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Simultaneous removal of C, N, P from cheese whey by jet loop membrane bioreactor (JLMBR)

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Abstract

The membrane bioreactor (MBR) used in this study consisted of a jet loop bioreactor (aerobic high rate system) and a membrane separation unit (microfiltration). Jet loop membrane bioreactor (JLMBR) system is a high performance treatment system. High organic loading rates can be achieved with a very small footprint. The JLMBR is a compact biological treatment system which requires much smaller tank volumes than conventional activated sludge system. Solid–liquid separation is performed with a membrane. The JLMBR system, of 35 L capacity, was operated continuously for 3 months with a sludge age of 1.1–2.8 days and chemical oxygen demand (COD) loads of 3.5–33.5 kg COD m^{-3} day^{-1}. The mean concentration values of COD, total nitrogen (TN) and PO_4^{3-} in cheese whey (CW) were found as 78,680 mg L^{-1}, 1125 mg L^{-1} and 378 mg L^{-1}, respectively. Ninety-seven percent COD removal rate was obtained at the sludge age (Θ_c) of 1.6 days and volumetric loads of 22.2 kg COD m^{-3} day^{-1}. TN removal was obtained as 99% at the loading rates of 17–436 g TN m^{-3} day^{-1}. PO_4^{3-} removals were between 65 and 88% for the loading of 30–134 g PO_4^{3-} m^{-3} day^{-1}. The system could simultaneously remove the COD, TN and PO_4^{3-} at high efficiencies. The sludge flocks were highly motile, dispersed and had poor settling properties.

Keywords: Jet loop reactor; Membrane filtration; Cheese whey treatment; Biologic nutrient removal

1. Introduction

Cheese-making operations in the dairy industry lead to the production of wastewater with high organic load that causes a serious environmental problem. Cheese whey (CW), which represents about 85–95% of milk volume and retains 55% of milk nutrient, is a protein and lactose rich byproduct of cheese industry and its cost-effective utilization or disposal has become increasingly important due to more stringent legislative requirements for effluent quality [1–3]. Although several possibilities for CW exploitation have been assayed over the last 50 years, approximately half of the world's cheese whey production is not treated, but is discharged as effluent. Cheese whey represents an important environmental problem because of its high volumes and its high organic mater content. Lactose is the main source of high biological oxygen demand (BOD) and high chemical oxygen demand (COD). The protein recovery reduces only about 12% of the whey COD [1]. CW also has high concentrations of nutrient in addition to high concentrations of COD (73,000–86,000 mg L^{-1}). For example, in this study total nitrogen (TN) was in the range of 897–1200 mg L^{-1} and phosphate (P-PO_4^{3-}) was in the range of 420–540 mg L^{-1}. CW is a favorable industrial wastewater in order to test the treatment performance of the JLMBR [4].

Discharging wastewater with high levels of phosphorous (P) and nitrogen (N) can result in eutrophication in receiving waters, particularly in lakes and slow moving rivers. Eutrophication leads to many water quality problems including increased purification costs, interference with the recreational and conservation value of impoundments, loss of live-stock and the possible sublethal effects of algal toxins on humans [5–7]. Furthermore, ammonia nitrogen (NH_4-N^+) with several milligrams per liter is known to impose a toxic effect on aquatic lives. To prevent these conditions, regulatory agencies in many countries have imposed strict nutrient discharge limits for wastewater effluents.

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Nomenclature

B_v	COD load per unit reactor volume (kg COD m^{-3} day^{-1})
B_{vTN}	TN loading (g TN m^{-3} day^{-1})
CW	cheese whey
DO	dissolved oxygen (mg L^{-1})
E	% efficiency
F/M ratio	kg of COD applied per kg of MLVSS per day (kg COD kg $MLVSS^{-1}$ day^{-1})
HRT	hydraulic retention time (day)
JLBR	jet loop bioreactor
JLMBR	jet loop membrane bioreactor
k_d	death coefficient (day^{-1})
M_{syn}	mass of synthesized cell
MBR	membrane bioreactor
MF	microfiltration
MLSS	mixed liquor suspended solid (mg L^{-1})
MLVSS	mixed liquor volatile suspended solid (mg L^{-1})
Q_w	waste sludge flow
SCOD	soluble chemical oxygen demand (mg L^{-1})
SVI	sludge volume index (mg L^{-1})
TCOD	total chemical oxygen demand (mg L^{-1})
TN	total nitrogen (mg L^{-1})
V	volume of wastewater
Y	excess sludge yield coefficient (kg MLVSS kg COD^{-1})
Θ_c	sludge age (day)

It is important that CW has to be treated at very high degree and then should be discharged to the receiving waters. If for any reason (economic, sanitary, local) whey valorization technologies (such as protein and lactose recovery, spray drying, etc.) or direct utilization of whey for animal feed is not applicable, anaerobic treatment has been suggested for the treatment of CW [3,8]. Many laboratory and pilot-scale trials of anaerobic treatment of whey have been conducted [9,10]. The majority of these studies dealt with de-proteinated or diluted whey, which is easier to treat [3]. However, raw whey is quite a problematic substrate to treat anaerobically because of low bicarbonate alkalinity (~50 mEq L^{-1}), high COD concentration (~70 g COD L^{-1}), the tendency to produce an excess of viscous exopolymeric materials of probable bacterial origin severely reduces sludge settleability [11]. Moreover, direct treatment of raw whey in high loaded anaerobic reactors is considered as not very reliable due to difficulties frequently encountered in maintaining a stable operation [3]. In the last few years there has been an increasing interest in high performance aerobic reactors for the treatment of high strength industrial wastewaters [4,12].

