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REUSE OF DAIRY WASTEWATER TREATED BY MEMBRANE BIOREACTOR AND NANOFILTRATION: TECHNICAL AND ECONOMIC FEASIBILITY

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Abstract - This study evaluated the technical and economic feasibility of membrane bioreactors (MBR) followed by nanofiltration (NF) for dairy wastewater treatment in order to reuse the treated effluent. It was observed that the MBR efficiently removed the organic matter and color of the feed effluent; however, due to the high concentration of dissolved solids in the permeate, it was necessary to use nanofiltration as a polishing step. The final treated effluent could be reused in the industry for cooling, steam generation and cleaning of external areas. A preliminary economic analysis showed the feasibility of the proposed system. The internal rate of return was greater than or equal to 32% when membrane lifespan was at least 2 years and the depreciation time was 15 years. The total cost of the proposed treatment system ranged from R$ 9.99/m³ to R$ 6.82/m³, depending on membrane lifespan.
Keywords: Wastewater reuse; Dairy effluent; Membrane bioreactor; Nanofiltration; Economic analysis.

INTRODUCTION

The dairy industry has great importance in both the national Brazilian and global economies. Brazil is the sixth largest milk producer worldwide (Embrapa, 2010), and has the potential to become one of the largest exporters of dairy products due to its competitive advantages, including water and land availability and low production cost. However, for this to become a reality, the Brazilian dairy industry needs to add value to its products and find more efficient and sustainable production processes to be more competitive in foreign markets.

In dairy industries, water is a key processing medium. Water is used throughout all processing steps of the dairy industry, including cleaning, sanitization, heating, cooling and cleaning of external areas - as a result, the water requirement is huge (Sakar *et al*., 2006; Brião and Tavares, 2007). Moreover, the liquid effluents generated through dairy product production exhibit high concentrations of organic matter, fats, suspended solids and nutrients. These are considered to be the main sources of pollution in this industry. Conventional treatment of these effluents normally includes a primary treatment to remove the suspended solids and fats and a secondary biological treatment; however, many problems have been reported during these processes. They are often related to the high production of foam, the low settleability of the sludge, the low resistance to shock loads, the difficulty in removing nutrients, and the problems associated with the degradation of fats, oils, and

*To whom correspondence should be addressed other specific types of pollutants (Cammarota and Freire, 2006; Machado *et al*., 2002).

The idea that natural resources are unlimited and can be used by humans in an unrestricted manner is no longer scientifically accepted. The current focus of society is to guarantee the maintenance of the environment and allow the next generations to enjoy the natural resources necessary for survival. Accordingly, institutions responsible for preserving the environment have gained strength and have expanded their involvement in the supervision of companies and in the control of pollution through increasingly restrictive legislation. Regarding pollution control and rational use of water, the imposition of increasingly restrictive water releasing standards is observed, as well as a global tendency towards establishing a charge not only for water collection, but also for wastewater disposal. The situation of the industry becomes progressively critical because the supply of high quality water, which needs only conventional treatments at the water treatment stations, is steadily decreasing.

Even though Brazil appears to have a stable water supply, the country has already felt the effects of shortage, since the distribution of water is unequal over the country and the higher water availability occurs in the states with lower population density and industrial activity. A large survey conducted by the *Agência Nacional de Águas* (ANA – National Water Agency) in 2010 (Brasil, 2010) showed that 55% of Brazilian cities would have a water supply deficit in 2015. Water shortage for public supply would cause a reduction in water availability for other users, such as the industrial sector, and an increase in its price.

Thus, water reuse has become an environmentally and economically feasible solution for industries. The practice of reusing effluents can improve the industry's image in terms of environmental impacts and raise its profits - as there is a reduction in purchase cost of treated water and in the dependence on local water sanitation companies. From an environmental perspective, the reuse contributes to a reduction in the uptake of natural water and allows the amount saved to be used for nobler purposes, such as public water supply. In the case of the dairy industry, due to the risk of contamination, one should avoid the use of treated effluent for washing equipments that are in direct contact with the products or for operations where there is a possibility of direct contact with raw milk. In contrast, the reuse of treated effluent should be encouraged for replacing the water in cooling towers or boilers and for good manufacturing practices such as washing the floors and external part of trucks and rinsing outside areas (Vourch *et al*., 2005; Asano *et al*., 2007; Wojdalski *et al*., 2013).

