Biochemical Engineering Journal 57 (2011) 46–54

Contents lists available at SciVerse ScienceDirect

Biochemical Engineering Journal

journal homepage: www.elsevier.com/locate/bej

The investigation of dairy industry wastewater treatment in a biological high performance membrane system

Burhanettin Farizoglu*, Suleyman Uzuner

Balikesir University, Engineering and Architecture Faculty, Department of Environmental Engineering, Balikesir, Turkey

ARTICLE INFO

Article history:
Received 17 May 2011
Received in revised form 10 August 2011
Accepted 14 August 2011
Available online 22 August 2011

Keywords:
Jet loop reactor
Dairy wastewater
Industrial wastewater treatment
Ultrafiltration
Membrane bioreactor
Membrane fouling

ABSTRACT

The dairy industry is generally considered to be the largest source of food processing wastewater in many countries. The highly variable nature of dairy wastewaters in terms of volumes and flowrates and in terms of high organic materials contents such as COD 921–9004 mg L^{-1}, BOD 483–6080 mg L^{-1}, TN of 8–230 mg L^{-1} and SS of 134–804 mg L^{-1} makes the choice of an effective wastewater treatment regime difficult. A high performance bioreactor, an aerobic jet loop reactor, combined with a ceramic membrane filtration unit, was used to investigate its suitability for the treatment of the dairy processing wastewater. The oxygen transfer rates of the bioreactor were found to be very high (100–285 h^{-1}) on the operating conditions. A loading rate of 53 kg COD m^{-3} d^{-1} resulted in 97–98% COD removal efficiencies under 3 h hydraulic retention time. The high MLSS concentrations could be retained in the system (up to 38,000 mg L^{-1}) with the contribution of UF (ultrafiltration) unit. During the filtration of activated sludge, the fluxes decreased with increasing MLSS. Cake formation fouling was determined as dominant fouling mechanisms. The results demonstrate that jet loop membrane bioreactor system was a suitable and effective treatment choice for treating dairy industry wastewater.

1. Introduction

The dairy industry is generally considered to be the largest source of food processing wastewater in many countries. Water is used throughout all steps of the dairy industry, including cleaning, sanitization, heating, cooling, and floor washing; naturally the industry's need for water is huge [1]. In general, wastes from the dairy processing industry contain a high concentration of organic material such as proteins, carbohydrates and lipids, high BOD and COD, and high concentrations of suspended solids and suspended oil-grease. All of these require specialized treatments to prevent or minimize environmental problems. Dairy wastewaters (DWs) are also characterized by wide fluctuations in flow rates, related to discontinuity in the production cycles of different products [2]. The highly variable nature of dairy wastewaters in terms of volume and flow rates and also in terms of the pH and suspended solids (SS) content makes it difficult to choose an effective wastewater treatment regime [3]. To comply with new discharge standards, the dairy industries have adopted an elaborate effluent treatment protocol that is affecting the overall economy of the plant and increasing the costs of conventional treatment systems.

Recently, researchers have shifted their interests to the possibilities of reuse or recycling of industrial wastewaters. Earlier researchers have investigated the dairy industry effluent treatment through the membrane process and the possibility of reuse [4,5]. There is a growing interest in combining membranes with biological wastewater treatment. The membrane bioreactors (MBR) offer distinct advantages over traditional biological processes: higher biodegradation efficiency, smaller footprint, better quality of treated water, the absolute control of solids and hydraulic retention time, retention of all microorganisms and viruses, and easy control of operating conditions [6,7]. In particular, the absolute rejection of sludge by the membrane makes it possible to overcome the problem of dependence on settleability [8]. Furthermore, membrane separation enables a significant increase in the biomass concentration in the bioreactor, thus reducing its size [9]. As the reaction rate is directly proportional to biomass concentration, a high concentration is desirable. On the other hand, to operate the bioreactor at high biomass concentrations, special reactor topologies should be chosen. In order to select and design the correct bioreactor topology, it is necessary to know the characteristics of effluents, volumes, laws of microorganisms' growth rate, and biokinetic parameters defined by mathematical models. Jet-loop reactors (JLRs), efficient third generation bioreactors, might represent an ideal reactor topology for an economic solution to DW treatment. JLRs are able to deal with very high organic loading rates due to their high efficiency of oxygen transfer, high mixing and turbulence achieved. Consequently,

---

* Corresponding author. Tel.: +90 02666121194; fax: +90 02666121426.
E-mail address: bfarizoglu@gmail.com (B. Farizoglu).

1369-703X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.bej.2011.08.007

reduced reactor volumes are needed for treatment, and less land is required; oxygen (air) is forced directly into the fermentation medium, resulting in significant savings in installation and maintenance costs [10]. The combination of a membrane module with a JLR is called a jet loop membrane bioreactor (JLMBR).

The objective of this study is to examine the performance of the JLMBR (high performance compact membrane system) in the treatment of DW and to compare the results with the literature. An extensive characterization of the wastewater and JLB was performed under various operating parameters. The filtration performance and back-washing efficiency was also examined.

2. Materials and methods

2.1. Materials

2.1.1. Bioreactor system set-up

The experimental setup of JLB (working volume of approximately 18 L) was designed at Balikesir University, Environmental Engineering Department, Balikesir, Turkey. The schematic representation of the reactor setup is given in Fig. 1. The JLB consisted of a draft tube open at both ends inside a cylindrical vessel (height 1400 mm, inner diameter 100 mm) and a degassing tank. Two-fluid nozzle consisted of two concentric tubes. The outer nozzle was made of Teflon material (inner diameter 14 mm). The inner nozzle was a stainless-steel tube of 8 mm in diameter and 1 mm thickness. The air to the reactor was provided from an air pump through the inner stainless-steel tube via a gas flow-meter. Gas and liquid flow rates were controlled by the valves and flow-meters on their respective pipelines. The two-phase jet located at the top of the reactor creates a downward directed two-phase flow inside the draft tube and at the same time disperses the air sucked in, through the gas tube located within the liquid jet. Due to the momentum of the liquid jet, the liquid and the gas inside the draft tube flows downwards and, after the reflection at the bottom of the reactor rises within the annulus between the wall of the reactor and the draft tube. At the upper end of the draft tube, part of the fluid is recycled into the draft tube through a suction of the two-phase jet resulting in a re-dispersion of the bubbles and the biomass produced in the biological reaction. The temperature of the bioreactor content was maintained around 22 ± 2 °C by circulating cold gas through a stainless steel heat exchanger immersed in the degassing tank. DW was pumped with a peristaltic pump from the feed tank into the degassing tank. The recycle flow from of both JLB and the ultrafiltration (UF) unit were measured by two electromagnetic flow-meters.