Jet loop bioreactors (JLBRs) are important type of high efficiency compact reactors, the efficiency of which has already been shown in both chemical and biochemical processes. These reactors may be ideal reactor typology for an effective solution for the treatment of CW [12,13]. JLBRs are able to deal with very high organic loading rates due to the high efficiency of oxygen transfer, high mixing and turbulence capacity [14]. In addition, JLBRs are generally characterized by reduced tank volumes, which means limited land requirements, reduced installation and maintenance costs and limited energy consumption [12,15].

In order to improve the performance of the JLBR, the bioreactor should be operated at high biomass concentrations. However, high biomass concentrations may cause sludge settling problems in the activated sludge process [16,17]. Membrane filtration is a suitable technique to allow high concentration of biomass in the bioreactor. Application of membrane separation techniques for bio-solids can overcome the disadvantages of sedimentation tank. A bioreactor integrated to membrane module system is usually referred as membrane bioreactor (MBR). The combination of a bioreactor and membrane filtration for various treatment schemes has also been investigated by other authors [17,18]. Yildiz et al. have obtained approximately 97% removal efficiency for volumetric organic loads of 2–97 kg COD m^{-3} day^{-1} at the JLMBR [19].

The aim of this study was to assess the technical feasibility of the aerobic treatment of raw CW using a JLMBR and to investigate the simultaneous treatment capability of C, N and P.

2. Materials and methods

2.1. Wastewater characteristics

Approximately 15–20 L of CW was collected from the cheese factory every two days for the whole experimental period. All experiments were carried out in mesophilic conditions, utilizing raw CW as substrate. CW main characteristics are presented in Table 1. High concentrations of organic materials (73,000–86,000 mg COD L^{-1}) were found mainly in dissolved phase where 82% of total COD (TCOD) was dissolved. The COD and other parameter values (e.g. TSS, TN, PO_4^{3-}) that were measured in this study lie in the range which is conformable to those given in literature [1,3,8].

2.2. Parameters investigated and methods of analyses

Samples of influent and effluent were taken daily from the JLMBR system during 120 days. Parameters such as COD, MLSS, MLVSS, N-NO_3^-, PO_4^{3-} and N-NO_2^- were analyzed as defined in Standard Methods [20]. Total nitrogen (TN)

Table 1
Raw CW characteristics

Parameter	Unit	Range
TCOD	mg L^{-1}	73,000–86,000
SCOD	mg L^{-1}	59,000–71,000
TSS	mg L^{-1}	20,000–22,000
VSS	mg L^{-1}	8500–13,200
TN	mg L^{-1}	897–1200
N-NH_4^+	mg L^{-1}	58–150
N-NO_3^-	mg L^{-1}	7–10
PO_4^{3-}	mg L^{-1}	336–434
TP	mg L^{-1}	420–540
pH		4.5–5.0

and $N\text{-}NH_4^+$ were measured by using commercial test kits obtained from Merck Company. The soluble (filtered) COD (SCOD) was defined as the filtrate through Whatman GF/C glass-fiber filters, also used in the determination of MLSS and MVLVSS.

2.3. Theoretical nitrogen removal analysis

In order to determine the nitrogen removal mechanism, a theoretical approach was performed. In this study, a theoretical solid retention time ($\text{SRT} = \Theta_c$) was calculated by the following equation [21]:

$$\frac{1}{\Theta_c} = Y\frac{F}{M}\frac{E}{100} - k_d \qquad (1)$$

It was assumed that the state of the microorganisms was similar to that of conventional activated sludge process. The amount of the cell growth that was equal to the excess sludge was calculated using the following equations assuming that the cell composition is $C_5H_7O_2N$. The nitrogen consumed by cell synthesis was calculated from the theoretical Θ_c [21].

$$\Theta_c = \frac{V}{Q_w} \qquad (2)$$

$$M_{syn} = Q_w\,\text{MLVSS} = \text{MLVSS}\left(\frac{V}{\Theta_c}\right) \qquad (3)$$

$$N_{consumed} = \frac{14}{113}M_{syn} \qquad (4)$$

$N_{consumed}$ is the amount of nitrogen consumed by cell synthesis (g per day).

It could be expected that nitrogen calculated from the above equations was consumed by cell synthesis while residual nitrogen in the influent was removed by nitrification–denitrification.

2.4. Jet loop bioreactor (JLBR)

JLBMR (working volume of approximately 35 L) used in this study is shown in Fig. 1. The down-flow jet loop bioreactor was connected to a cross-flow microfiltration unit (CFMF). The reactor consists of a cylindrical vessel (height 1400 mm, inner diameter 140 mm) with a height to diameter ratio of about 7:1. It carries inside a draft tube open at both ends and a degassing tank. The two-phase jet located at the top of 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 liquid jet. Due to the momentum of liquid jet, the liquid and the gas inside the draft tube move downwards and after reaching the bottom of the reactor, they rise within the

