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Evaluation of a membrane bioreactor on dairy wastewater treatment and reuse in Uruguay

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ABSTRACT

Eutrophication episodes have been recently observed in the Santa Lucia river basin (SLRB) in Uruguay, the main drinking water source for approximately 60% of the Uruguayan population. The local environmental authorities have been strengthening the discharge standards for that particular river basin. There are several industries currently discharging their wastewater directly into the SLRB; some of these industries are required to upgrade their current wastewater treatment systems to comply with the new regulations. This study evaluated the performance of a membrane bioreactor (MBR) on dairy wastewater as a potential treatment technology for fulfilling the new discharge standards. A pilot MBR was placed at the dairy industry wastewater treatment system at two different locations: (i) receiving the wastewater from the industrial process after passing through a grease removal pond (high load stream); and (ii) receiving the wastewater after passing through the grease removal pond and an anaerobic pond (low load stream). The pilot MBR was operated at the following conditions for approximately four months: total sludge retention, hydraulic retention time (HRT) of 25 h, an average influent flow rate of 1.3 m^3 day^{-1}, and at two different average chemical oxygen demand (COD) influent concentrations: 1300 mg L^{-1} (high load stream) and 385 mg L^{-1} (low load stream). The average reported removal efficiencies on COD, biological oxygen demand (BOD), and ammonium (NH_4-N) were 94.1, 98.1, and 99.6%, respectively. In addition, it was observed that for a COD/N ratio above 10, total nitrogen (TN) and total phosphorous (TP) were well removed with average removal efficiencies of 93.1 and 91.0%, respectively. The MBR effluent met the new Uruguayan standards for discharging into the SLRB, and it can be further considered for water reuse at the industrial process. Moreover, a financial feasibility study was carried out for the implementation of a full scale MBR at the existing dairy facility. The results of the feasibility study suggested to accept the investment for the implementation of the MBR technology at the dairy industry. The results of the feasibility analysis considered the high impact of penalties and fines imposed by the local government to the industry when not complying with the effluent discharge standards, as well as the critical situation regarding eutrophication of the SLRB while being the most important source for drinking water in Uruguay.

1. Introduction

The SLRB is one of the most important sources of fresh water for human consumption in Uruguay providing drinking water to approximately 60% of the Uruguayan population. Approximately 400,000 m^3 day^{-1} of water are extracted from the SLRB to supply drinking water to the metropolitan area of Montevideo, the capital of Uruguay. The water quality of the SLRB has deteriorated by the uncontrolled discharge of nutrients to the basin; trophic conditions have been frequently observed (El País, 2015a). Several industries are located at the proximities of the SLRB including slaughterhouses, dairy processing plants, tanneries, fertilizer production industries, among others. A study conducted at several industrial wastewater treatment plants located at the SLRB concluded that most of the industries were not complying with the local standard

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(Decree 253/79 regulating the water code Law No: 14859) as follows: 86% of the industries were not complying with the NH_4-N effluent standard set at 5 mg L^{-1}, 71% were not to complying with the TP standard set at 5 mg L^{-1}, and 43% exceeded the BOD standard set at 60 mg L^{-1} (DINAMA, 2010).

The dairy sector is one of the main industrial activities in Uruguay. This sector has been continuously growing in terms of production capacity and exports during the last four decades. Approximately more than half of the total dairy industries in Uruguay are located in the proximity of the SLRB, and are currently discharging their wastewater into the SLRB. The dairy industry is considered among the food industries as one of the most polluting sectors (Andrade et al., 2013; Mendes et al., 2014). Dairy wastewater is characterized by a high content of BOD, COD, dissolved and suspended solids, fats and oils, and nutrients (Praneeth et al., 2014; Farizoglu and Uzuner, 2011). The dairy sector in Uruguay continuously discharges to the SLRB approximately 275 kg of BOD day^{-1}, 46 kg of TN day^{-1}, and 21 kg of TP day^{-1} (DINAMA, 2010).

Most of the dairy industries in Uruguay are provided with their own wastewater treatment system; commonly, natural wastewater treatment systems such as ponds and wetlands. Disadvantages of natural systems include the requirement of large surface area and low wastewater treatment removal efficiencies on organic matter and nutrients. Therefore, intensive and modern wastewater treatment systems must be considered for assuring that the effluent quality from these industries comply with the current legislation for discharging into water courses (Decree 253/79 - regulating the water code Law No: 14859).

The compliance with new standards introduces extra costs and challenges for the industrial sector (Sarkar et al., 2006); therefore, alternatives for recovering the investment are being explored such as promoting water reclamation (Bixio et al., 2006; Buntner et al., 2013). Water reclamation in the food processing sector, such as in the dairy sector, needs to be carefully analysed since there is a high risk of potential contamination of the dairy products with the treated wastewater. However, water reclamation may be feasible for supplying service water for cooling, heating, and/or cleaning of floors and external areas (Mendes et al., 2014). Several studies have been conducted evaluating the possibilities of water reclamation in the dairy sector by using membrane filtration processes (Balannec et al., 2002; Hoinkis et al., 2012; Melin et al., 2006). The production of high water quality by reverse osmosis systems has gained interest in the sector (Lawrence et al., 2003). However, the most commonly applied wastewater post-treatment or tertiary treatment processes nowadays for water reuse at the dairy industries consist of chlorination and UV disinfection and not membrane filtration processes (Chowdhury, 2014; Hai et al., 2014).

MBRs may be considered a feasible wastewater treatment technology for promoting water reclamation at the dairy industry. MBRs combine a biological wastewater treatment process (based on the activated sludge process) with a membrane filtration process (either micro or ultrafiltration). The conventional biological process aims at removing most of the biodegradable compounds in the wastewater, while the membrane filtration process performs a very effective solid/liquid separation of the treated water from the mixed liquor. Advantages of MBRs include: (i) the production of a clarified and largely disinfected treated effluent; (ii) the reduced footprint when compared with conventional wastewater treatment systems; and (iii) the possibility for reusing the treated wastewater. Major disadvantages of membrane processes include membrane fouling, and high capital and operational costs (Judd, 2011). As shown in the recent literature, MBR processes are versatile, promising, and they have been applied in different configurations for the treatment of wastewater containing a wide range of pollutants from different process industries (Cappello et al., 2016; Friha et al., 2016; Sun et al., 2016; Waheed et al., 2016).

The widespread application of large-scale MBRs is still limited compared to other conventional wastewater treatment systems (Frederickson, 2005). Moreover, despite the high potential for the application of MBRs for the treatment of dairy effluents, only a few technical studies have been reported on that subject (Andrade et al., 2013). Some of the main reasons limiting the broader implementation of advanced wastewater treatment technologies such as MBRs were described by Frederickson (2005) as follows: (i) the high required capital expenditures (CAPEX); (ii) the high operational costs (OPEX); and (iii) the minimization of risks adopted by conservative local governments. However, financial considerations are the main limitation for implementing modern technologies such as MBRs.

The main objective of this research was to evaluate the performance of a pilot scale MBR treating dairy wastewater at a dairy industry located at the proximities of the SLRB and to investigate the potential for water reuse. The specific objectives of the present study included: (i) the characterization of the influent dairy wastewater; (ii) the evaluation of the pilot MBR considering operational conditions as well as compliance of the treated effluent with the Uruguayan standards; and (iii) the evaluation of the water quality of the treated effluent for promoting water reclamation reducing the water consumption at the dairy industry. Moreover, a preliminary financial analysis was carried out discussing the financial viability for implementing a large-scale MBR system at the dairy industry.

2. Materials and methods

2.1. Experimental procedures

2.1.1. Location of the MBR pilot plant

The pilot MBR was placed at the industrial facilities of one of the largest dairy company in Uruguay. The dairy plant produces powdered milk (whole and skimmed), cheese whey powder (demineralised), butter whey, butter, caramel cream, and butter oil. The production process generates two different raw wastewater streams which are combined and treated together at the wastewater treatment system at the dairy industry: the powder effluent stream (1620 m^3 d^{-1}) and the butter effluent stream (350 m^3 d^{-1}).