The block diagram showed the flow direction of the system is given in Fig. 2

2.1.2. Membrane filtration unit

The separation of activated sludge took place in the ceramic membrane UF unit (JIUWU HITECH, China), which was integrated into the system through an external circuit to the jet loop bioreactor (Fig. 1). In the external circuit, permeate was extracted by circulating the mixed liquor at high pressure along the membrane surface. In this case, the concentrated mixed liquor at the feed side recycles back to the degasification tank. The pump used for the circulation is made out of stainless-steel. The excess sludge was removed via a peristaltic pump from the degasification tank, once the desired biomass concentration was reached or exceeded. The specifications of the UF membrane (tubular type ceramic membrane) are shown in Table 1. Permeate was measured via a flow meter placed on the permeate side. The flow readings were transmitted to a computer and recorded at the desired time intervals.

After each run, the system was stopped and the UF unit was studied for backwashing and cleaning performance by one or more cleaning methods in sequence, for the recovery of membrane permeability.

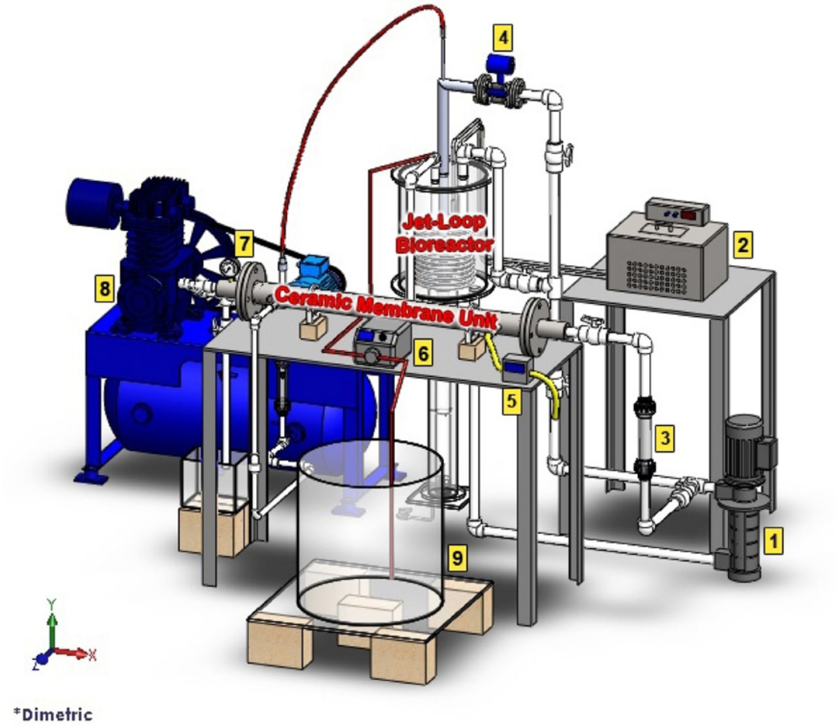

Fig. 1. Schematic layout of the JLMBR reactor system [1 – circulation pump, 2 – heat-exchanger, 3 – flow meter (for the membrane unit), 4 – electromagnetic flow meter (for JLB), 5 – flow meter (for the permeate stream), 6 – peristaltic pump, 7 – manometer, 8 – air compressor, and 9 – wastewater feed tank].

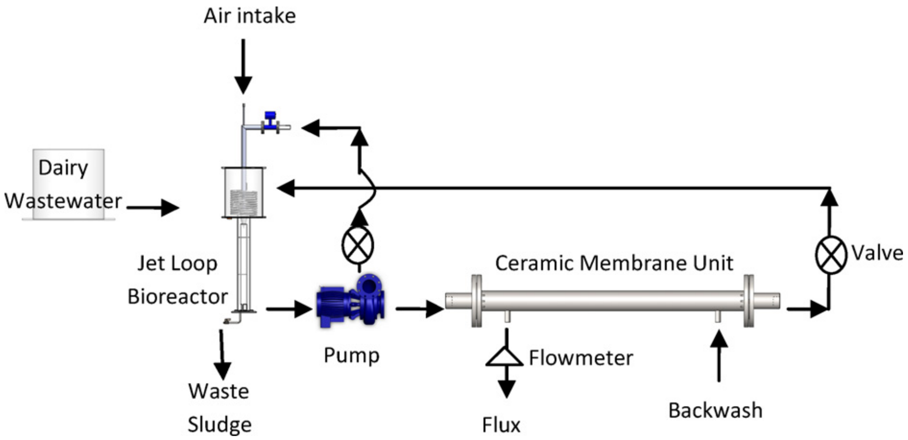

Fig. 2. The block diagram of the JLMBR system.

2.1.3. *Dairy wastewater (DW)*

During the experimental period, approximately 250 L of DW were obtained 3–4 times a week from a dairy factory, Onur Sut Co. (Balikesir, Turkey), near the University Campus and collected in the laboratory. All experiments were carried out in mesophilic conditions. DW collected from the factory was characterized according to the discharge parameters.

2.2. *Methods*

2.2.1. *Analytical methods*

Samples of influent and effluent were taken daily from the JLMBR system. Parameters such as COD, MLSS (mixed liquor suspended solids), MLVSS (volatile liquor suspended solids), and N-NO_3^-, and N-NO_2^- were analyzed as defined in Standard Methods [11]. Total nitrogen (TN), N-NH_4^+ and total phosphate (TP) were measured by using commercial test kits obtained from Merck Company. The organic nitrogen (ON) was calculated by subtracting the sums of the N-NH_4^+, and N-NO_3^-, N-NO_2^- concentrations from TN. The soluble (filtered) COD was defined as the filtrate through Whatman GF/C glass-fiber filters, also used in the determination of MLSS and MLVSS. Dissolved oxygen (DO), temperature, pH and conductivity were measured with a multi-parameter measurement device (supplied from WTW Company) placed in the bioreactor. The DO data obtained through the DO meter were sent to a computer for further analysis.