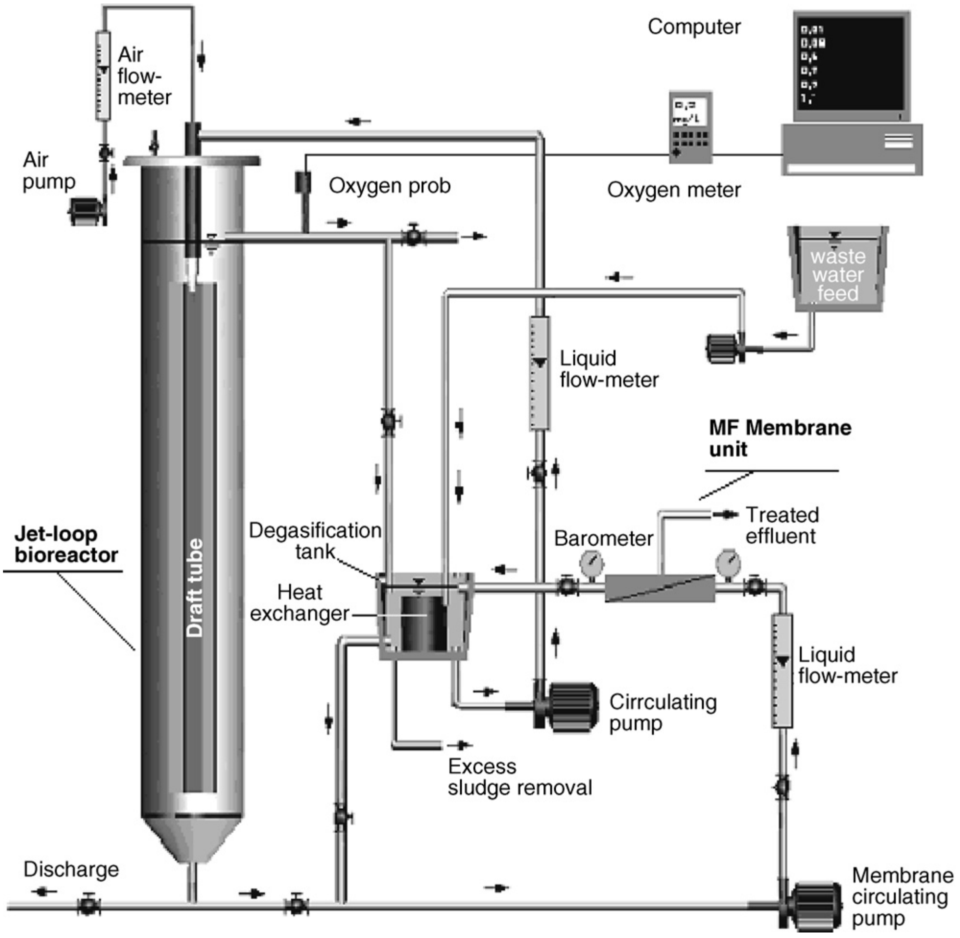

Fig. 1. The experimental setup of JLMBR.

Table 2
Specifications of the microfiltration membrane

Manufacturer	Schleicher & Schuell
Material	Cellulose acetate
Surface area	155 cm^2
Pore diameter	0.45 μm
Maximum membrane pressure	3.5 bar
Maximum temperature	28 °C

annulus between the wall of the reactor and the draft tube. At the upper end of the draft tube, some part of fluid is recycled into the draft tube by sucking action of the two-phase jet resulting in a re-dispersion of the bubbles and the biomass produced in the biological reaction. The temperature of bioreactor content was maintained around 24 ± 2 °C by circulating tap water through a stainless steel heat exchanger immersed in the degassing tank. CW was pumped from the feed tank into the degassing tank by a peristaltic pump. The recycle flows (for JLBR and CFMF unit) were measured by two flow meters and airflow supplied to bioreactor was measured by an air flow meter. Dissolved oxygen (DO), temperature and pH were measured with a multi-parameter measurement device (WTW multi 340i) placed in the recycle side. The DO data obtained through DO meter were collected in a computer for further analysis.

2.5. Membrane filtration unit

The separation of activated sludge took place in the ultrafiltration or microfiltration unit (Osmonics) which was integrated into the external circuit of the JLBR. In the external circuit, permeate was extracted by circulating the mixed liquor at high pressure through the membrane surface. The concentrated mixed liquor at the feed side was recycled back to degasification tank. The pump used for circulation was made of stainless steel. The excess sludge was removed via a peristaltic pump from the degasification tank, once desired biomass concentration was reached or exceeded. The specifications of the microfiltration membrane are shown in Table 2.

2.6. Operating conditions

The operating parameters for the reactor and microfiltration unit varied throughout the test period (approx. 90 days). These parameters are presented in Table 3.

The sludge age of the system was adjusted based on the values of membrane flow rates. The amount of the waste sludge was computed by subtracting the membrane flow rate value from feed flow rate. The following variables were kept constant:

- the flow of air: 6 L min^{-1};
- the temperature of reactor: 24 ± 2 °C;
- pH value: 7.6 ± 0.3;
- energy input: 0.9 kW m^{-3}.

Table 3
Operation conditions

Biomass concentration in the reactor	5800–14,000 g $MLSS^{-1}$ L^{-1}
COD loading (B_v)	3–33 kg COD m^{-3} day^{-1}
TN loading (B_{vTN})	17–436 g TN m^{-3} day^{-1}
PO_4^{3-} loading (B_{vP})	30–134 g PO_4^{3-} m^{-3} day^{-1}
Sludge loading	0.5–6.5 kg COD kg $MLVSS^{-1}$ day^{-1}
Hydraulic wastewater retention time	0.82–2.8 days
Sludge age	1.1–2.8 days

2.7. Start-up and treatment conditions

The JLBR was seeded with mixed liquor from an activated sludge plant treating mainly food industry wastewater. The initial operating temperature of the reactor was 23–25 °C. In order to increase the amount of activated sludge within the bioreactor, initially, the JLBR was operated in repeated-batch process, of 2–3 days each for a total period of 30 days. At the end of this period, the JLBR fed continuously and the concentration of activated sludge reached was approximately 5800 mg L^{-1}. During both the batch and continuous operating conditions, DO levels in the reactor were maintained in the range of 1.5–3.0 mg L^{-1}.

3. Results and discussions

The JLBRs, which are developed as a high-rate compact biological process for high organic loadings, achieve high efficiency of oxygen transfer, high mixing and turbulence. The JLB having a draft tube with square cross-sectional area was used in this study. Farizoglu [4,22] stated that the JLBR having a draft tube with square cross-sectional area provided higher K_La than a draft tube with circular cross-sectional area.