It is noteworthy that the literature reports several studies focused on the treatment and reuse of evaporator condensate, spent clean in place (CIP) solutions and other product disposal streams of the dairy industry (Trägardh and Johansson, 1998; Dresch *et al*., 2001; Balannec *et al*., 2002; Vourch *et al*., 2008; Fernández *et al*., 2010; Riera *et al*., 2013; Wojdalski *et al*., 2013). However, there are few studies that address the treatment of end-of-pipe wastewater, especially aiming at its reuse in cleaning processes and auxiliary purposes (Sakar *et al*., 2006; Luo *et al*., 2011; Andrade *et al*., 2014).

Some of the most promising treatment technologies for effluent reuse are membrane separation systems and the combination of these systems with other technologies, such as membrane bioreactors (MBR) (Subtil *et al*., 2014). The MBRs consist of the combination of biological reactors with membrane separation processes, usually micro or ultrafiltration. Among the advantages of MBRs are the fact that they are very compact and are modular systems; the production of excess sludge to be disposed of is relatively small; it can be operated with high solids retention time; it can completely remove suspended solids independent of the biomass setlleability characteristics; and it can produce high quality treated effluents (Judd, 2006).

The MBR effluent can be directly reused as water for irrigation (Bixo *et al*., 2006) or for recreational purposes after removal of residual color (Oota *et al*., 2005). However, if a higher water quality level is required, such as water for indirect potable reuse or industrial reuse, a tertiary treatment, such as nanofiltration or reverse osmosis, could be necessary (Brik *et al*., 2006; Jacob *et al*., 2010).

Nanofiltration (NF) is an intermediary process between ultrafiltration and reverse osmosis. It shows good performance in the removal of dissolved solutes, including multivalent ions and organic compounds with molecular weight ranging between 200 and 1,000 g/mol (Yu *et al*., 2010). Moreover, it has lower pressure requirements and higher flux compared to reverse osmosis (Suksaroj *et al*., 2008). Studies show that NF is an efficient treatment system for secondary or tertiary effluents aiming at the generation of water for industrial, agricultural, or indirect potable reuse (Koyuncu *et al*., 2000; Dresch *et al*., 2001; Shu *et al*., 2005; Acero *et al*., 2010; Jacob *et al*., 2010; Luo *et al*., 2011; Riera *et al*., 2013; Andrade *et al*., 2014).

Thus, the goal of this study was to evaluate the feasibility of the use of MBR followed by NF for the treatment and the reuse of wastewater from the dairy industry. The study initially evaluated the removal efficiency of the combined BRM + NF system and checked if the treated effluent characteristics met the standards for water reuse. Finally, a preliminary economic analysis was conducted to evaluate the feasibility of the proposed system.

METHODOLOGY

Dairy Industry Wastewater

The wastewater used for this study came from a large Brazilian dairy factory located in the state of Minas Gerais that produces UHT milk, yogurt, "minas" cheese, *requeijão* (cream-cheese), and *petit suisse*. The milk processing capacity of this factory is 800 m^3/day. In this factory, approximately 77% of the effluent comes from CIP (clean in place) operations, starting, equilibrating, interrupting and rinsing of plant units, and product disposal, and 23% from the cooling and heating systems, cleaning of external areas, laundry and toilets.

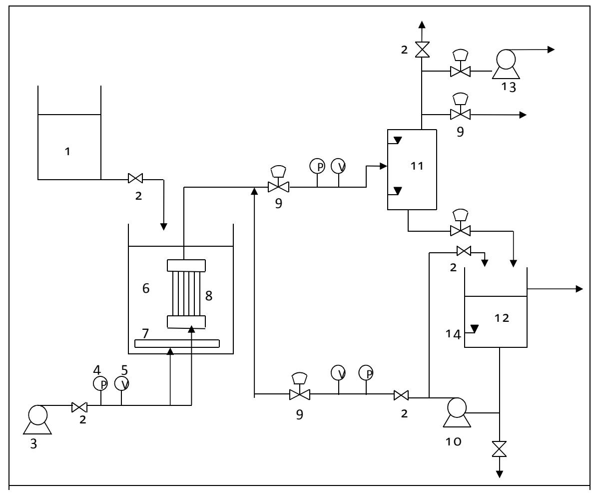
The company's wastewater treatment system receives all the effluent generated in the industrial processes, as well as the sewage from the administrative buildings, and comprises a preliminary sieving stage, followed by dissolved air flotation and biological treatment with activated sludge. The effluent used in this study was collected after sieving and flotation stages.