2.2.2. *Membrane cleaning*

Backwashing with compressed air (CA) and chemical cleaning methods were investigated in the experiments on membrane cleaning. Backwashing was performed in a flow direction opposite to UF by forcing CA through the ceramic membrane at 4.0 bar for 3 min. Chemical cleaning was performed by immersing the module in each of the cleaning agent for 12 h. The sequence of the chemical cleaning was alkali treatment of the module, followed by a brief rinse of the module with de-ionized (DI) water, then acid treatment. The alkali solution containing 1–2% NaOH and 1–2% HNO_3 solution were used for the chemical treatment. To be sure that the condition and performance of the membrane module were as similar as possible in all the experiments, post-cleaning was performed after every experiment to remove any fouling not removed by a specific cleaning method in the experiment. This was accomplished by first soaking the module in an alkaline solution for 12 h. The membrane module was then backwashed with DI water for 5 min to remove the alkali and any unclogged material from the interior of the membrane. The module was then immersed in an acidic solution for 12 h, and again backwashed with DI water for 5 min. The effectiveness of the post-cleaning operation was evaluated by measuring the clean water flux to determine the degree of initial flux recovery. The proportion of irreversible fouling was minimized less than 7% of the flux reduction.

Table 1
Specifications of the ceramic membrane coupled in the system.

Manufacturer	Jiuwu Hitech, Chinese
Type	Ceramic membrane
Raw membrane material	99% α-Al_2O_3/ZrO_2
Pore size	50 nm
Outside diameter	40 mm
Numbers of channel	37
Diameter of channel	3.6 mm
Total length	1000 mm
Membrane area	0.24 m^2
Net weight	2.40 kg
Permeate direction	Inside to outside
pH range	0–14
Temperature	<150 °C

2.2.3. *Membrane fouling analysis*

The permeation flux of particle-free water across a clean membrane can be described by Darcy's Law as:

$$J = \frac{\Delta P}{\mu R_m} \tag{1}$$

where J ($m^3\,m^{-2}\,s^{-1}$) is the permeate flux, ΔP (Pa) trans-membrane pressure (TMP), μ (Pa s) the absolute viscosity of the water, and R_m (m^{-1}) the hydraulic resistance of the clean membrane (or clean membrane resistance). For suspension filtration, the permeation flux will always be lower than that given by Eq. (1). Flux decline is a result of the increase of membrane resistance to the permeating flow, resulting from membrane fouling or particle deposition on or in the membrane [12]. Thus, the permeation flux through a UF unit treating suspensions, like wastewater including activated sludge can be given, by modifying Eq. (1), as:

$$J = \frac{\Delta P}{\mu (R_m + R_p + R_c)} \tag{2}$$

where R_p (m^{-1}) is the resistance due to pore blocking and R_c (m^{-1}) the resistance arising from cake formation.

2.2.4. *Mass transfer analysis of the jet loop bioreactor*

All the mass transfer tests were performed with tap water while the system was running under batch mode (broken flow lines and relevant equipment excluded). Before each test, the DO in the water was stripped down to 0.5 mg L^{-1} by nitrogen purging. After switching over to an air supply line, the concentration of oxygen was measured as a function of time using a DO meter (WTW, 350i) equipped with an oxygen probe. Temperature and pH were also measured with the same device. The DO data obtained through the DO meter were input into a computer for further analysis.

Mass transfer is generally expressed in terms of mass transfer per unit volume of the reactor and the mass transfer coefficient (K_La) is expressed as the overall volumetric mass transfer coefficient. K_La can be computed by using a non-linear expression:

$$C = C_s^* - (C_s^* - C_i) \times e^{-(K_La)t} \tag{3}$$

where, C is the DO concentration in the medium at a given time t, C_s^* is saturation and C_i is initial ($t = 0$) oxygen concentration under experimental conditions.

2.2.5. Start-up and treatment conditions

Activated sludge of different origins (Balikesir Urban Wastewater Treatment Plant and Manisa Organized Industrial Region Wastewater Treatment Plant) was adapted to the DW and then used as inocula for the JLMBR. In order to increase the amount of activated sludge in the bioreactor, initially, the JLMBR was operated in a repeated-batch process of 2–3 days each for a total period of 20 days. At the end of this period, the JLMBR was fed continuously and the concentration of activated sludge reached was approximately 2300 mg L^{-1}. During both the batch and continuous operating conditions, DO levels in the reactor were maintained at a range of approximately 1.0–3.0 mg L^{-1}. During the test period of about 35 weeks the following operating conditions for the reactor and UF unit were varied:

- √ Biomass concentration in the reactor: 2312–38684 mg L^{-1}
- √ Load per unit reactor volume: 4.8–53.6 kg m^{-3} g^{-1}
- √ Hydraulic wastewater residence time: 1.9–7.7 h
- √ Sludge age: 2.6–79.6 h
- √ Velocity within the membrane module: 1.32–2.65 m s^{-1}
- √ Transmembrane pressure: 0.6–4.0 bar

3. Results and discussion

3.1. Characterization of the DW

The volume, concentration and composition of the effluent from in a dairy plant are dependent on the type of product being processed, the production program, operating methods, design of processing plant, the degree of wastewater management being applied, and subsequently, the amount of water being conserved [13]. Information about the general characteristics of dairy wastewaters from full-scale operations is in fact scarce in literature [3], and few comprehensive studies have been carried out that might provide extensive information about the particular characteristics of dairy wastewaters from various full-scale operations. In this study, dairy wastewaters supplied from a cheese factory (Onur Sut Co.) nearby the University Campus in which various types of cheese produced were used as the wastewater. The factory has been treating its effluents in a biological wastewater treatment plant (anaerobic sludge blanket reactor + classical activated sludge). Since the waste effluents from the dairy industry are usually generated intermittently, the flow rates of these effluents change substantially, so the wastewater was taken from the equalization tank of the plant. The DW was then characterized in detail according to discharge parameters. The characterization experiments continued over a 2-year period and the data were then analyzed statistically. The summary of data obtained from the characterization experiments on the general properties of dairy waste effluents is given in Table 2.

Dairy industry wastewaters are generally produced in an intermittent way and thus differ in concentration and volume over the production period. Thus, the DW concentrations fluctuated in a wide band. Significant fractions of the organic components and nutrients in dairy waste streams are derived from milk and milk products. In industrial dairy wastewaters, nitrogen originates mainly from milk proteins, and is present in various forms; either an organic nitrogen (proteins, urea, nucleic acids), or as ions like NH_4^+, and NO_2^- and NO_3^-. Phosphorus is found mainly in inorganic forms like orthophosphate (PO_4^{3-}) and polyphosphate ($P_2O_7^{4-}$), but can also be found in organic forms [14]. Suspended solids in dairy wastewaters originate from coagulated milk, cheese curd fines or flavouring ingredients. Concentrations of SS and volatile SS are used to evaluate wastewater strength and treatability. There is also a strong tendency towards high COD concentrations in dairy industry wastewaters although these concentrations tend to fluctuate.