3.1. The COD removal performance

The JLMBR was continuously operated over the 12 weeks period. Fig. 2 shows time course of the CW wastewater treatment performance of JLMBR system. The organic loading rate (B_v) was gradually increased from 3.5 to 22.5 kg COD m^{-3} day^{-1} after only 25 days from start-up and than reduced to 16 kg COD m^{-3} day^{-1}. Then, it was increased again to 24 kg COD m^{-3} day^{-1} and then 33.5 kg COD m^{-3} day^{-1}. Each volumetric loading to the reactor continued until the amount of incoming wastewater was more than 4–5 folds of the reactor volume that passed through the JLMBR. When the system was in steady-state, the effluent COD values remained in a narrow band. After the 60th day, B_v was decreased to 10 kg COD m^{-3} day^{-1} and than gradually increased to 22 kg COD m^{-3} day^{-1}. With the exception of the time intervals 24th–34th days and 50th–60th days, the COD removal efficiencies were always more than 94%. Except for these two periods, it is interesting to note that fluctuations in the inlet loading result in only minor reductions in the system performance. First 18 days, B_v was increased from 3.5 to 12 kg COD m^{-3} day^{-1} resulting in a reduction of COD removal efficiency of 99–94%. In general, the JLMBR demonstrated a high tolerance to short time changes in the applied B_v. The excellent reactivity of the system to sudden variations of loading rate was a clear indication of good adaptability and flexibility. This appears to be of particular interest in view of final practical applications at the industrial level considering the wide

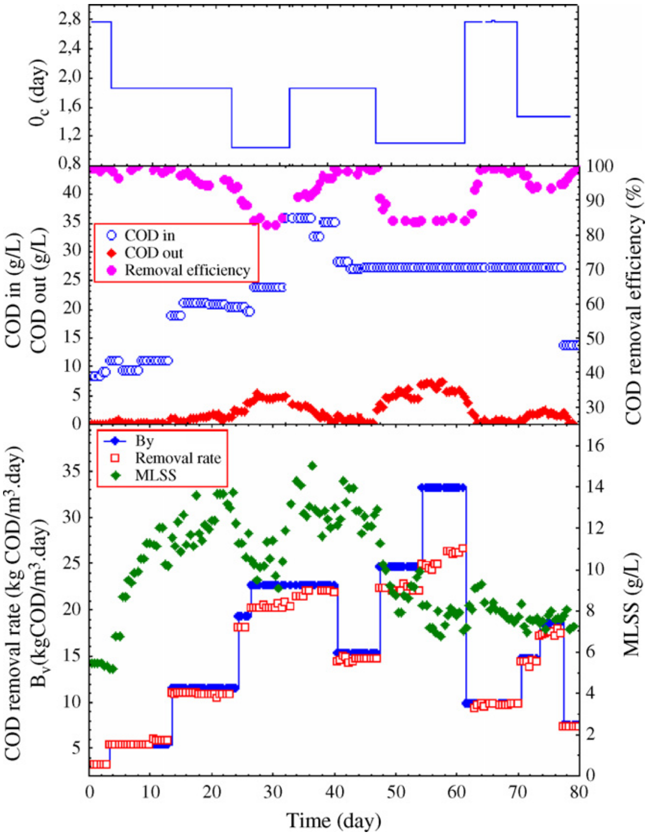

Fig. 2. Time course of the CW wastewater treatment process using the JLMBR.

variability of CW in terms of organic matter and volumes. The excellent performance of the JLMBR was due to the result of very large surface area of the oxygen bubbles. In addition to that, shear field also leads to the formation of very small bacterial agglomerates, with a correspondingly high specific surface area, allowing improved transfer of both oxygen and substrate [23].

The hydraulic retention time (HRT) varied between 0.82 and 2.8 days. During the experiments, the sludge retention time (Θ_c) was changed between 1.1 and 2.8 days. Fig. 2 shows the effect of influent COD and Θ_c on the removal efficiency of the JLMBR system. It was shown that the COD removal efficiency decreased below 90% if Θ_c was less than 1.1 days. Likewise, it was determined that if Θ_c was higher than 1.4 days, the COD removal efficiencies were continually above 95%. Influent COD concentration varied in the range 8400–36,000 mg L^{-1}. Despite this wide range of influent COD concentration, effluent COD removal efficiency showed a satisfactory performance (84–99%).

COD removal rate is an important performance parameter in biological processes, which defines organic matter removal in unit volume and time. Organic matter removal rates, removal efficiencies and effluent COD concentrations are shown in Fig. 2. At loading rates in the range of 3.5–22 kg COD m^{-3} day^{-1}, COD removal efficiencies were highest (between 95 and 99%). Within this range, the relation between B_v and COD removal rate was linear. In that way, at B_v of 22 kg COD m^{-3} day^{-1}, organic removal rate was 20.6 kg COD m^{-3} day^{-1}. In contrast, over the B_v of 22 kg COD m^{-3} day^{-1}, the differences between B_v and organic removal rates began to increase. Thus, at B_v of 33.5 kg COD m^{-3} day^{-1}, the organic removal rate was 24.5 kg COD m^{-3} day^{-1}. In this case, the COD removal efficiency was approximately 85%.

Fig. 2 also shows the relationship among MLSS concentration, B_v, and COD removal rate. It was seen that increasing MLSS concentration increased the COD removal rate. For example, when the MLSS concentration reached 12,000 mg L^{-1}, the COD removal rate measured as 22 kg COD m^{-3} day^{-1} at 36–42nd days. Since the reaction rate in wastewater treatment is directly proportional to the biomass concentration, organic removal rate increased with the amount of MLSS concentration. Nonetheless, the increase of biomass concentration is limited by the physical properties of the sludge-wastewater-suspension. The investigations illustrated that with increasing biomass concentration, the mass transfer (oxygen transfer) decreases depending on composition of wastewater [18].