Six samples of approximately 150 liters were collected throughout the study and placed in 50-liter containers. They were stored in a cold chamber at 3 °C until the effluent was used in the experiments.

Experimental Apparatus

The wastewater collected from the dairy factory was treated using a laboratory scale membrane bioreactor and nanofiltration system.

PAM Selective Membranes (Rio de Janeiro, Brazil) built the membrane bioreactor (MBR) and the membrane module used. The submerged MBR had one microfiltration hollow fiber module (polyetherimide, average pore size of 0.5 µm, membrane area of 0.044 m², average hydraulic permeability for the clean membrane 177L/h.m^2.bar). The permeate was collected at the upper end of the module. At the opposite end there were small holes for air introduction and promotion of aeration between the fibers. The MBR was composed of four acrylic tanks (one tank of 13.4 liters for feed storage, one biological tank with useful volume of 4.4 liters and two tanks for permeate storage of 4.0 L each, in one of which a vacuum was created to promote filtration), a vacuum pump used in microfiltration, a diaphragm pump used in backwash, solenoid valves, level sensors, control valves, flow indicators of permeate, backwash and air, a pressure indicator for the permeate and the backwash and a skid with an electrical panel (Figure 1).



1. Feed tank	6. Biological tank	11. Permeate tank
2. Needle valve	7. Air diffuser	12. Permeate and backwash tank
3. Air compressor	8. Membrane module	13. Vacuum pump
4. Manometer	9. Solenoid valve	14. Level sensor
5. Flow indicator	10. Diaphragm pump	

Figure 1: Layout of the MBR system used.

The MBR was inoculated with sludge provided by the activated sludge reactor from the industry that supplied the wastewater. After an initial phase of acclimatization of the microorganisms to the MBR and effluent conditions, the system operated continuously for 40 days. The acclimatization lasted 28 days, the hydraulic retention time (HRT) was set to 8 hours and there was no sludge discharge. The continuous operation conditions were: HRT of 6 hours and sludge retention time of 60 days (values defined based on the literature and from experiments by Andrade (2011)). The permeate flow rate was kept constant at 0.70L/h. The system operated with continuous aeration to supply oxygen to the microorganisms and to remove particles deposited on the membrane surface (1 Nm³air/h). Automatic backwash, performed with MBR permeate, was activated for 15 seconds after every 15 minutes of permeation with a flow rate of 2.0L/h. This frequency is similar to the one used by other authors (Bouhabila *et al*., 2001; Artiga *et al*., 2005; Matošića *et al*., 2008).

During the 40 days of operation, the MBR was continuously monitored and the critical flux was determined four times using the TMP-step method. To this end, the membrane module was initially chemically cleaned and immersed in the bioreactor; permeate flux was monitored for fixed values of pressure. For each pressure value, the filtration time was 18 minutes, after which the applied pressure was increased by 0.05 bar. Critical flux corresponded to the value where flow reduction was observed during the 18 minutes of permeation at constant pressure. The value presented is the average of the four results obtained.

The MBR permeate was sent to the NF system in order to generate a final effluent with sufficient quality for industrial reuse. The NF process occurred in batches using a unit composed of a feed tank (FT), which stored the MBR permeate, a pump connected to a velocity control, a rotameter to read the feed flow, a valve to adjust the pressure, a manometer, and a temperature gauge (Figure 2).

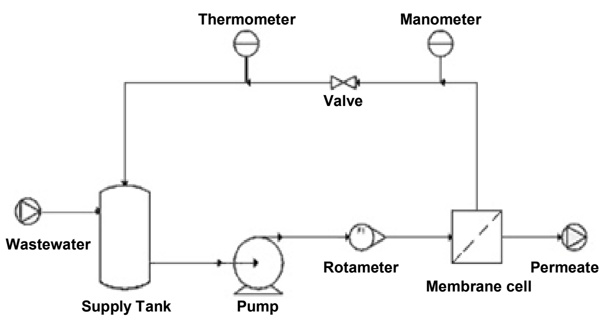


Figure 2: Layout of the NF system

The commercial membrane NF90 from Dow-Filmtec was used. The flat-sheet membrane was properly cut and inserted in a cross-flow stainless steel cell of 8.9 cm in diameter, providing a filtration area of 0.0062 m^2. Water permeability of the clean NF90 membrane had an average value of 2.3 L/h.m^2.bar, indicating that it was a tightly packed NF membrane (Krieg *et al*., 2004; Yüksel *et al*., 2013). The filtration took place at a pressure of 10 bar, feed cross-flow velocity of 7.8m/s, and permeate recovery rate of 45%, defined as the optimal conditions by Andrade *et al*. (2014). Permeate flux was monitored by measuring the volume of permeate generated in a given time interval. Critical flux was measured according to the methodology described before, with the only difference being the higher pressure increment equal to 5 bar (instead of 0.05 bar).