Dairy wastewaters include easily degradable carbohydrates, mainly lactose, as well as less biodegradable proteins and lipids. In cheese-processing wastewater, 97.7% of total COD was accounted for by lactose, lactate, protein and fat [15]. Lactose is the main carbohydrate in dairy wastewater and is readily biodegradable by the bacteria. However, dairy wastewater, because of its protein and lipid content, can easily be defined as a complex substrate type. Lipids are potentially inhibitor compounds that are always encountered during anaerobic treatment of dairy wastewaters.

3.2. Mass transfer capacity of the JLB

In the treatment of high organic content industrial wastewaters, anaerobic treatment processes tend to be favoured over aerobic processes due to their well-known benefits such as methane yields, less sludge generation, and lower nutrient requirements. However, the disadvantages associated with anaerobic treatments are high capital cost, long start-up periods, and the need for strict control of operating conditions, greater sensitivity to variable loads and organic shocks, as well as toxic compounds [2]. Aerobic treatment processes are thus commonly used along with anaerobic processes

Table 2
The characteristics of dairy waste effluents.

Parameter	Concentration (mg L^{-1})			
	Maximum	Minimum	Average	Standard Deviation
Total COD (COD_t)	9004	921	3445	1323
Soluble COD (COD_s)	8064	635	2445	1236
COD_s/COD_t	0.90	0.68	71	0.14
BOD	6080	483	1860	394.5
Suspended solids (SS)	804	134	398.31	143.8
Volatile suspended solids	506	168	329.25	121.16
Total nitrogen (TN)	230	8.00	108.84	51.50
Ammonium N	91.00	2.5	23.42	29.38
Nitrate N	8.2	1.8	6.7	5.40
Total phosphor	111.5	9	35.7	18.32
Oil-Gress	142	400	288	77.86
pH	5.78	5.52	5.63	0.07

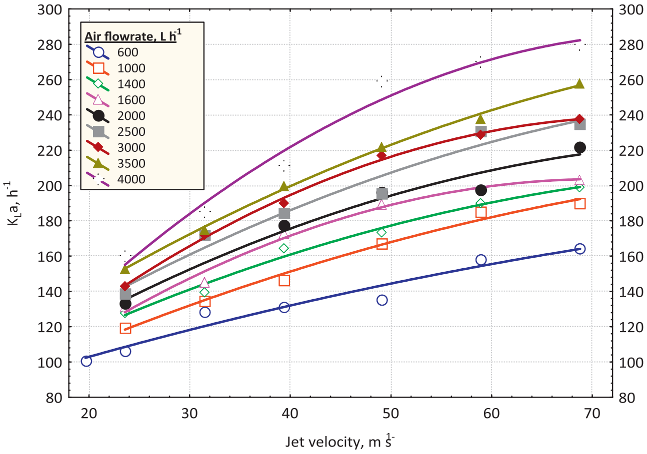

Fig. 3. The evolution of K_La versus the jet velocities at different air flow rates.

in dairy wastewater treatment in order to achieve the effluent discharge limits for agro-industry wastewaters [3].

In this study, we examined and compared the performance and efficiency of an aerobic system for DWs, which are a high strength industrial wastewater. JLB, which is classified as a third-generation compact reactor, was chosen as the aerobic system. The aim of this choice was to operate the system at high organic loadings and lower hydraulic retention times. In the aerobic systems, the most favourable contribution from the bioreactor is its ability to produce high oxygen transfer capacity as the oxygen supply plays an active part in the success and economics of the system. In this stage of the study, the oxygen transfer characteristics of the JLB were investigated and discussed because of the mass transfer kinetics quantified by the volumetric oxygen transfer coefficient K_La in practice. Fig. 3 shows the evolution of K_La versus the jet velocities at different air flow rates.

The JLB achieved K_La values between 101 and 280 h^{-1} under various operating conditions. It can be seen that the K_La values in the present study are about 100 times higher than those of the conventional reactor system. K_La values increased with the increasing jet velocities, as seen in Fig. 3. The principle in this reactor type is the utilization of the kinetic energy of a high velocity liquid jet to maintain the gas phase and create a fine dispersion of two phases. The high shear rates from the liquid jet produced very fine gas bubbles, thus the equipment generated very high interfacial areas and high volumetric mass transfer rates. Also, the more clear-cut increases in K_La values were observed with increasing air flow rates. Gas hold-up and interfacial area for the mass transfer also increased with the increasing air flow rates. In the experiments, impact of jet velocities on mixed liquor temperature was not investigated because a heat exchanger was used to keep the reactor content at a fixed temperature.

3.3. *The treatment efficiencies and performance of the JLMBR system*

The energy consumption increases with the increasing jet velocity in JLB. Consequently, it has been wanted to operate the system at minimum jet velocities. But at lower velocities, the reactor mixed liquor was not recirculated and looped in the JLB. Therefore, at the fixed air flow rate, the minimum jet velocity was selected for the liquid (reactor mixed liquor) loop. After the characterization experiments for the JLB, the system was set to an air flowrate of 1000 $\mathrm{L\,h^{-1}}$ and a jet velocity of 40 $\mathrm{m\,s^{-1}}$. The JLMBR was then seeded with mixed liquor from activated sludge plants treating domestic wastewater (Balikesir Municipal Wastewater Treatment Plant [trickling filters]) and industrial wastewater (Manisa Organized Industry Region Wastewater Treatment [activated sludge]). The DW was chosen for the feed because it has a very high BOD and ease of transportation to the laboratory in its concentrated state, which was essential because of the large amount of BOD required to run the jet loop reactor at high loading rates. Although the JLMBR was continuously operated for more than 15 months, Fig. 4 shows results taken over a period of 250 days. This period could be considered as representative of all the experiments. The applied loading rates were kept high over a period of several days to allow the biomass to become acclimatized to the DW. Since the collected wastewater from the plant was fed directly into the system at the selected influent flow rates, the organic loads varied according to the concentration of DW. During the first 7 days, COD removal efficiencies were measured as instable due to the change from batch to continuous operation. After this acclimation period, efficiencies started to improve. JLMBR was fed organic loads with loading rates that varied from 4.8 to 53.6 $\mathrm{kg\,m^{-3}\,d^{-1}}$ and with hydraulic retention times (HRT) that varied, correspondingly, from 1.9 to 7.8 h. Each volumetric loading to the reactor was continued until an incoming wastewater amount of more than 10–12 times the reactor volume had passed through the JLMBR. When the effluent COD values remained in a narrow band, the system was in steady-state.