The wastewater treatment system consists of the following treatment units: (i) grease removal ponds; (ii) anaerobic ponds; (iii) an intermittent aeration complete mixed reactor; (iv) a sedimentation pond; (v) polishing ponds; and (vi) wetlands. The MBR was evaluated at two different locations at the wastewater treatment system: (i) receiving the wastewater coming from the industrial process after passing through the grease removal pond (high load stream); and (ii) receiving the wastewater after passing through the grease removal and anaerobic ponds (low load stream). The MBR was evaluated at these two different locations to compare the performance of the MBR when treating a high load stream and a low load stream. When treating the high load stream the MBR can replace the entire existent wastewater treatment system; however, when treating the low load stream, the MBR can be used as a polishing treatment system for achieving the new challenging standards or for water reclamation.

2.1.2. Description of the MBR pilot plant

A submerged MBR pilot plant was built by the company Almes-eko (Rijeka, Croatia). The MBR was provided with two ultrafiltration tubular membrane modules (MEMOS, Germany) vertically arranged with an average pore size of 0.04 μm and a total filtration area of 6.6 m^2. The direction of the flow was from the outer to the inner surface of the tubular elements. The tubular individual

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membranes were arranged in a circular array; they were fixed at one side by the permeate collector, and they were free at the other side. The MBR was composed of four chambers: (i) an anoxic tank in which the influent wastewater was introduced; (ii) a biological aerobic tank receiving the overflowing wastewater from the anoxic tank; (iii) a permeate storage tank containing the treated effluent; and (iv) a sludge stabilization tank. The MBR was provided with three pumps: an influent pump, a permeate pump, and a recirculation pump from the aerobic to the anoxic tank. The MBR was also provided with a compressor and two air bubble diffusers (find and coarse bubble diffusers); the fine bubble diffuser for providing dissolved oxygen, while the coarse bubble diffuser for membrane scouring. The nominal air discharge for the compressor at a pressure of 250 mbar was 205 L min^{-1}. Between 70 and 100% of that flow was used for membrane scouring, while the rest of the flow was directed to supply air to the fine bubble diffusers. Control valves, level sensors, flow indicators, a trans-membrane pressure indicator, and a control panel with a PLC system were also part of the system. Fig. 1 shows a complete schematic of the MBR pilot plant. The MBR main operational conditions are described in Table 1.

Table 1
MBR operational conditions.

Parameters	Values
Sludge retention time (SRT) [d]	Infinite (without purge)
Aerobic volume [m^3]	1.4
Anoxic volume [m^3]	0.6
Hydraulic retention time (HRT) [h]	25.5
Filtration time [s]	600
Filtration area [m^2]	6.6
Backwash time [s]	60
Duration of relax phase [s]	30
Permeate flow [m^3 day^{-1}]	1.3
Permeate flux [L m^{-2} h^{-1}]	7.3

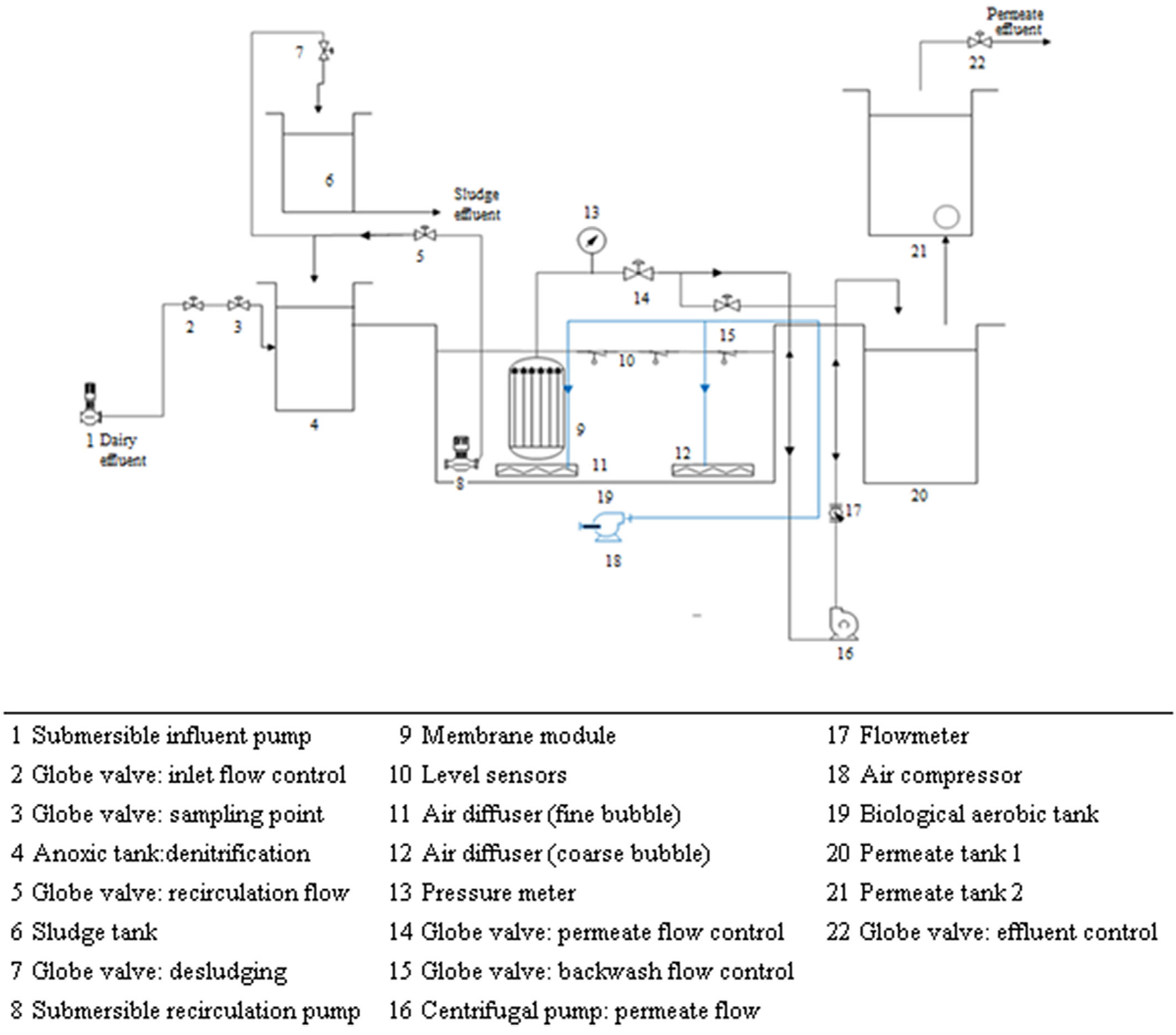

Fig. 1. MBR pilot plant schematic.

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2.1.3. *Wastewater characteristics*

The MBR was evaluated at two different locations at the existing wastewater treatment plant as described in Section 2.1.1. Initially, the MBR was fed effluent from an anaerobic pond wastewater treatment system (low load stream). Later on, the MBR was fed wastewater coming from the industrial process after passing through a grease removal pond (high load stream). The wastewater characteristics for both wastewater streams are presented in Table 2. The values indicated in the table are the average of approximately 17 grab samples taken during the evaluated period. The study was performed during the warmer summer months in Uruguay; the ambient temperatures ranged from 25° to 32 °C.

2.1.4. *Membrane filtration operation*

The pilot MBR was initially hydraulically evaluated at the dairy industry facilities. Fig. 2 shows the pilot MBR located inside a cargo container, the storage tank, and the pumping system at the evaluated location in the field.