In this study, foaming of the bioreactor was found to be a common occurrence when changed or increased organic loading rates were applied. During steady-state conditions the foaming reduced to a minimum. At the same time, it was observed that the activated sludge formed a biofilm layer, adhering to the reactor inner wall. The biofilm layer reached a maximum thickness then mixed to circulation and broken down from the reactor inner wall. The JLMBR system was operated at high food/microorganism (*F*/*M*) ratios such as 6 (kg of COD applied per kg of MLSS per day). The *F*/*M* ratio was markedly increased with increasing organic loading. Fig. 3 shows the relation between *F*/*M* and COD removal rate. The possibility of operating at high *F*/*M* ratios was extremely important since this means low amounts of waste sludge [15]. In classical activated sludge systems, *F*/*M* ratio changes in the range of 0.42–0.84 kg COD kg MLVSS^{-1} day^{-1}.

It was seen that the activated sludge formed in the JLMBR was having poor settling capacity and very slimy characteristics. Since the sludge flocks remained unsettled for a long time it was unable to determine the sludge volume index (SVI). Poor sludge settleability is one of the most serious problems with JLBRs. The activated sludge in JLMBR was highly motile when observed

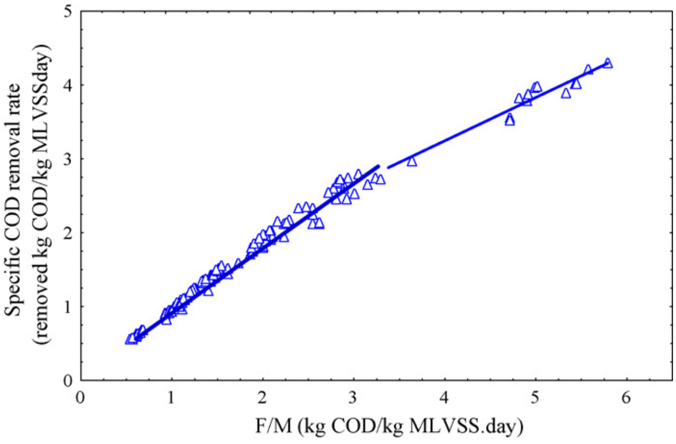

Fig. 3. COD removal vs. *F*/*M* ratio for CW wastewater.

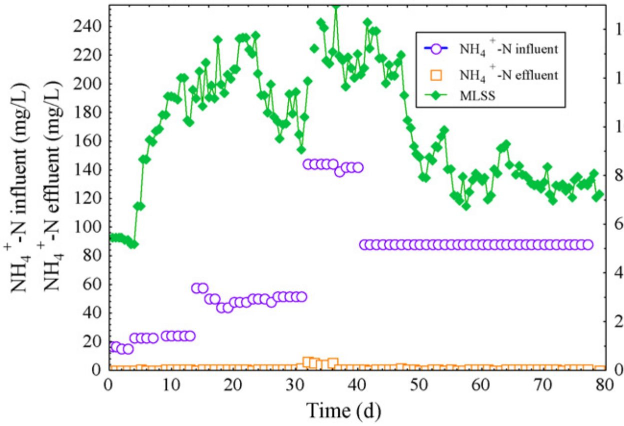

Fig. 4. Influent–effluent NH_4^+-N and MLSS concentrations in JLMBR against operating time.

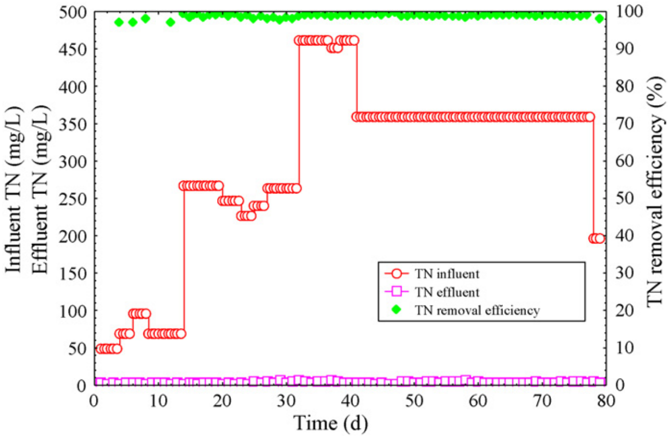

Fig. 5. Influent–effluent TN concentration and removal efficiency in JLMBR against operating time.

under a microscope and appeared to flocculate less readily than sessile bacteria. Also, microscopic examination of the biomass showed that no filamentous bacteria or protozoa were present in the flocks. It was considered that 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 were all the factors in high degree of observed microbial selection. Moreover, in the case of poor settling sludge, the nature of the CW played an important role. In typical CW, proteins and fats are present at considerable concentrations. Therefore, problems of sludge settleability and development of sludge with low functioning potential were also attributed to presence of fats in CW. It is stated that sludge fed with wastewater rich in protein had a very slimy appearance and its settling characteristics were lower [24,25]. It was most likely that the presence of poor settleability sludge was a combination of those factors.

As conventional sedimentation does not allow for an efficiently solid–liquid separation, due to the reasons mentioned above, the application of membrane process had been investigated in our study. The advantage of a membrane separation was that the wastewater was completely free of any solids or infectious organisms. In addition, by choosing the proper cut-off size of the membrane, it is possible to decouple the residence time of the wastewater from the residence time of the higher molecular weight compounds of the wastewater [13]. Compounds with high molecular weight were retained in the system until special microorganisms capable of degrading the large molecules developed. Thus, the performance of the biological treatment was enhanced.