JLMBR was operated at a loading rate of 26.7 $\mathrm{kg\,m^{-3}\,d^{-1}}$ between 10 and 13 days, under 32.4 $\mathrm{kg\,m^{-3}\,d^{-1}}$ between 56 and 62 days, and under 34.3 $\mathrm{kg\,m^{-3}\,d^{-1}}$ between 85 and 89 days. Under these organic loading rates, the efficiencies were estimated at 95.5–97.7% between 10 and 13 days, 95–97% between 56 and 62 days, and 96–98% between 85 and 89 days. Organic loading rate was then increased to 53.6 $\mathrm{kg\,m^{-3}\,d^{-1}}$ on day 92. In these conditions, 95.6–97.8% COD treatment removal efficiencies were achieved from the system. JLMBR was run under varying organic loading rates until day 220. During this time period, various process and operating parameters were examined. The organic loading rates were increased to 32.6 $\mathrm{kg\,m^{-3}\,d^{-1}}$ on day 220 and 40.3 $\mathrm{kg\,m^{-3}\,d^{-1}}$ on day 224. In the meantime, treatment efficiencies of approximately 99% and 98%, respectively, were obtained. In the last period of the study, the loading rates went up to 45.0 $\mathrm{kg\,m^{-3}\,d^{-1}}$ on day 233, 53.1 $\mathrm{kg\,m^{-3}\,d^{-1}}$ on day 238, and 50.5 $\mathrm{kg\,m^{-3}\,d^{-1}}$ on day 246. Even for these very high organic loads, treatment efficiencies between 95 and 98% were obtained.

It is interesting to note that very high fluctuations in the inlet loadings resulted in only minor reductions in the system performance. On day 53 the COD loading was increased from 17.4 to 32.4, resulting in a reduction of COD removal efficiency from 99% to 95%. Similarly, on day 232, an increase in COD loading from 25 to 45 resulted in a 3% reduction in COD removal efficiency.

The JLMBR system could be operated at very high F/M ratios (food/microorganism) compared to conventional activated sludge systems. While on day 146, F/M ratios were increased from 2.07 to 14.9 $\mathrm{kgCOD\,kgMLVSS^{-1}\,d^{-1}}$, the COD removal efficiency decreased slightly, from 98% to 96.5%. Similarly, on day 184, an increase in F/M ratio from 1.8 to 11.4 $\mathrm{kgCOD\,kgMLVSS^{-1}\,d^{-1}}$ resulted in a 1% reduction in COD removal efficiency. Fluctuations in the applied F/M as observed during days 87–94 similarly resulted in only a small reduction in COD removal efficiency. In general, JLMBR has demonstrated a high tolerance to short-term changes in the applied high COD loading rates [16]. The conditions prevailing in the JLB, with much higher F/M values than conventional activated sludge systems and with a very high growth rate of active bacteria, may be beyond the limits within which filamentous organisms can complete successfully with the rest of the population [17].

Foaming in the reactor was found to be a common occurrence when changing loading rates and feeding with high influent COD concentrations. In other words, excessive foaming was observed in the bioreactor at high F/M ratios. When the system reached

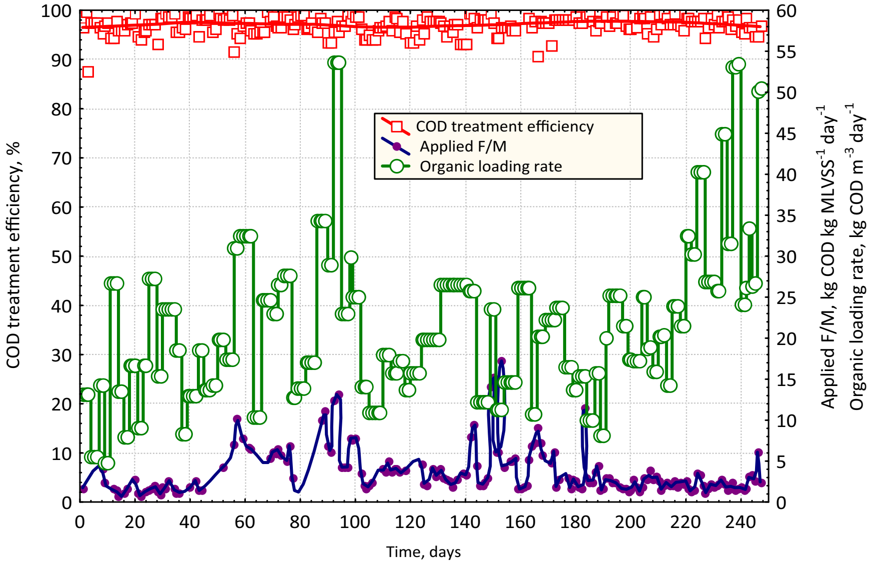

Fig. 4. The effects of organic loading rates and F/M ratios on COD removal efficiencies in DW treatment using JLMBR system.

steady-state conditions, the foaming decreased to a minimum. Fig. 5 shows the changes of MLSS and HRT versus time. MLSS concentrations in the JLMBR system were measured between 1000 and 38,000 mg L^{-1}. The system was mainly operated at MLSS concentrations over 5000 mg L^{-1}. HRT varied between 1.9 and 7.7 h. Nevertheless, the system was usually operated with an HRT of 4 h. It was observed that the effluent concentrations were badly affected under HRT of 1.9 h. The sludge ages were changed from 2.6 to 79.6 h