The MBR system was started up by performing a backwash at a low flow rate and low membrane pressure for approximately 30 min; then, the suction process (permeate production) was gradually started. The permeate and backwash flows were regulated by flow control valves, aiming at achieving a filtration (permeate) flow rate between 1 and 2 m^3 day^{-1} without exceeding the maximum operational pressure (−0.4 bar for suction). The recirculation flow rate (from the aerobic tank to the anaerobic tank) was controlled by the recirculation valve and by the PLC system setting the on/off intervals for the recirculation pump. A recirculation flow rate of 4.5 times the influent wastewater flow rate was achieved.

During the permeate production (suction) the absolute value for the transmembrane pressure (TMP) increased from approximately 0.17 to 0.35 bar; when the pressure reached an absolute value of 0.40 bar, a chemical cleaning was conducted with sodium hypochlorite, and the TMP was significantly reduced. The absolute value for the system's TMP alarm was set at 0.50 bar; when this point was reached, the PLC stopped the operation of the entire system avoiding damages to the membranes.

2.1.5. *Membrane cleaning procedure*

The membranes were cleaned during the entire evaluated period by performing the following cleaning procedures: (i) air scouring (air was continuously supplied from the bottom of the membrane modules through coarse bubble diffusers); (ii) backwash cleaning (one minute of backwash was performed every ten minutes of suction); and (iii) chemical cleaning both performed in place (to avoid the suction pressure to reach an absolute value of 0.40 bar), and external (after the 0.40 bar value was reached). The in place chemical cleaning was carried out by performing a backwash from the permeate tank with sodium hypochlorite at a concentration of 750 mg L^{-1}; the backwash procedure lasted for 1–2 h (Mijatović et al., 2009). The external cleaning was carried out by soaking the membranes in an external water bath first with hydrochloric acid at pH 3.0 and later on with an oxidative agent such as hypochlorite at pH 11.0; the cleaning lasted for approximately 60 min, and it was conducted at a temperature ranging from 30 to 40 °C.

Fig. 2. Pilot MBR located at the dairy industry.

2.2. *Experimental analysis*

2.2.1. *Physical/chemical analytical determinations*

The following parameters were measured during this study: pH, dissolved oxygen (DO), temperature, COD, BOD, total Kjeldahl nitrogen (TKN), TN, NH_4-N, nitrate (NO_3-N), nitrite (NO_2-N), TP, mixed liquor total suspended solids (TSS), and mixed liquor volatile suspended solids (VSS). The TSS and VSS were measured according to SM 2540 D/E Standard Method (Jenkins et al., 2009). The rest of the parameters (except pH and DO) where outsourced to an analytical credited UNIT/ISO-IEC 17025:2005 environmental laboratory (ECOTECH – Laboratorio Química Ambiental) located in Montevideo, Uruguay.

Samples were taken with a frequency of approximately two to five times per week. The samples were taken at four different points in the MBR: influent, effluent, aerobic tank, and anoxic tank. Once the samples were taken, they were labelled and conserved at low temperatures with silica gel in a cooler. On the same sampling day, the samples were transported from the dairy industry to the laboratory for subsequent analysis. The samples taken from the influent and permeate were measured for COD every 2–4 days, while for BOD, NO_2-N, NO_3-N, NH_4-N, TKN, TN, and TP were measured every 3–5 days. Temperature, pH and DO were measured every 3–5 days in the aerobic reactor. The mixed liquor TSS and the mixed liquor VSS concentrations were determined at the aerobic reactor every 1–3 days. Nitrates and nitrites were measured in both aerobic and anoxic reactor every 1–3 days.

Table 2
Wastewater influent characterization on the basis of grab sample analysis (average 17 samples).

Parameter	Low load stream (mg L^{-1})	High load stream (mg L^{-1})
COD	385	1300
BOD_5	111	843
Total phosphorous	12	12
Ammonia-nitrogen (NH_4-N)	51	33
Nitrate (NO_3-N)	2	1
Total nitrogen (TN)	100	90
Total suspended solids (TSS)	106	646

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2.2.2. Chemical phosphorous removal: jar test procedure

A jar test was performed in the laboratory in order to determine the optimum concentration of ferric chloride to be added to the membrane bioreactor to achieve chemical phosphorous removal. For this, different dosages of ferric chloride were evaluated. The evaluation was carried out according to the Standard Practice for Coagulation-Flocculation Jar Test of Water (ASTM, 2003). Results obtained were scaled up in order to find the exact dosage of ferric chloride for achieving chemical phosphorous removal and comply with the local discharged standards.

2.3. Financial analysis

A financial analysis was carried out to determine the feasibility of implementing a full scale MBR at the dairy industry. Three financial indicators were selected to conduct the financial analysis: (i) the net present value (NPV); (ii) the internal rate of return (IRR); and the payback period (PB). The selected financial indicators specify whether or not to undertake a particular investment, the risks of investing, and how long to wait until recovering the initial investment.

2.3.1. NPV determination

The NPV was calculated by subtracting the expected incomes of the investment in the future years from the cost of the project. The NPV indicates the total gain or lost that an investment produces compared to the amount that can be earned by simply saving money in the bank. The NPV was calculated as shown in Equation (1):

$$NPV = \sum_{i=1}^{n} \frac{F_i}{(1+k)^i} - I_i \tag{1}$$

where

F_i = cash flow at each period i
I_i = Initial investment = CAPEX
n = number of periods
k = reference rate

The cash flows (F_i) at each period (year) were calculated by subtracting the OPEX after the investment (that is, after placing the MBR at the dairy industry) from the OPEX before introducing the investment. The fines issued by the local environmental authorities for not complying with the discharge standards were included in the OPEX before introducing the investment. The initial investment (I_i) was calculated as the CAPEX. A number of periods (n) of 10 years was considered. The reference rate (k) was determined in accordance with the Central Bank of Uruguay for foreign currency of medium and large enterprises at 4.7%.

2.3.2. IRR determination

The IRR was considered as an indicator of the profitability of the investment. The IRR was calculated as shown in Equation (2):

$$\sum_{i=1}^{n} \frac{F_i}{(1+IRR)^i} - I_i = 0 \tag{2}$$

where

F_i = cash flow at each period i
I_i = Initial investment = CAPEX
n = number of periods

Same assumptions for the cash flows (F_i), the initial investment (I_i), and the number of periods (n) as for the NVP were considered.

2.3.3. PB determination

The payback period is the time required to completely recover the cost of the investment. The PB is calculated by dividing the total cost of the investment over the yearly cash flow.

2.3.4. Investment acceptance criteria

The following criteria were set to accept the investment on the new proposed scenario. The investment is accepted when the NPV indicator yields a positive value, and the IRR is larger than the reference rate (k). A PB period no greater than five years was desired to better justify the investment.

3. Results

3.1. Membrane pressure and membrane permeability

Fig. 3 illustrates the changes in TMP observed at the MBR operating in suction/permeate and backwash modes. Four membrane cleaning events and one module replacement were observed during the reported operational days. Fig. 3 shows a gradual increase of the TMP between cleaning intervals due to the progressive fouling of the ultrafiltration membrane. As observed in Fig. 3, there were four events where the pressure remained at 0 bar indicating a pause in the operation of the system. The events are described as follows. The first event was observed at the day 19 and it was caused by a low level in the influent tank. That is, the MBR was out of service due to the lack of wastewater in the influent tank where the influent pump was submerged. The second event was observed at the day 28 and it was caused by a power outage. The third event was due to a high-pressure alarm (during a long backwash) taking the system out of service. The fourth event was noticed at day 47, and it was due to an excessive membrane fouling. The system was over dosed with ferric chloride. The MBR system was out of operation for 6 days as it is indicated in Fig. 3. A thorough emptying and cleaning of the MBR system was carried out to remove any traces of iron; in addition, the membranes modules were replaced. After cleaning the reactor and replacing the membranes, the reactor was restarted inoculating with fresh sludge from a local municipal wastewater treatment plant.