3.2. The nitrogenous matter removal performance

If it is not treated, CW is a high concentrate wastewater with respect to nitrous and phosphorous matter content. Therefore, CW wastewaters must be discharged to the receiving stream after treated at high efficiency. From Table 2, it is seen that the majority of TN was present as organically bound N (e.g. proteins) and that the conversion of amino groups to ammonia was incomplete. Fig. 4 shows the change of influent and effluent NH_4^+-N concentrations with the operating time. It was seen that while the influent NH_4^+-N concentrations were differing between 15 and 144 mg L^{-1}, the effluent NH_4^+-N concentrations differed between 0.3 and 6.0 mg L^{-1}. During the study period, except for the days 31–36, the effluent NH_4^+-N concentrations were measured less than 1 mg L^{-1} and corresponding $NH4^+$-N removal efficiencies were calculated around 99%.

The influent and effluent TN concentrations and TN removal efficiencies of CW are shown in Fig. 5. It was seen that the influent TN concentrations varied between 50 and 460 mg L^{-1}. Although, the values were too high, the TN removal efficiencies were always higher than 99% during the operation time (Fig. 5).

The variations of TN removal rates and efficiencies against the TN loading rate (B_{vTN}) are shown in Fig. 6 during the operation time. It was seen that the TN removal rates of the system increased linearly with the B_{vTN}. The influent TN was completely removed by the JLMBR system.

The nitrous matter in the CW is derived from the protein content of milk. Therefore, the treatment of CW wastewater is difficult by conventional aerobic methods. Biological nitrogen removal can be accomplished in two different ways. Nitrogen is consumed as nutrient for synthesis of new cells (assimilation) and can be removed by nitrification–denitrification [21,26]. One of the most critical parameters of the nitrification pro-

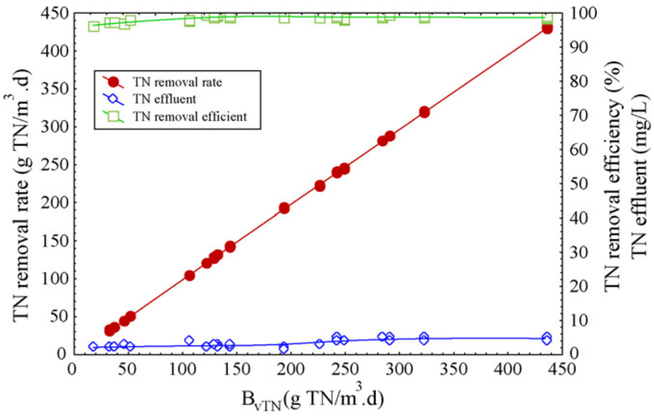

Fig. 6. The TN removal performance vs. B_{vTN}.

Table 4
Obtained Θ_c and theoretical nitrogen consumed by cell synthesis

Θ_c (day)	Influent TN (g day^{-1})	Cell synthesis (g day^{-1})	Consumed nitrogen (g day^{-1})
1.11	10.4	183	23
1.48	8.1	131	16
1.58	9.3	194	24
2.78	4.2	74	9

cess is the influent chemical oxygen demand to nitrogen ratio (COD/N). It directly influences the growth competition between autotrophic and heterotrophic microorganism populations. It has been reported that when the BOD to TKN ratios were 1, 5, and 9, the nitrifier fractions would be 21, 5.4, and below 3%, respectively. In this study, since the BOD to TN ratios were high (from 55 to 65); it was assumed that nitrifiers were not significantly cultured in the bioreactor. It is also true that nitrification process should not occur under these low sludge ages (1.1–2.8 days). Besides, measured low NO_3^- concentrations (<2 mg L^{-1}) in the bioreactor demonstrate that the nitrification process did not occur despite the jet loop bioreactor (JLBR) had a very high O_2 transfer capacity. Hence, it was assumed that the TN removal was only by cell synthesis. The amounts of theoretical nitrogen necessary for cell synthesis at various Θ_c are shown in Table 4. The theoretical values of nitrogen by cell synthesis were 1–2 folds higher than the amount of influent nitrogen. The theoretical analysis showed that nitrogen was mainly consumed by cell synthesis. Thus, nitrogen might be a limiting nutrient for cell growth. Since nitrification and denitrification did not take place, nitrite and nitrate were not measured in the effluent and bioreactor mixed liquor.

3.3. The phosphorus matter removal

The influent and effluent PO_4^{3-} concentrations and MLSS contents of the JLMBR system during the operation time are shown in Fig. 7.

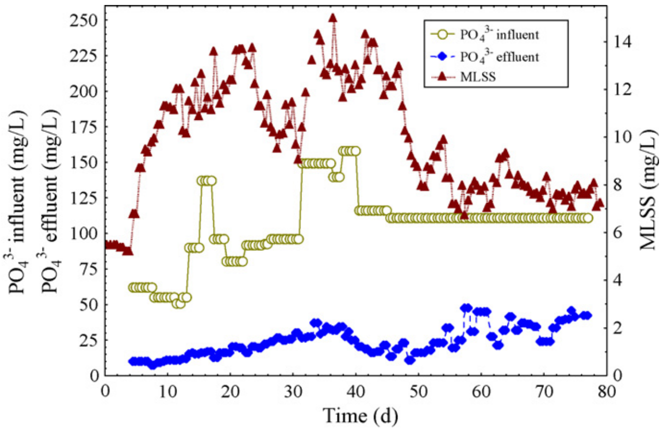

Fig. 7. Influent–effluent PO_4^{3-} and MLSS concentrations in JLMBR against operating time.