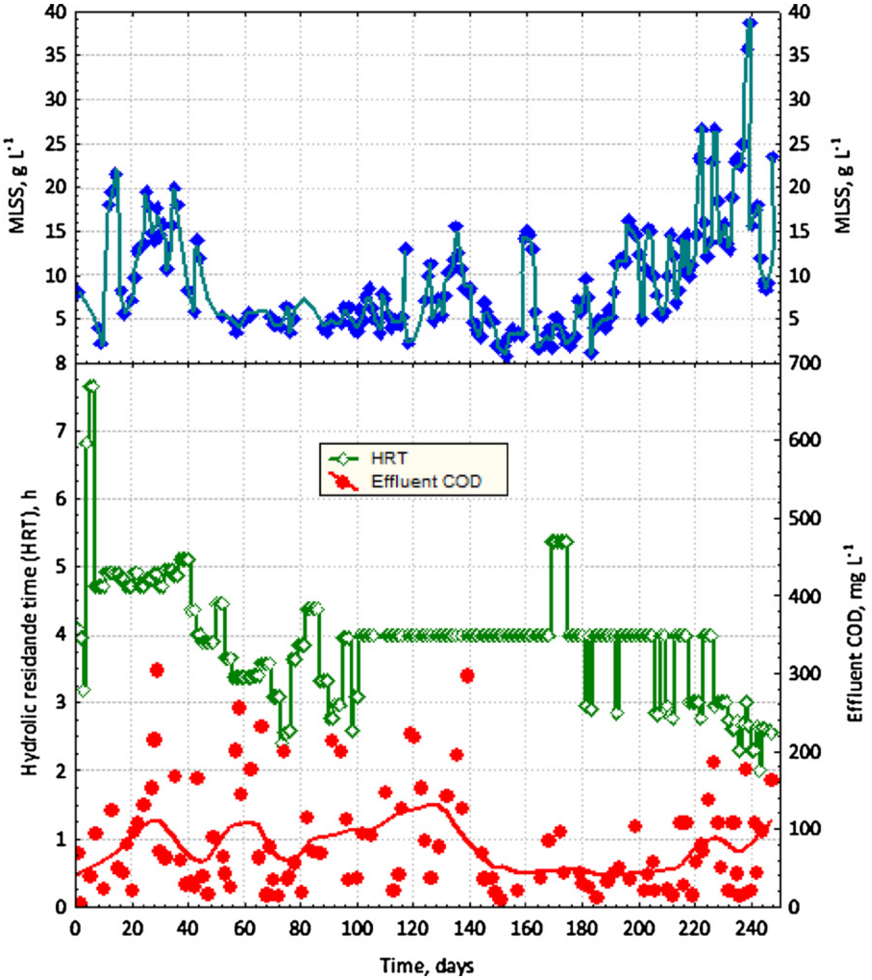

Fig. 5. The effects of MLSS and HRT to the effluent COD concentrations by the time.

during the study. Under these operating conditions, the effluent's COD concentrations were measured to be below 300 mg L^{-1} (Fig. 5). Nevertheless, effluent COD values were evaluated at approximately 100 mg L^{-1} or lower for most of the loading conditions.

The activated sludge in the JLB was highly motile when observed under a microscope and appeared to flocculate less readily than sessile ciliates/protozoa. Besides, microscopic examination of biomass showed that no filamentous bacteria or protozoa were present in the flocks. The situation of the activated sludge may be attributed to the high shear forces in the nozzle combined with high growth rates of the active bacteria, together with the high applied F/M and the nature of the wastewater. All of these factors achieved a high degree of microbial selection in the activated sludge of the bioreactor. Otherwise, the structure with the smallest flock size allowed high cross-sectional surface area exposure to oxygen and substrate transfer for the microorganisms in the flock. This also contributed to the strong performance of the JLB.

As the reaction rate in wastewater treatment is directly proportional to biomass concentration, the organic removal rate increases with MLSS concentration [18]. The study was achieved at a high biomass concentration. The JLMBR, as a high mass transfer performance reactor, allowed much higher biomass concentrations than would apparatus with a conventional mass transfer. Nonetheless, the increase in biomass concentration is limited by the physical properties of the sludge-wastewater-suspension [18]. Otherwise, a clear relationship could not be seen between MSSS and COD removal efficiency, in Fig. 5. This result could be attributed to two main factors. First, since a high MLSS concentration and active biomass were generally obtained in the system, high performance was achieved in all situations. Secondly, with the increasing in biomass concentration increased the particle sizes of the flock considerably [16], and thus the oxygen and substrate transfer to the microorganisms were decreased. In addition, the increasing MLSS concentration increased the viscosity in bioreactor content, which also increased bubble sizes and caused bubble coalescence in the system. Thus, mass transfer decreased because of decreased cross-sectional surface area and gas hold-up.

3.4. Ultrafiltration of the sludge and backwashing performance

The effluent quality arising from abnormal bacterial activities such as bulking and foaming in the aeration tank makes separation of sludge from water difficult. This has given space for membrane filtration to be increasingly used with the activated sludge process [12]. The rate of sludge separation from effluent is no longer limited by the settleability of the activated sludge, with a membrane filtration unit replacing a clarifier. In this study, the membrane filtration unit was a determinant factor for the system's performance since the reactor content was operated with a small and dispersed flock structure and the sludge had poor settleability. The tubular ceramic membrane filters were chosen as ultrafiltration unit and operated at cross-flow filtration mode. Ceramic membranes have many unique advantages; such as excellent resistance to acid/alkaline and oxidation chemicals, solvent stability, high thermal stability, excellent mechanical and abrasive resistance, extremely long work life compared with polymeric membrane, and easy cleaning and sanitizing with back flushing [19]. Fig. 6 presents the permeate flux of the ceramic membrane as a function of time for the filtration of various MLSS concentrations.

As seen in Fig. 6, after a sharp decrease in the permeate flux of the UF membrane due to adsorption and pore blocking followed by the formation of a fouling layer within the first 10 min, the permeate flux reached a pseudo-steady state. In this period, the attachment of foulants onto the membrane surface due to the drag force of permeate flow was almost balanced by the detachment of foulants from the membrane surface due to shear force by crossflow velocity and back diffusion by concentration gradient. Membrane fouling is generally characterized as a reduction of permeate flux through the membrane as a result of increased flow resistance to pore blocking, concentration polarization, and cake formation [12,20]. Many sharp decreases were observed in the fluxes at low MLSS concentrations (in Fig. 6). This could be explained in that the fouling at low MLSS concentrations resulted in different mechanisms. The literature suggests that pore blocking is the fouling mechanisms at low MLSS and cake formation is the fouling mechanism at high MLSS concentrations [12,21,22].