The permeate flow decreased as the TMP increased due to the progressive membrane fouling. Consequently, to sustain a constant flow higher suction pressures were needed impacting on the energy demand. Proper membrane cleaning and maintenance procedures are needed to reduce the suction operational pressures; therefore, reducing the system's operational costs.

3.2. Monitoring mixed liquor TSS and VSS concentrations in the MBR

The biomass concentration in the MBR is one of the most critical parameter to monitor the MBR performance. The biomass concentration has an impact on the footprint requirements of the MBR, on the permeability, and on the oxygen transfer efficiency (OTE). That is, the operational biomass concentration may influence the capital and operational costs of a MBR system. Fig. 4 shows the biomass development on the MBR reported both as TSS and VSS for the entire operation of the MBR without wasting sludge. When the MBR was fed the low load stream (from start up until approximately day 73 as shown in Fig. 4), a maximum concentration of 4 g L^{-1} was achieved. However, when the system was fed the high load stream (starting on day 73) the TSS concentration was continuously increasing up to a final concentration of

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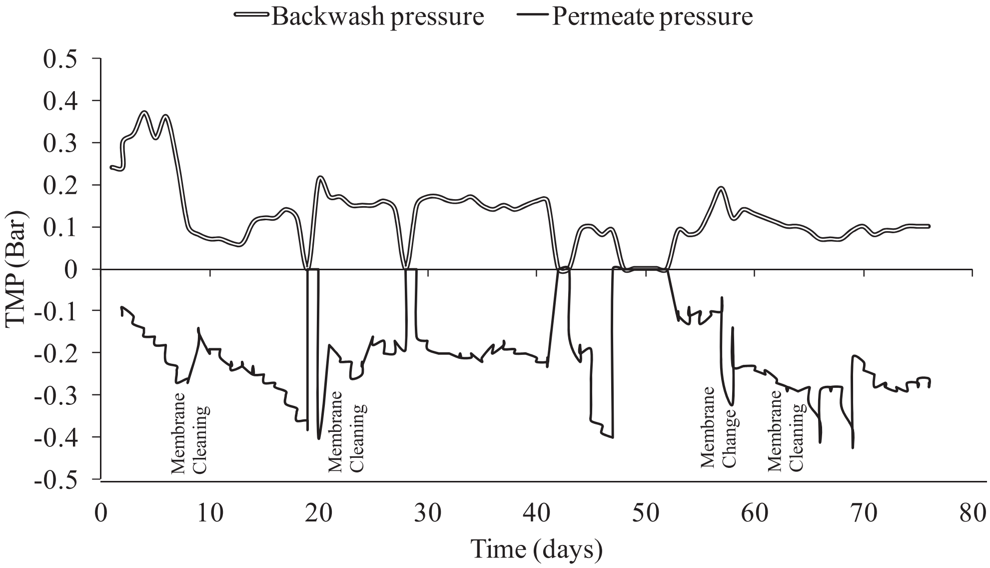

Fig. 3. TMP values recorder for the MBR operated in suction and backwash mode.

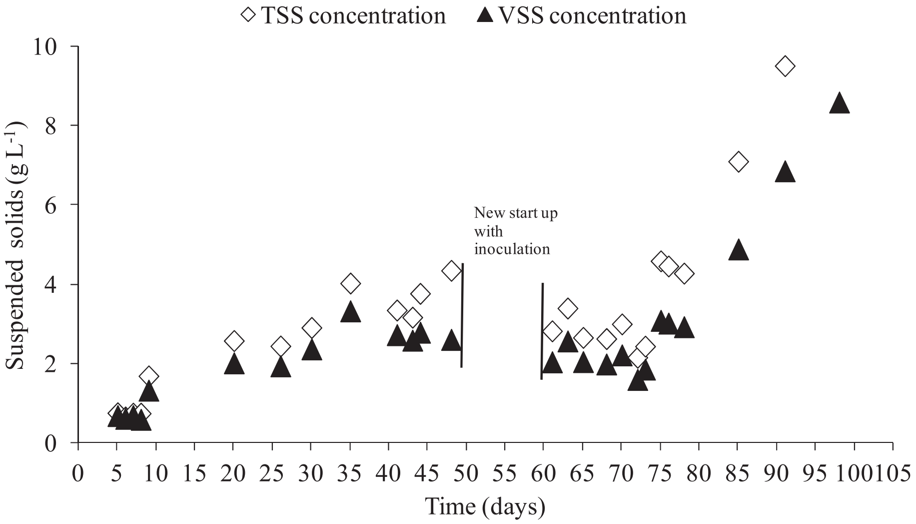

Fig. 4. The evolution of the biomass concentration (as TSS and VSS) in the MBR.

approximately 10 g L^{-1}. The VSS/TSS ratio remained between 0.71 and 0.81 throughout the entire period. Therefore, during this condition of total sludge retention, a major accumulation of inorganic solids in the MBR was not observed.

3.3. Monitoring temperature, pH, and DO in the MBR

The temperature in the aeration basin of the MBR ranged from 21 to 27 °C during the evaluated period. The MBR was evaluated at the end of the spring and beginning of summer season in Uruguay. The reported temperatures were favourable in terms of carbon and nitrogen removal. The pH remained relatively constant for the entire period at values between 8.1 and 8.4. The medium, maximum, and minimum DO concentrations measured at both the aerobic and anoxic chambers at the MBR are reported in Table 3.

The DO concentrations were relatively stable during the evaluated period. Oxygen was necessary for the heterotrophic and autotrophic microorganisms in the aerobic chamber of the MBR for carbon removal and nitrification, respectively. However, anoxic conditions were needed in the anoxic chamber, so denitrification could occur. When the MBR was fed the low load stream, the DO concentrations in the aerobic chamber were relatively high (always above 1.5 mg L^{-1}). Therefore, the DO concentrations in the anoxic tank could not be lower than 0.5 mg L^{-1} due to the DO coming from the recirculation aerobic-anoxic flow. In order to decrease the DO concentrations, the fine bubble diffuser aeration was turned off. All the DO to the MBR was supplied through the coarse bubble diffusers used mainly for membrane scouring. However, since a minimum aeration flow was needed for membrane scouring (to avoid membrane fouling) the aeration flow through the coarse bubble diffusers could not be significantly reduced; that is, relatively high dissolved oxygen concentrations were still measured in the anoxic chamber. When the MBR was fed the high load stream (after day 73), a higher oxygen demand was experienced; therefore, the average DO in the aerobic and anoxic chambers were approximately 1 mg L^{-1} and 0.3 mg L^{-1}, respectively.

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Table 3
DO concentrations during the evaluated period.

	Median (mg L^{-1})	Maximum (mg L^{-1})	Minimum (mg L^{-1})	Number of samples
Aerobic tank	2.48	5.96	0.46	38
Anoxic tank	0.38	0.8	0.04	23

3.4. *Removal of organic matter*

The performance of the MBR in terms of COD and BOD (influent, effluent, and removal efficiencies values) is shown in Figs. 5 and 6, respectively for the entire evaluated period. The dash lines on Figs. 5 and 6 indicate when the influent wastewater to the MBR was switched from the most diluted (low load stream) to the most concentrated (high load stream).

Excellent COD removal efficiencies were observed during the entire evaluated period. As shown in Fig. 5, permeate COD concentrations as low as 8 mg L^{-1} were observed. Average COD removal efficiencies were approximately 95%. The highest removal efficiency of 98.3% was achieved when the MBR was fed the most concentrated wastewater (COD concentration of 2142 mg L^{-1}).

In addition, an almost complete removal of BOD was observed for the reported period as indicated in Fig. 6. The influent BOD values ranged from 46 to 231 mg L^{-1} when the MBR was fed the most diluted wastewater (after the sedimentation pond), and from 346 to 1273 mg L^{-1} when the MBR was fed the most concentrated wastewater (after the anaerobic ponds). The BOD removal efficiencies ranged between 89% and 100% with a median of 97%.