The raw wastewater, MBR permeate, NF permeate and NF retentate were analyzed for COD, color, and total solids following the recommendations of Standard Methods for the Examination of Water and Wastewater (APHA, 2005) to verify the removal efficiency obtained by each system.

Evaluation of the Technical Feasibility of the Reuse of the Final Treated Effluent

The technical and economic feasibility of the NF permeate reuse was verified considering its reuse in the industrial process itself, and the disposal of the NF retentate in domestic wastewater collection system.

The technical feasibility was based on the comparison of the physicochemical quality of the permeate and concentrate with standards for reuse and disposal, respectively. The NF permeate was analyzed for pH, alkalinity, total dissolved solids, COD, and metals, including Ca, Mg, Cu, Zn, and Fe (atomic absorption spectrophotometer Perkin Elmer 3300); and the results were compared with standards for replacement water in cooling system and boilers. The NF retentate was also analyzed for pH and COD and compared with legislative standards for effluent discharge.

Evaluation of the Economic Feasibility of System Implementation

A preliminary economic analysis for the proposed treatment system was conducted. The net present value (NPV), the internal rate of return (IRR), and the payback period for the investment were calculated considering a period of 15 years. The NPV was calculated using the following equation (Wiesemann *et al*., 2010):

$$NPV = \sum_{t=1}^{n} \frac{S}{(1+i)^t} \tag{1}$$

in which S is the profit or loss in the year (cash flow), i is the interest rate considered, t is the number of the year.

The IRR was also calculated using Equation (1). This parameter is equal the interest rate, i, when NPV is equal zero. To calculate the payback, the profit or loss of the period is added to that of the previous year. The payback is the year in which the overall result becomes a positive value.

The influence of membrane lifespan on these indices was evaluated. The indices were calculated considering module replacement every 1, 2, 3, 4, 5, 6, or 7 years. According to Ayala *et al*. (2011), who indicate that the average lifespan of submerged MBR membranes, the upper limit is over six years. According to Liikanena *et al*. (2006), NF membrane lifespan can be estimated at five years; however, good operation and adoption of rejuvenation procedures can increase this value (da Silva *et al*., 2012).

For this economic analysis, a dairy industry with water consumption of 1,300 m^3/d and wastewater production of 1,000 m^3/d was considered. Thus, a composite MBR and NF system with total capacity of 1,000 m^3/d was evaluated. Considering a permeate recovery rate of 45% for the NF, the total effluent flow rate results in 450 m^3/d of permeate and 550 m^3/d of concentrate. Thus, only 450 m^3/d of reuse water was being generated, equivalent to the NF permeate, since, in principle, the retentate cannot be industrially reused due to inferior quality.

Even though this value appears to be low, it is consistent with the reality of the dairy industry. The water demand in the studied industry showed that 60% of daily demand is used for washing operations (CIP) and must meet the standards for drinking water set by the *Portaria* 2.914/2011 of the *Ministério da Saúde* (Health Ministry). Next, 30% of daily demand is used for replacing water in cooling towers and boilers. Finally 10% of daily demand is used in good manufacturing practices (washing of floors, bathrooms, outside areas, etc.). Accordingly, since direct reuse of industrial effluents for potable purposes is not advisable (Mancuso and Santos, 2003), the objective was to generate a treated effluent flow for reuse that could meet the needs of water consumption for washing and refilling cooling towers and boilers. That value is equivalent to 40% of 1,300 m^3/d, or 520 m^3/d.

Although the aim of this work was not to define a route for water reuse exclusively for this specific dairy industry, we believe that this water balance should be similar to those of other factories in the sector, so that similar decisions could be made in more global scenarios.

We supposed that the industry was located in an intensely industrialized region and that there were no surface water bodies or groundwater sources for water collection or effluent disposal nearby. Thus, it was considered that all of the water used in the industrial processes and in the building facilities was purchased from the local sanitation department and the wastewater generated was discharged into the public sewage system, after sieving and flotation with compressed air (refer to “Effluent in the dairy industry” in the Methodology). The economic analysis conducted aims to evaluate the replacement of this traditional form of water management (scenario one) by the combined MBR and NF wastewater treatment system (scenario two). This combined system generates two streams: one of treated water for industrial reuse (NF permeate) and another of treated effluent for discharge into the public sewage system, however with higher quality (NF retentate).