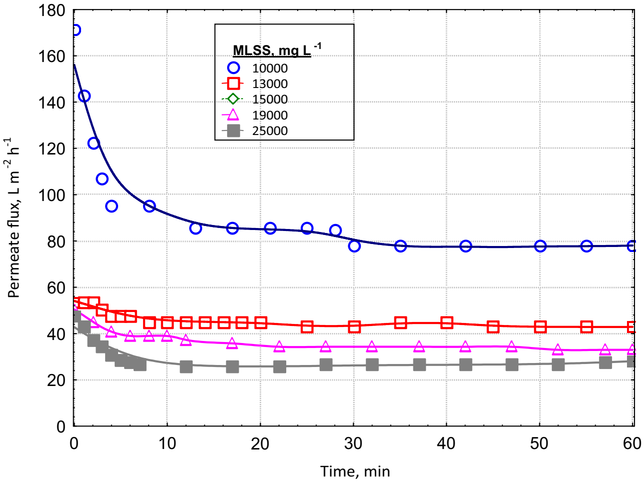

Fig. 6. Variation of fluxes with time at different MLSS concentrations of the membrane unit ($\Delta P = 2$ bar, $V_c = 2.87$ m s^{-1}).

Biofouling is another major problem arising from biofilm formation in the pores or on the surface of the membrane [23]. During the study, biofilm formation was observed in the ceramic membrane's flow channels. At long operation times, it was seen that the thickness of the biofilm layer increased. Biofouling may be initiated with the deposition of individual bacteria cells on the membrane surface; the cells then multiply and form a biofilm.

However, the development of membrane bioreactors has been limited by problems of membrane fouling during filtration of the activated sludge. Fouling of the membrane decreases the filtration fluxes and thus the treated water flow, and increases the operating costs. Since the clogged membranes must be cleaned and/or replaced, researchers have developed various strategies to reduce membrane fouling and to improve membrane cleaning efficiency for flux recovery. These strategies include the development of new membrane materials, new design of a membrane module, modification of flow patterns and incorporation of in situ or ex situ cleaning regimes in the membrane unit [20,24–26]. A combination of these strategies may be used in some processes [12,27]. In this research, the efficiency of backwashing with CA, immersing the module in DI water, and chemical cleaning were also examined. Fig. 7 shows the efficiency of backwashing with air.

The acceptable flux recovery was obtained by backwashing with CA. Instead of; high flux recoveries were achieved at high MLSS concentrations by backwashing with CA. Namely, the backwashing process with CA was an effective procedure to separate the loosely attached cake from the membrane along with the soluble microbial product entrapped in it. This result explained that the effective mechanism in membrane fouling was in cake formation. During the first stages of the filtration cycle, under the elevated flux applied, strong permeation drag would accelerate MLSS accumulation. A cake layer would quickly form to act as a secondary or dynamic membrane to entrap further soluble microbial products. In this study, backwashing was applied at one-hour periods and

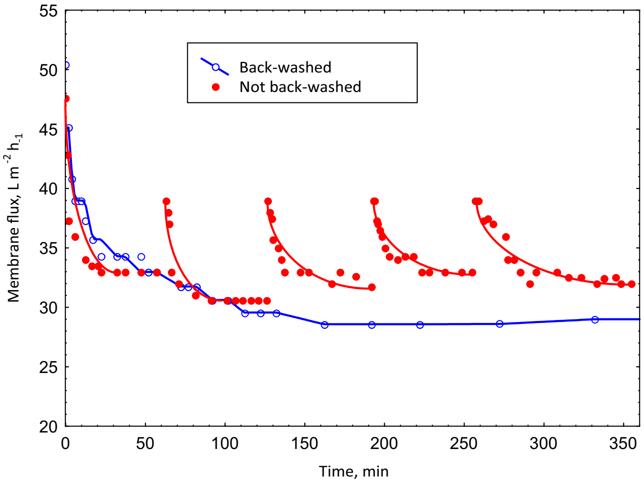

Fig. 7. Effect of backwashing with air on flux recovery at the membrane unit ($\Delta P = 2$ bar, $V_c = 2.87\ \text{m s}^{-1}$).

thus further fouling was diminished or decreased to a minimum. Nonetheless, all fouling mechanisms were eventuated together, especially with activated sludge filtration [12,28].

The experiments on fouling mechanisms and backwashing or cleaning the membrane are ongoing.

4. Conclusions

In this study, the treatment of dairy industry wastewater with a high performance JLMBR was investigated and found to work at very high efficiencies. The results obtained are summarized as follows:

- From the characterization experiments, the concentrations were determined to be 6080–483 mg BOD L^{-1}, 9004–921 COD_T mg L^{-1}, 8064–635 mg COD_S L^{-1}, 230–8 mg TN L^{-1}, 112–9 mg TP L^{-1}, and 804–134 mg SS L^{-1}, giving a BOD/COD_T ratio of 0.68–0.52 and a COD_S/COD_T ratio of 0.90–0.68. The substantial fluctuations especially in COD and BOD concentrations originated from the ratio of cheese whey introduction.
- In the investigated experimental operating conditions, K_La ranged between 100 and 285 h^{-1}. These values are 100 times higher than those for a conventional air diffuser (supplier apparatus).
- A loading rate of 45 kg COD m^3 d^{-1} was achieved with a 98% COD removal efficiency at an HRT of 2.8 days. Also, treatment efficiencies of 97–98% were achieved under 53 kg COD m^3 d^{-1} organic loading rate and 3 h HRT. The performance values (efficiencies according to organic loading rates and HRT) achieved in this study coincide with the highest values in the literature for DW treatment. Experimental results showed that the combination of a high rate biological reactor and membrane filtration was an efficient, reliable and compact process for biological DW treatment. Moreover, excellent purification results (96–99% COD removal) from the combination JLBR and ceramic membrane UF system reduced the cost of additional treatment.
- High MLSS concentrations could be retained in the bioreactor (up to 38,000 mg L^{-1}) with the contribution of the UF membrane unit. Consequently, the high MLSS applied contributed considerably to the high removal efficiencies and performance. In addition, the JLBR could be used for the oxygen transfer for the activated sludge.
- Assuming an excess sludge concentration of 15,000 mg MLSS L^{-1} for a conventional activated sludge plant [18] and 38,000 mg MLSS L^{-1} for the JLMBR system, the excess sludge volume of the JLMBR costs was reduced by about 70%. This is a huge economic advantage.
- During the study, the activated sludge in the bioreactor formed a non-flocculating motile bacteria structure that was slimy and poorly settleable. It was observed that the fluxes decreased with increasing MLSS concentrations. Cake formation fouling was determined as the dominant fouling mechanism and resulted in slower permeation flux decay over time. MLSS in the cake layer were best removed with backwashing. Compressed air was used to clean the membrane effectively of fouling caused mainly by cake formation. A combination cleaning method of chemical cleaning, DI water immersion and compressed air backwashing was the most effective in recovering permeation flux.