3.5. *Biological nitrogen removal*

As can be seen in Fig. 7, the influent concentration of nitrate to the MBR was negligible for the entire evaluated period. When the

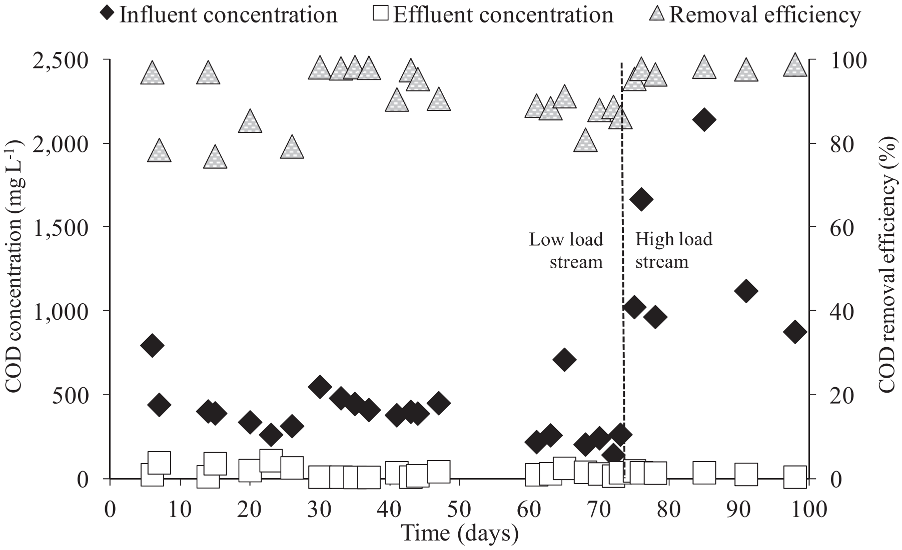

Fig. 5. COD influent, effluent and removal efficiencies.

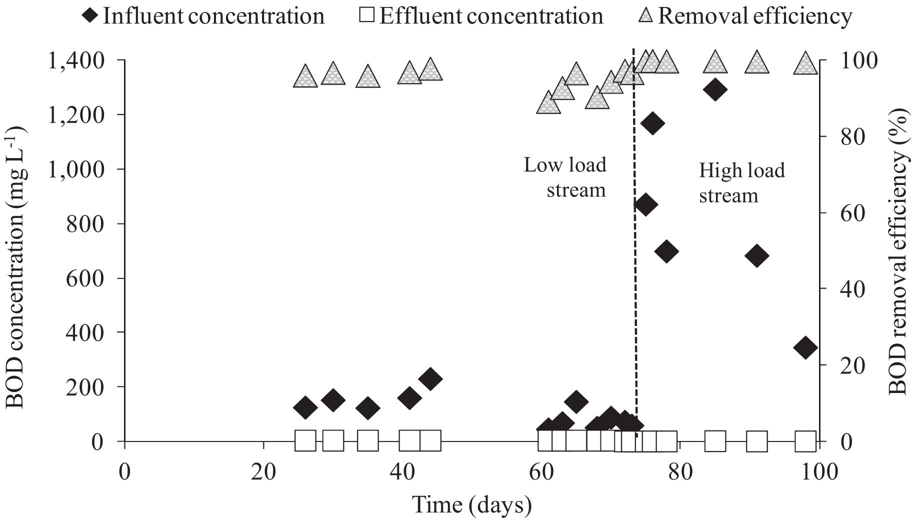

Fig. 6. BOD influent, effluent and removal efficiencies.

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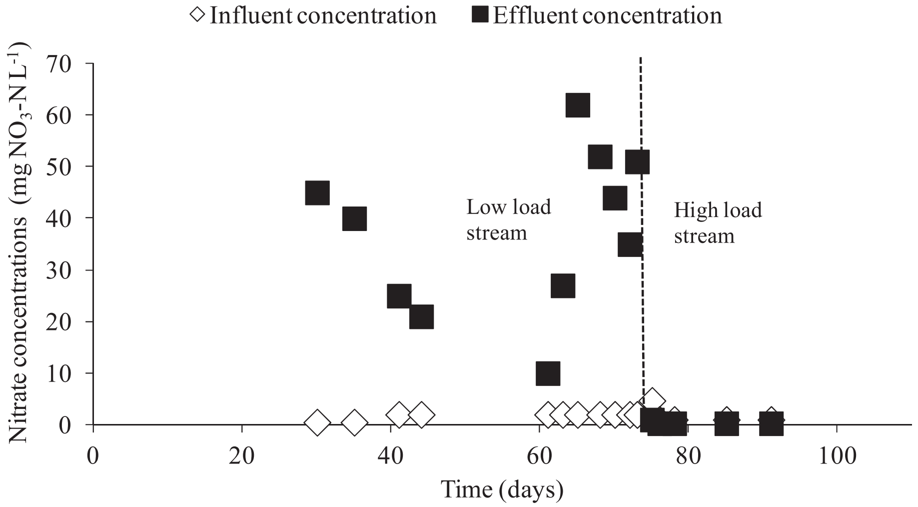

Fig. 7. NO3-N influent and effluent concentrations.

system was fed the most diluted wastewater (from the sedimentation pond), nitrate was present in the treated effluent (permeate). The concentrations of nitrate in the permeate were between 15 and 45 mg L^{-1}. However, when the system was fed the most concentrated wastewater (from the anaerobic ponds), nitrate was not present in the treated effluent. Moreover, as indicated in Fig. 8, TKN-N was almost completely removed both when the system was fed with the diluted and concentrated wastewater. However, in Fig. 8 it is observed that when the system was fed with the most diluted wastewater, there were some occasions at which noticeable TKN-N concentrations were observed in the treated effluent. After 60 days of operation the TKN-N concentrations were almost negligible. In addition, from looking at the results presented in Fig. 9, it can be concluded that total nitrification occurred in the MBR when fed both the diluted and concentrated wastewater. Therefore, the TKN-N effluent concentrations observed in Fig. 8, when the system was fed the most diluted wastewater, may correspond to non-degradable organic nitrogen.

Therefore, from analysing the results presented in Figs. 7–9, it can be concluded that the system was achieving full nitrification for the entire reported period regardless the source of wastewater (diluted or concentrated); however, the presence of nitrate in the treated effluent when the system was fed the most diluted wastewater indicated that denitrification was not occurring at that time. When the system was fed the most diluted wastewater, the influent organic load reaching the MBR system was relatively low (COD < 400 mg L^{-1} and BOD < 250 mg L^{-1}). The influent total nitrogen concentration for the entire period ranged from approximately 70 to 140 mg L^{-1}; therefore, the amount of organic load reaching the MBR system when the MBR was fed with the most diluted wastewater was not high enough for promoting denitrification. This situation resulted in the accumulation of nitrate in the effluent. When the MBR was fed with the most concentrated wastewater, the organic load reaching the MBR system was much higher (COD approximately 1500 mg L^{-1}, and BOD 900 mg L^{-1}), promoting denitrification. Therefore, negligible nitrate concentrations were observed when the system was fed the most concentrated influent wastewater. Fig. 10 shows the performance of the MBR system on the removal of TN for the entire reported period.

