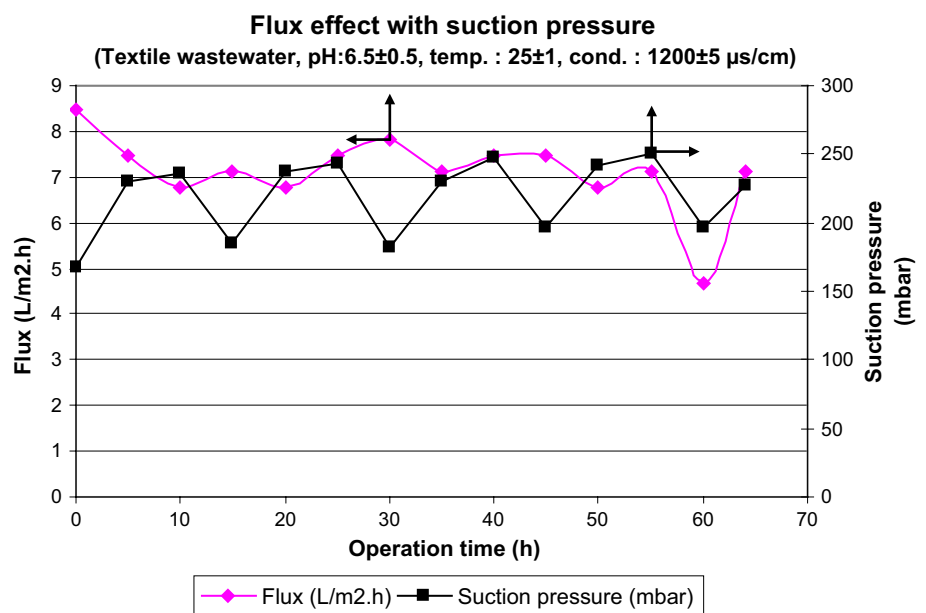
different processes. To judge the test performance of the trials, some process parameters of one operation cycle and COD removal efficiency are shown in Figs. 3 and 4, respectively.

### Results and discussion

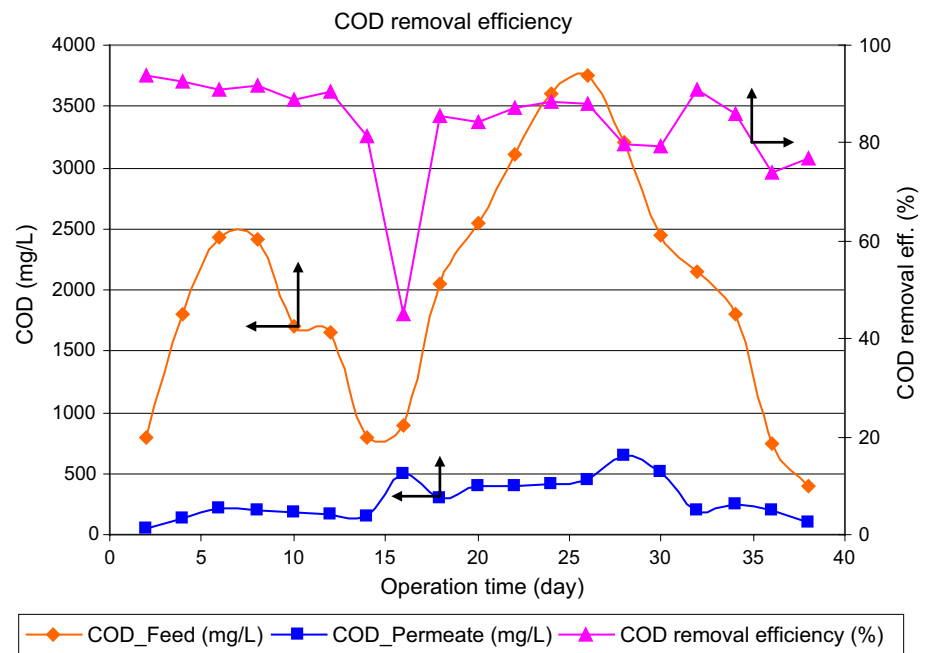
From Fig. 2, it is noticed that the fluxes of the start-up were 25 and 20 L/m<sup>2</sup> h with 50 and 160 mbar of TMPs using DI water and tap water, respectively. Design of the pure water flux of this membrane is supposed to be 15–25 L/m<sup>2</sup> h with the operating TMP range of 40–400 mbar provided by membrane provider (Microdyn-Nadir 2010). So, the

start-up results were in line with the expected results. From Fig. 3, it is noticed that the permeate flux is around 9 L/m<sup>2</sup> h with TMP of 200 mbar and the COD removal efficiency was around 90% as indicated in Fig. 4 for 800–3500 mg/L inlet COD fed to the membrane bioreactor. In conventional activated sludge (CAS) system, COD removal efficiency is around 50–60% since it only works by microorganisms in aerobic conditions. In MBR system, physical separation of permeate also happens along with biological degradation in aerobic conditions which increases the efficiency of the overall wastewater treatment system. That's why high COD removal efficiency was observed in the applied MBR system along with expected flux production. Even higher performance could be achieved if it continues for longer time

Fig. 3 Process parameters of pilot MBR



**Fig. 4** COD removal efficiency of pilot MBR



so that the microorganism can be adapted further with the system. This high-level COD removal efficiency opens up an option to recycle the permeate as process water in the industry.

## Conclusion

The start-up experiment with pure water/tap water and the field trial with real textile wastewater show very good results with around 90% COD removal efficiency. The HRT and other parameters of the trials were well fitted to the design conditions. The applied aeration rate was 1.0 m<sup>3</sup>/h which was quite high compared to the designed aeration rate. But this aeration was also used to create cross-flow beside the oxygen transfer. Generally, it can be concluded that the testing results indicate more or less perfection of the design for pilot-scale MBR plant. This MBR plant is recommended to test with textile wastewater for several months investigating flux, TMP, COD, MLSS, *F/M* ratio, etc., for further verification of the design.

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