Acknowledgement

The authors wish to thank The Scientific and Technological Research Council of Turkey (TÜBİTAK) for their financial support of this research (Project No: 107Y260).

References

[1] B. Sarkar, P.P. Chakrabarti, A. Vijaykumar, V. Kale, Wastewater treatment in dairy industries—possibility of reuse, Desalination 195 (1–3) (2006) 1–306.
[2] T.J. Britz, M. Van Der Merwe, K.H.J. Riedel, Influence of phenol additions on the efficiency of an anaerobic hybrid digester treating landfill leachate, Biotechnol. Lett. 14 (1992) 323–328.
[3] B. Demirel, O. Yenigun, T.T. Onay, Anaerobic treatment of dairy wastewaters: a review, Process Biochem. 40 (8) (2005) 2583–2595.
[4] B. Balannec, G. Gesan-Guiziou, B. Chaufer, M. Rabiller-Baudry, G. Daufin, Treatments of dairy process waters by membrane operations for water reuse and milk constituent's concentration, Desalination 147 (2002) 89–94.
[5] I. Koyuncu, M. Turan, D. Topacik, A. Ates, Application of low pressure nanofiltration membranes for the recovery and reuse of dairy industry effluents, Water Sci. Technol. 41 (1) (2000) 213–221.
[6] C.H. Xing, X.H. Wen, Y. Qian, D. Sun, P.S. Klose, X.Q. Zhang, Fouling and cleaning of microfiltration membrane in municipal wastewater reclamation, Water Sci. Technol. 47 (1) (2003) 263–270.
[7] E. Bouhabila, R. Ben, Aim and Buisson Fouling characterisation in membrane bioreactors, Sep. Purif. 22–23 (2001) 123–132.
[8] T.H. Bae, T.M. Tak, Interpretation of fouling characteristics of ultrafiltration membranes during the filtration of membrane bioreactor mixed liquor, J. Membr. Sci. 264 (1–2) (2005) 151–160.
[9] J. Manem, R. Sanderson, Water Treatment Membrane Process, AWWA Research Foundation, McGraw-Hill, 1996 (chapter 17).
[10] C.J. Bloor, G. Anderson, A.R. Willey, High rate aerobic treatment of brewery wastewater using the jet loop reactor, Water Res. 29 (1995) 1217.
[11] APHA, Standard Methods for the Examination of Water and Wastewater, American Public Health Association, Washington, DC, 2005.
[12] A.L. Lim, R. Bai, Membrane fouling and cleaning in microfiltration of activated sludge wastewater, J. Membr. Sci. 216 (1–2) (2003) 279–290.
[13] T.J. Britz, C. Schalkwyk, Y.T. Hung, Treatment of dairy processing wastewater, in: L.K. Wang, Y.-T. Hung, H.H. Lo, C. Yapijakis (Eds.), Waste Treatment in the Food Processing Industry, Taylor and Francis Group, New York, 2006, pp. 1–29.
[14] E. Guillen-Jimenez, P. Alvarez-Mateos, F. Romero-Guzman, J. Pereda-Martin, Bio-mineralization of organic matter as affected by pH, the evolution of ammonium and phosphates, Water Res. 34 (2000) 1215–1224.
[15] S. Hwang, C.L. Hansen, Characterization of and bio production of short-chain organic acids from mixed dairy-processing wastewater, Trans. Am. Soc. Agric. Eng. 41 (1998) 795–802.
[16] S. Lübbecke, A. Vogelpohl, W. Dewjanin, Wastewater treatment in a biological high performance system with high biomass concentration, Water Res. 29 (3) (1995) 793–802.
[17] F.B. Dilek, G.K. Anderson, J. Bloor, Investigation into the microbiology of a high rate jet-loop activated sludge reactor treating brewery wastewater, Water Res. 34 (5–6) (1996) 107.
[18] G. Tchobanoglous, F.L. Burton, Wastewater Engineering: Treatment, Disposal and Reuse, third ed., Metcalf & Eddy Inc., McGraw-Hill, New York, 1991.
[19] S. Judd, B. Jefferson, Membranes for Industrial Wastewater Recovery and Reuse, Elsevier Science Ltd., New York, 2003.
[20] R.B. Bai, H.F. Leow, Microfiltration of activated sludge wastewater—the effect system operation parameters, Sep. Purif. Technol. 29 (2002) 189.
[21] B. Farizoglu, B. Keskinler, Sludge characteristics and effect of crossflow membrane filtration on membrane fouling in a jet loop membrane bioreactor (JLMBR), J. Membr. Sci. 279 (1–2) (2006) 578–587.
[22] J.S. Kim, C.H. Leeand, H.D. Chun, Comparison of ultrafiltration characteristics between activated sludge and BAC sludge, Water Res. 32 (1998) 3443–3451.

[23] H.F. Ridgeway, H.C. Flemming, Membrane biofouling, in: J. Mallevialle, P.E. Odendal, M.R. Wiesner (Eds.), Water Treatment Membrane Processes, McGraw-Hill, New York, 1996, pp. 6.1–6.62.

[24] P. Wang, K.L. Tan, E.T. Kang, K.G. Neoh, Plasma-induced immobilization of poly (ethylene glycol) onto poly (vinylidene fluoride) microporous membrane, J. Membr. Sci. 195 (2003) 103.

[25] K. Parameshwaran, A.G. Fane, B.D. Cho, K.J. Kim, Analysis of microfiltration performance with constant flux processing of secondary effluent, Water Res. 35 (2001) 4349.

[26] K. Yamamoto, M. Hiasa, T. Mahmood, T. Matsuo, Direct solid–liquid separation using hollow fibre membrane in an activated sludge aeration tank, Water Sci. Technol. 21 (1989) 43.

[27] C. Chiemchaisri, Y.K. Wong, T. Urase, K. Yamamoto, Organic stabilization and nitrogen removal in membrane separation bioreactor for domestic wastewater treatment, Water Sci. Technol. 25 (1992) 231.

[28] J. Wu, P. Le-Clech, R.M. Stuetz, A.N. Fane, V. Chen, Novel filtration mode for fouling limitation in membrane bioreactors, Water Res. 42 (14) (2008) 3677–3684.