The TN removal efficiencies depended on the influent that was fed to the MBR. This behaviour was as expected. During most part of the research, the MBR was fed with a low concentrated wastewater

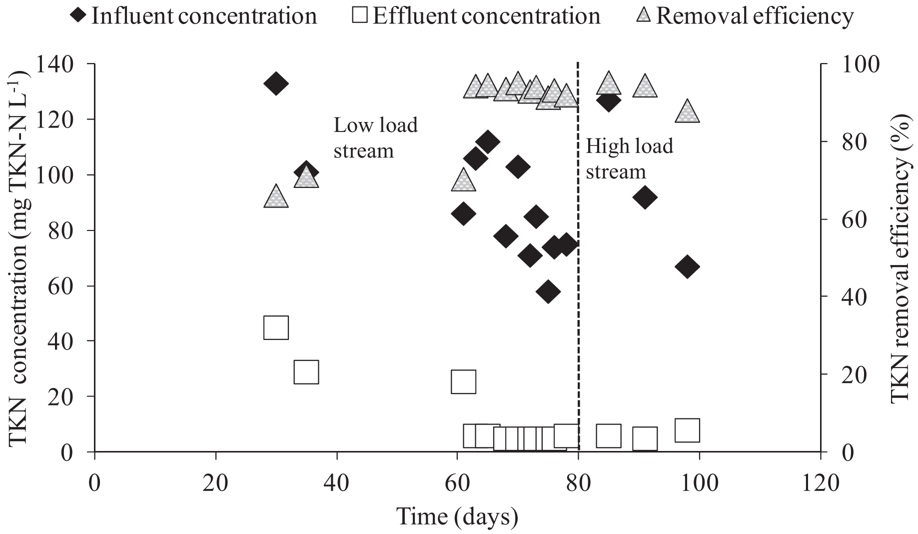

Fig. 8. TKN-N influent, effluent, and removal efficiencies.

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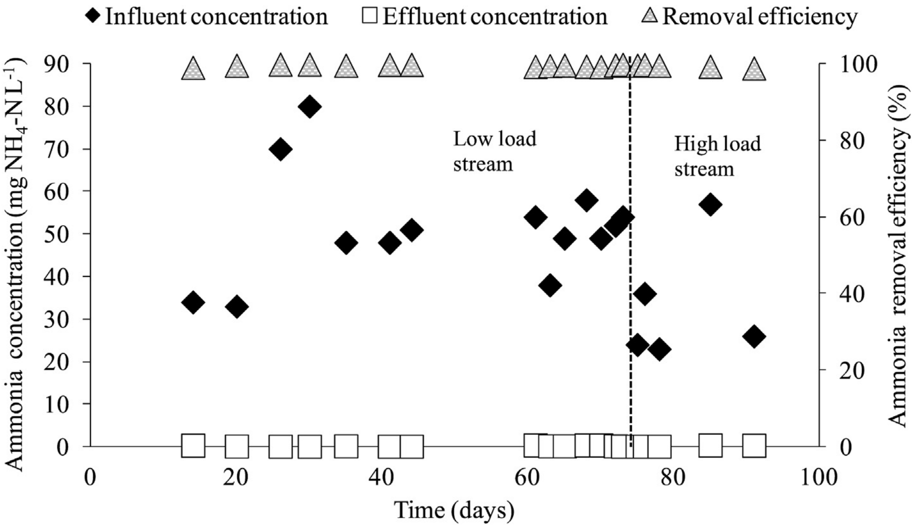

Fig. 9. NH4-N influent, effluent, and removal efficiencies.

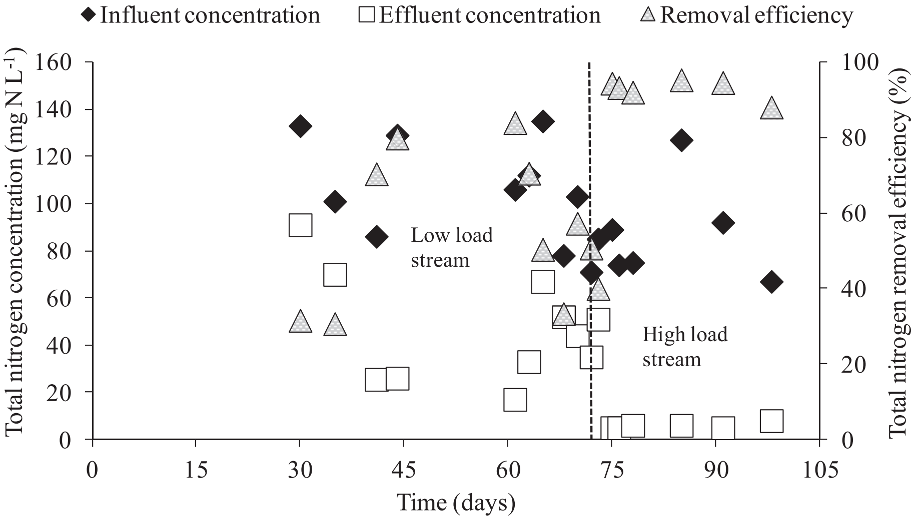

Fig. 10. TN influent, effluent, and removal efficiencies.

(low load stream) with a low COD/N ratio. Therefore, it was not possible to achieve denitrification. When the systems were fed with the more concentrated wastewater (high load stream), denitrification was fully achieved.

3.6. Phosphorous removal

The jar test results indicated that 300 mg $FeCl_3 \cdot 6H_2O$ L^{-1} would be an adequate dose of ferric chloride for obtaining an effluent phosphorous concentration of approximately 1.5 mg L^{-1}. With this dosage of ferric chloride, the concentration of phosphorous on the treated effluent would comply with the discharges standards of the Legislation 14859 (Decree 253/79) (Decreto 253, 1979) in Uruguay for direct discharges to water courses, in which the maximum allowable level of the TP is 5 mg L^{-1}. Even though a jar test was performed to evaluate the required dose of ferric chloride to achieve chemical phosphorous removal, phosphorous removal was not achieved by chemical precipitation. Ferric chloride was only dosed at an early stage of the research, and due to excessive fouling observed on the membranes, the addition of ferric chloride was interrupted.

The MBR was not designed to biologically remove phosphorous by an enhanced biological phosphorous removal process. However, the performance of the MBR system regarding phosphorus removal was evaluated. As observed in Fig. 11, when the system was fed the most diluted wastewater (low load stream) no or little removal of phosphorous was observed (removal efficiencies not higher than 14%). However, when the system was fed the most concentrated wastewater (high load stream), removal efficiencies on TP as high as 92% were observed (with effluent TP concentrations as low as 1.5 mg P L^{-1} on average). The removal of phosphorous can be attributed to both the amount of phosphorous required for bacterial growth (which according to calculations was on average 7.2 mg P L^{-1}) and to particulate phosphorous that may be removed/rejected by the ultrafiltration membrane process. Thus, the phosphorous concentrations on the treated effluent complied with the Uruguayan standards set at 5 mg P L^{-1}.

3.7. Effluent quality overview

Table 4 presents a summary of all the evaluated parameters including the Uruguayan discharge standards. The MBR treated

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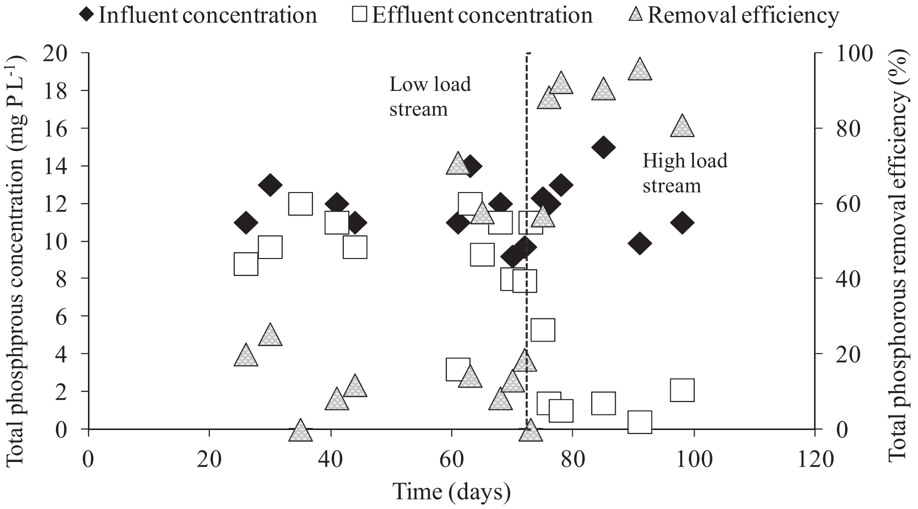

Fig. 11. TP influent, effluent and removal efficiencies.

effluent complied well (when fed the most concentrated wastewater - from the anaerobic pond) with the Uruguayan standards.