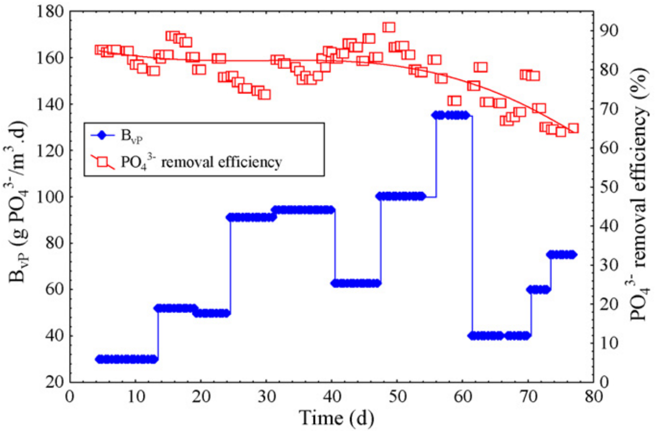

Fig. 8. The B_{vP} and PO_4^{3-} removal efficiency changes in JLMBR system during the operation time.

While the influent PO_4^{3-} concentrations to the system were varying in the range 55–150 mg L^{-1}, the effluent PO_4^{3-} concentrations changed between 7 and 47 mg L^{-1}. It can be seen from Fig. 7 that the influent PO_4^{3-} content of the wastewater was very high. Also, the B_{vP} and PO_4^{3-} removal efficiencies are shown in Fig. 8. Accomplished removal efficiencies were between 65 and 85%.

Conventional secondary biological treatment systems accomplish partial phosphorus removal by using phosphorus for biomass synthesis during BOD removal. A typical phosphorus content of microbial solids is 1.5–2% based on dry weight. Wasting of excess microbial solids may result in a total phosphorus removal of 10–30%, depending on the BOD to phosphorus ratio, the system sludge age, sludge handling techniques and side stream return flows [27]. On the other hand, additional biological phosphorus removal will occur if the mixed liquor is subjected to both anaerobic and aerobic conditions. When an anaerobic stage (absence of DO and oxidized nitrogen) precedes an aerobic stage, fermentation products are produced from the BOD in the wastewater by the action of facultative microorganisms. The phosphorus-storing microorganisms are able to assimilate the fermentation products under anaerobic conditions. This is the phosphorus microorganisms' distinct advantage over other organisms in activated sludge system. Because many competing microorganisms cannot function in this manner thus, the anaerobic phase results in the development of phosphorus storing microorganisms [28,29]. During the aerobic phase the stored substrate products are depleted and soluble phosphorus is taken up by the microorganisms in quantities greater than what is needed to function.

In this study, PO_4^{3-} was not readily removed due to the limit of the biological process. This limit could be attributed to the fact that removal of phosphorus ultimately depends on the amount of excess sludge wasting. It was assumed that cell synthesis provides a substantial contribution to the PO_4^{3-} removal efficiencies because of high MLSS concentrations (between 6000 and 14,500 mg L^{-1}) in the JLMBR system. In addition, CW includes the considerable concentrations of ions, e.g. Na^+, Ca^{2+}. These ions could constitute phosphate precipitates. This was assumed as another way of PO_4^{3-} removal.

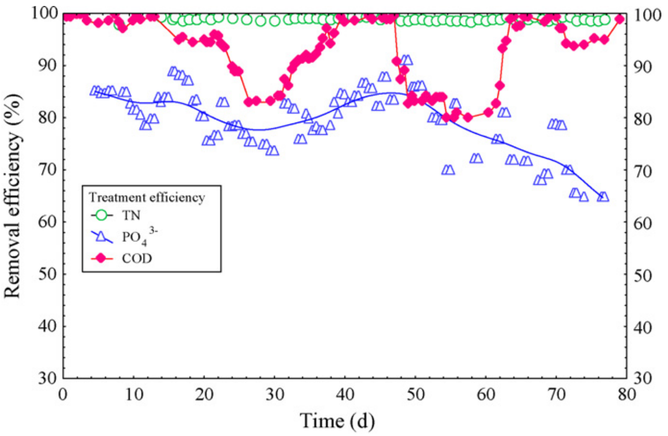

Fig. 9. The simultaneous COD, TN, and PO_4^{3-} treatment performance of the JLMBR.

Despite the fact that the system was not projected and operated for the phosphorus removal, it was so affirmative that the JLMBR obtains the PO_4^{3-} removal efficiencies between 64 and 85%. In order to achieve better PO_4^{3-} treatment performance, various operation conditions should be examined in the JLMBR system. Fig. 9 shows simultaneous COD, TN and PO_4^{3-} treatment performance of the JLMBR.

4. Conclusions

Raw CW wastewater from dairy industry was successfully treated in a JLMBR system. Results obtained from the JLMBR system are summarized as follows:

1. In continuous operating regime, volumetric loading rates increased up to 33.5 kg COD m^{-3} day^{-1}. Ninety-seven percent of COD removal efficiency was obtained under the B_v of 22.2 kg COD m^{-3} day^{-1} and 1.6 days of sludge age. Suspended solids free effluent could be obtained using membrane separation.
2. B_{vTN} were varied between 17 and 440 mg TN m^{-3} day^{-1}. Nitrogen removal efficiency was achieved around 99% throughout the operation. Nitrifying bacteria were not cultivated adequately due to the high COD/N ratios of influent and low sludge ages. Therefore, nitrogen was mainly consumed as a nutrient for the synthesis of new cells (assimilation).
3. JLMBR accomplished PO_4^{3-} removal efficiencies between 64 and 85%. The high phosphorus concentration of the influent yielded low removal efficiency due to the limitation of the biological removal process.

After 3 months of laboratory experience, it could be stated that the combination of a high performance JLBR and MF membrane unit was an efficient, reliable and compact process for biological treatment of raw cheese whey. The higher investment and operating costs of the MF unit compared to a clarifier are among the disadvantages of the MF technique. With regards to the economics of a treatment system it was vital to take into account the respective effluent data, the remaining high loads and their removal, the safety and flexibility of operation and local requirements. Taking this into account, a combination of a JLBR and a membrane filtration may be economically advantageous. In conclusion, the aerobic treatment of cheese whey using jet loop membrane bioreactors at high performance is technically feasible and appears to be encouraging.

References

[1] G.M.I. Siso, The biotechnological utilization of cheese whey: a review, Biores. Technol. 57 (1996) 1–11.
[2] A.J. Mawson, Bioconversions for whey utilization and waste abatement, Biores. Technol. 47 (1994) 195–203.
[3] S.V. Kalyuzhny, E.P. Martinez, J.R. Martinez, Anaerobic treatment of high-strength cheese-whey wastewaters in laboratory and pilot UASB-reactors, Biores. Technol. 60 (1997) 59–65.
[4] B. Farizoglu, B. Keskinler, E. Yildiz, A. Nuhoglu, Cheese whey treatment performance of an aerobic jet loop membrane bioreactor, Process Biochem. 39 (2004) 2283–2291.
[5] S. Yeoman, T. Stephenson, J.N. Lester, R. Perry, The removal of phosphorus during wastewater treatment: a review, Environ. Pollut. 49 (1988) 183–233.
[6] J.W. Mcgrath, S. Cleary, A. Mullan, J.P. Quınn, Acid-stimulated phosphate uptake by activated sludge microorganisms under aerobic laboratory conditions, Water Res. 35 (18) (2001) 4317–4322.
[7] S.I. Lee, S.Y. Weon, C.W. Lee, B. Kopman, Removal of nitrogen and phosphate from wastewater by addition of bittern, Chemosphere 51 (2003) 265–271.
[8] F. Malaspina, C.M. Cellamare, A. Tilche, Anaerobic treatment of cheese-whey with a downflow–upflow hybrid reactor, Biores. Technol. 55 (1996) 131–139.
[9] J.Q. Yan, K.V. Lo, P.H. Liao, Anaerobic digestion of cheese whey using up-flow anaerobic sludge blanket reactor, Biol. Waste 27 (1989) 289–305.
[10] A. Cohen, J.H. Thiele, J.G. Zeikus, Pilot scale anaerobic treatment of cheese whey by substrate shuttle process, Water Sci. Technol. 30 (12) (1994) 433–442.
[11] T.H. Ergüder, U. Tezel, E. Güven, G.N. Demirer, Anaerobic biotransformation and methane generation potential of cheese whey in batch and UASB reactors, Waste Manage. 21 (2001) 643–650.
[12] M. Petruccioli, J.C. Duarte, A. Eusebio, F. Federici, Aerobic treatment of winery wastewater using a jet loop activated sludge reactor, Process Biochem. 37 (8) (2002) 821–829.
[13] A. Vogelpohl, Wastewater treatment by the HCR-process, Acta Biotechnol. 20 (2) (2000) 119–128.
[14] 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) 107–112.
[15] J. Bloor, G. Anderson, A.R. Willey, High rate aerobic treatment of brewery wastewater using the jet loop reactor, Water Res. 29 (1995) 1217–1223.
[16] A.D. Bailey, G.S. Hansford, P.L. Dold, The use of microfiltration to enhance the performance of activated sludge reactor, Water Res. 28 (1994) 297–301.
[17] L. Defrance, M.Y. Jaffrin, B. Gupta, P. Paullier, V. Geaugey, Contribution of various constituents of activated sludge to membrane bioreactor fouling, Biores. Technol. 73 (2000) 105–112.
[18] 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.
[19] E. Yildiz, B. Keskinler, T. Pekdemir, G. Akay, A. Nuhoglu, High strength wastewater treatment in a jet loop membrane bioreactor: kinetics and performance evaluation, Chem. Eng. Sci. 60 (4) (2005) 1103–1116.
[20] American Public Health (APHA), Standard Methods for Examination of Water and Wastewater, 16th ed., APHA, Washington, DC, 1992.
[21] G. Tchobanoglous, F.L. Burton, Wastewater Engineering: Treatment, Disposal and Reuse, third ed., Metcalf & Eddy Inc., McGraw-Hill, New York, 1991.

[22] B. Farizoglu, The treatment of cheese whey in jet loop bioreactor equipped with membrane filtration unit, Ph.D. thesis, Ataturk University, Erzurum, Turkey, 2003.

[23] E.A. Naundorf, Biological treatment of wastewater in the compact reactor, Chem. Eng. Process. 17 (1985) 229–233.

[24] R. Samson, B. Van den Berg, R. Peters, C. Hade, Dairy waste treatment using industrial-sale fixed-film and up flow sludge bed anaerobic digester: design and start-up experience, in: Proceedings of the 39th Industrial Waste Conference at Purdue, Lafayette, IN, 1985, pp. 235–241.

[25] M. Perle, S. Kimchie, G. Shelef, Some biochemical aspects of the anaerobic degradation of dairy wastewater, Water Res. 29 (6) (1995) 1549–1554.

[26] C.W. Randall, J.L. Barnard, H.D. Stensel, Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal, Technomic Publishing, Lancaster, PA, 1992.

[27] Process Design Manuel for Phosphorus Removal, EPA/625/1-87/001, Environmental Protection Agency, Cincinnati, Ohio, 1987.

[28] M.C. Goronszy, D. Rigel, Biological phosphorus removal in a fed-batch reactor without anoxic mixing sequences, Res. J. Water Environ. Federation 63 (5) (1991) 248–258.

[29] R.Y. Surampalli, R.D. Tyagi, O.K. Scheible, J.A. Heidman, Nitrification, denitrification and phosphorus removal in sequential batch reactors, Biores. Technol. 61 (1997) 151–157.