To compare the treatment performance of the pilot MBR system with the performance of the existent wastewater treatment system at the dairy plant, samples were taken from the discharge of the existent wastewater treatment system to the SLRB. Fig. 12 shows a comparison of the performance of the two treatment systems (pilot MBR and existent natural wastewater treatment system at the dairy industry) with respect to carbon, suspended solids, and nutrients removal. The raw influent and MBR effluent described in Fig. 12 were averages of the measured concentrations during the entire reported period when the MBR was fed the most concentrated wastewater (high load stream). The discharge standards in Fig. 12 are indicated by a dashed line. As can be observed from Fig. 12, the current/existing wastewater treatment at the dairy industry in Uruguay did meet the effluent standard for BOD and TSS, but was unable to comply with the new local (stricter) standards for TN, NH_4-N, and TP.

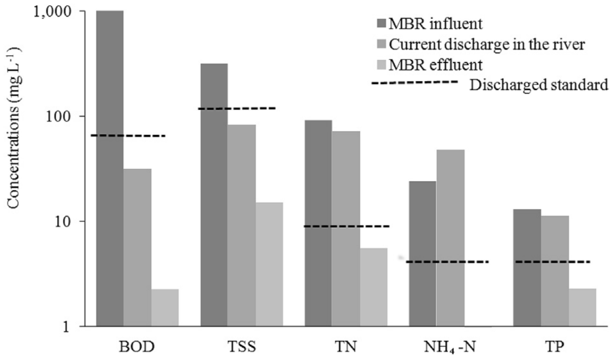

Fig. 12. BOD, TSS, TN, NH4-N, and TP concentrations for: (i) MBR influent fed the most concentrated wastewater (high load stream); (ii) Current discharge into the SLRB; and (iii) MBR effluent obtained by the pilot MBR. The dash lines indicate the Uruguayan discharge standards.

3.8. *Reuse parameters*

MBRs exhibit a great potential for water reuse, although, as reported in the literature, MBRs not always meet the required disinfection levels (Chae et al., 2007). As a part of this evaluation, a more comprehensive water quality analysis was carried out for the MBR treated effluent (permeate). Even though the MBR performed well removing organic matter and nutrients as explained on the previous sections, post disinfection treatments may be required if there is a need to inactivate all the pathogens for promoting water reuse at the industrial plant.

The water quality of the permeate was compared to the Uruguayan standard for the provision of drinking water quality (set by

Table 4
Influent concentrations, permeate concentrations, mean removal efficiencies values, and discharged standards for the evaluated parameters.

Parameter		MBR influent (mg L^{-1})	MBR permeate (mg L^{-1})	Number of samples	Mean removal efficiency (%)	Discharged standard (253/1979)
COD	**Low load stream**	142–795	8–108	22	91	–
	High load stream	965–2142	26–47	6	98	
BOD_5	**Low load stream**	46–231	2–5	12	96	60
	High load stream	683–1293	2–3	6	100	
TN	**Low load stream**	71–135	17–91	14	51	10
	High load stream	74–127	5–6	6	94	
NH_4-N	**Low load stream**	33–80	0.1–0.4	14	100	5
	High load stream	23–57	0.1–0.4	6	100	
TP	**Low load stream**	9.2–22	3.2–12	12	14	5
	High load stream	9.9–15	0.4–5	6	91	
TSS	**Low load stream**	30–186	<15	2	85	150
	High load stream	238–344	<15	2	95	

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the Administration of Sanitary Works of the State) (OSE, 2006). These parameters are imposed to the dairy plant for reusing water in their production process. The water quality of the treated effluent indicated that the treated effluent cannot be used directly as an alternative source of water for the production process. Several parameters do not comply with the drinking water standard including: bacteriological parameters, total dissolved solids, and sodium content. From a water audit conducted at the dairy industry, it was observed that the cleaning agent most commonly used was caustic soda. In addition, the butter production process requires high amounts of salt introducing high amounts of sodium and dissolved solids into the process wastewater to be treated. In addition, a chlorination post treatment step might be probably sufficient (Tam et al., 2007) to comply with the bacteriological requirements. Therefore, by both deeply analysing and proposing minor adjustments to the production process, and by incorporating subsequent post treatment disinfection processes, water reuse alternatives for the production process can be proposed.

3.9. Financial viability

At the time of conducting the financial evaluation the dairy industry was using three different sources for water supply: (i) ground water (200 m^3 day^{-1}); (ii) surface water taken from the SLRB (700 m^3 day^{-1}); and (iii) reclaimed water from the milk evaporation process (600 m^3 day^{-1}). The ground water was used directly (without passing through any water treatment process) to clean the milk reception area. The raw surface water was treated by a water purification portable unit (UPA, for its acronym in Spanish) and subsequently used in the production process. The water produced by the milk evaporation process is treated by a reverse osmosis (RO) filtration system; the produced RO permeate was used as a source of service water.

The proposed new scenario at which the financial evaluation was carried out is described as follows: (i) the two sources of fresh water supply (ground water and surface water) are not used anymore; therefore, the water purification portable unit (UPA) is taken out of service; (ii) the RO treatment plant is kept, but the produced RO permeate supply water for both cleaning the milk reception area, and for the production process; (iii) a full scale MBR designed to treat 2000 m^3 day^{-1} is incorporated with post chlorination treatment capacities; currently, the dairy industry produces 1500 m^3 day^{-1} of wastewater; (iv) 900 m^3 day^{-1} of the MBR treated water (permeate) are reused at the dairy production process after chlorination for both service water supply, and as the main source of water for cleaning the milk reception area; and (v) the remaining amount of the MBR permeate is discharged into the SLRB complying with the current environmental standards. The new scenario is presented in Table 5. The financial analysis focused on comparing the current situation observed at the dairy industry with the new proposed scenario.

The following assumptions were considered for calculating the CAPEX for the new proposed scenario: (i) the volume of the MBR was determined using the influent high load stream wastewater characteristics; (ii) a solid retention time (SRT) value of 20 days (Meng et al., 2009; Verrecht et al., 2010) and a mixed liquor TSS concentration of 12 g L^{-1} were assumed as the main MBR operational conditions (Judd, 2011); (iii) a design flux of 15 L m^{-2} h^{-1}, and a maximum influent flow of 2000 m^3 day^{-1} were used for calculating the required membrane area of the MBR; (iv) one mixer was assigned for every 450 m^3 of reactor volume (Praneeth et al., 2014; Verrecht et al., 2010); (v) the membrane costs were assumed at 60 USD m^{-2}, and the air diffuser costs were estimated at 3 USD Nm^{-3} h^{-1} (Praneeth et al., 2014); and (vi) the costs for the pumps and the mixing equipment were established at 45 USD m^{-3} h^{-1} and 25 USD m^{-3} of tank volume, respectively (Verrecht et al., 2010).

The following assumptions were considered for calculating the OPEX for both options: (i) Energy needs: 0.025 kWh Nm^{-3} were assumed for aeration needs (Maere et al., 2011; Praneeth et al., 2014; Verrecht et al., 2010); 0.04 kWh m^{-3} were assumed for the energy demand for the permeate pumps (including backwash), recirculation pumps, and sludge pumps (Verrecht et al., 2010); and 8 W m^{-3} were assumed for the mixing requirement; (ii) Sludge treatment and disposal costs: 0.35 USD m^{-3} of dry solids (DS); and (iii) Chemical needs: 395 USD Ton^{-1} of ferric chloride 39%; 697 USD m^{-3} of sodium hypochlorite 90 g L^{-1}; and 1.0 USD L^{-1} of hydrochloric acid 37%. The chemical consumption rates were obtained based on the requirements showed by the pilot scale MBR installed at the dairy facility; the prices for the chemical substances were provided by local suppliers.

Table 6 shows the financial evaluation results describing the financial indicators calculated considering two different penalty/fines levels. The investment is accepted when the NPV indicator yields a positive value, and the IRR is larger than the reference rate (k). A PB period no greater than five years was desired to better justify the investment. The implementation of an MBR introduces more OPEX compared to the previous existent situation. Two main reasons were identified: (i) the low OPEX for the current water supply sources (surface water and ground water); and (ii) the low OPEX for the current wastewater treatment system. However, the current wastewater treatment system is not complying with the discharge standards. Therefore, the associated penalties (fines) issued by the local the authorities were included in the OPEX calculations. Considering this new variable (penalties/fines) on the analysis, the MBR becomes cost-effective for the industry. The analysis established that if the penalties/fines imposed are larger than USD 380,000 per year, the investment (new scenario) becomes feasibly. Moreover, considering penalties/fines of above USD 450,000 per year the project is highly feasible. The penalties/fines issued to the industry so far were approximately USD 110,000 per year; however, according to what is established in the new regulations, the penalties/fines will increase considering the number of previous warnings/fines that the government issued already to that particular company. That is, four to five warnings in one year could increase the total fines to approximately USD 500,000 per year for the selected industry.

Table 5
Future proposed scenario at the dairy industry incorporating water reuse from an MBR.

Water source (m^3 day^{-1})		Water treatment (m^3 day^{-1})		Water consumption (m^3 day^{-1})		Wastewater (m^3 day^{-1})	
MBR permeate	900	Chlorination	900	Milk reception	500	MBR permeate for reuse	900
Milk evaporation	600	Reverse osmosis	600	Powder mill production	100	Effluent discharge into the SLRB	600
				Whey production	200		
				Butter and cream milk	100		
				Services (boiler, washings)	500		
				Reverse osmosis discharge to wastewater treatment plant	100		
Total	**1500**		**1500**		**1500**		**1500**

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Table 6
Financial indicators including two different fines/penalties scenarios.

Penalties	USD 310,000/year	USD 500,000/year
NPV	USD -24,613	USD 1,466,311
IRR	4%	17%
Payback period (PB)	7.8 years	4.6 years
Reference rate (k)	4.7%	4.7%

4. Discussion

On March 18th, 2015, the president of Uruguay stated in several reports that implementing solutions to deal with the observed pollution episodes at the SLRB must not be delayed (El País, 2015a). The reported toxicity issues on the main source of drinking water in Uruguay introduced serious concerns, and it is becoming a priority for the government in the coming months. A resolution issued by the Ministry of Housing, Territorial Planning and Environment (MVOTMA) established progressive deadlines allowing industries to update their wastewater treatment systems to comply with the new standards (MVOTMA, 2015); otherwise, the corresponding sanctions will be applied (El País, 2015b). New technologies and investments are required to comply with the new standards that may promote a technological shift regarding wastewater treatment at the Uruguayan industries. The previous statement confirms and supports the urgency for the evaluation of new technologies as carried out in this research.

At the evaluated experimental conditions, the treated effluent produced by the MBR complied by far with the discharge standards regarding BOD, TSS and NH_4-N. The mean removal efficiencies depended on the influent fed to the MBR. Reported COD/N for achieving denitrification ranged between 4 and 15 g COD g N^{-1} (Peng et al., 2007). When the MBR was evaluated fed the more diluted wastewater (low load stream), the amount of COD reaching the reactor was not sufficient enough for achieving full denitrification; on the other hand, when the system was fed the more concentrated wastewater (high load stream) the organic load was increased and full denitrification was achieved. In addition, the evaluated pilot MBR experienced high removal efficiencies (all above 95%) on COD, NH_4-N, BOD and TSS. The results reported on this study are consistent with previous studies as in Meng et al. (2009) and Feng et al. (2012).

The MBR achieved very good phosphorous removal when fed the most concentrated wastewater (high load stream). The nutrients requirements for industrial aerobic biological treatment system were reported as a C:N:P ratio of 100:5:1 (Ammary, 2004; Henze et al., 2008). When the MBR was fed the most diluted wastewater (low load stream), the COD/P ratio was on average 27; on the other hand, when the MBR was fed the most concentrated wastewater (high load stream) the COD/P ratio was on average 105. Even though some phosphorus removal was observed when the MRB was fed the most diluted wastewater, the most significant removal was observed when the system was fed the more concentrated wastewater at a COD/P ratio of approximately 105. When operating the MBR fed the more concentrated wastewater, the treated effluent phosphorous concentrations ranged between 0.4 and 5 mg L^{-1}, for an influent phosphorous concentration ranging from 9 to 22 mg L^{-1}. In addition to the removal of phosphorous observed by bacterial growth, some of the TP (the particulate fraction) could be removed by particle size exclusion exerted by the ultrafiltration membrane process.

Considering the potential of the evaluated technology for water reuse, it was observed that the dairy industry demanded high water quality for the dairy production process. As expected, and according to the literature, the MBR technology does not always meet the requirements for disinfection (Chae et al., 2007). Therefore, post disinfection treatment shall be incorporated on MBR system to completely disinfect the treated effluent for water reuse applications.

The current discharge of the existent WWTP into SLRB do not meet the NH_4-N and TN requirements established by the local legislation, whereas with the implementation of the MBR the removal efficiency of these parameters (considering the MBR fed the high organic load stream) fulfil the requirements. This shows a clear advantage for the implementation of the MBR. In addition, the MBR footprint requirements are much smaller. Results also indicates the possibility for water reclamation. In addition, the MBR also provides a reduction on the sludge production, and it offers a high degree of automation. Thus, a reduction on the operational and maintenance costs can be also achieved.

The financial issues are the most critical component for a company when evaluating the implementation of a full-scale membrane bioreactor. The financial evaluation carried out in this research indicated that the investment (new scenario) is economically feasible considering penalties/fees imposed by the local authorities to the industry exceeding the amount of USD 380,000 per year. However, the production activities at the company may be interrupted until the company does not comply with the new standards. In other words, although the investment results economically unfavourable for the company, the crucial situation of the SLRB may force the industry to achieve the standards. That is, not complying with the standards may force the government to suspend the production activities in the industry.

5. Conclusions

The MBR was effective in removing organic matter with observed COD removals efficiencies of 80–98%. Ammonium removal efficiencies higher than 99% were observed, regardless the type of influent wastewater to the MBR. The treated effluent produced by the MRB complies with the discharge standards imposed by the local authorities. The TSS at the MBR ranged on average from 3 to 10 g L^{-1}. The VSS/TSS ratio remained between 71 and 81% thorough the evaluated period. Therefore, under the condition of total sludge retention, there was no major accumulation of inorganic solids in the sludge. When the system was fed the more concentrated wastewater (high load stream), high denitrification efficiencies were observed and total nitrogen was removed. The TP was almost completely removed (average treated effluent concentrations of approximately 2 mg L^{-1}) when the MBR was fed the most concentrated wastewater (high load stream). The treated effluent complies with most of the standards for drinking water in Uruguay with the exception of pathogen content, total dissolved solids concentration, and sodium concentration. Regarding the financial aspects, the results indicated that the economic feasibility to replace the existing treatment system by an MBR depends on the penalties/fines imposed to the industry by the governmental agencies. Nevertheless, the critical situation of the Santa Lucia River Basin and the environmental requirements will force the dairy industry to achieve the discharge standards, regardless the associated costs.

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