In scenario two, the quantity of water purchased from the local sanitation department is reduced by 450 m^3/d (NF permeate). Moreover, 450 m^3/d of wastewater ceases to be cast into the public sewage system, and the remaining 550 m^3/d (NF retentate) are released with higher quality. Thus, revenue is obtained from the reduction in costs associated with these above operations, as well as from the environmental value obtained with the reuse of water and with the release of higher quality effluent into the receiving water bodies.

The costs considered were related to: initial units purchase investment; labor force for plant operations (1 engineer and 4 technicians-operators); treatment and disposal of the MBR sludge (considering solids retention time of 60 days); energy consumption; chemical agents for membranes cleaning; units maintenance; and exchange of membrane modules (Molinos-Senante *et al*., 2012). Table 1 shows the values considered for each of these variables. The values refer to year zero and were readjusted at a rate of 4.5% per year for the following years, which is the inflation target for Brazil (*Banco Central do Brasil*, 2013).

The unit investment cost and the prices per m^2 of microfiltration (MF) and NF membranes were obtained by estimates made by two membrane suppliers in the market. To calculate the total membrane area required, it was considered permeate flux of 15 $L/h.m^2$ for both MF and NF (which is consistent with experimental results). Payment of 13 annual salaries plus 70% corresponding to taxes and labor charges were applied for spending on labor calculations (Zanluca, 2013).

Energy consumption of 0.54 kWh/m^3 for NF (Costa and Pinho, 2006) and 0.14 kWh/m^3 for MBR (Gil *et al*., 2010), were considered. The electricity rate was obtained on the CEMIG website (CEMIG, 2013) considering a blue hour-seasonal rate A3a. To calculate the daily average rates through the rates for the hours of "peak" and "off-peak", it was considered that the devices are connected 24 hours a day.

The price of treated water and of discharging wastewater in the public sewage system was obtained on the website from the *Companhia de Saneamento de Minas Gerais* (Sanitation Company of Minas Gerais) (COPASA, 2013 a) for the water industrial consumption of 1,000 m^3 daily. The multiplication factor K was calculated based on the standard T

187/4 (COPASA, 2012), which establishes criteria and conditions for the release of non-domestic wastewater in the COPASA sewage system. This rule states that, for the disposal of industrial effluents with concentrations of COD above 450 mg/L and Total Suspended Solids (TSS) above 300 mg/L, the multiplication factor K must address the basic cost of collection and treatment of wastewater. This procedure is based on the principle that the polluter must pay, which requires that the most pollutant sources should pay more for effluent treatment. To determine the K factor applied to the wastewater in scenario one (industry purchase all the water and discharge all the effluent), the average values of wastewater characteristics determined by Andrade *et al*. (2011) were used. In scenario two (combined MBR and NF for reuse of a fraction of the effluent), the pollutant concentration found in the NF retentate was used.

Table 1: Value of items considered for calculating the economic evaluation.

Item	Value
Initial unit cost	R$ 5,000,000.00
Monthly salary of an engineering professional	R$ 4,500.00
Monthly salary of a technical professional	R$ 2,500.00
Sludge disposal	R$ 7.72/m³
Electricity rate (daily average cost per kW)	R$ 11,86/kW
Electricity rate (daily average cost per kWh)	R$ 0,20507/kWh
Treated water rate	R$ 6.881/m³
Wastewater disposal in public sewage system rate	R$ 6.193/m³
Multiplication factor K for the wastewater disposal rate of scenario 1	3.34
Multiplication factor K for the wastewater disposal rate of scenario 2	1.00
Environmental value added	R$ 0.06/m³
Maintenance	5% of initial investment
Chemical agents for membrane cleaning	2% of initial investment
Microfiltration membrane replacement	R$ 280/m²
Nanofiltration membrane replacement	R$ 400/m²

The release of wastewater to public sewage collection systems that already met the legislation parameters for effluent discharge in water bodies before its treatment in the sanitation company, was considered as an environmental gain, subject to valuation. As a result, the difference between the COD load of a current with 550 m^3/h flow and concentration of 75 mg/L (NF concentrate) (scenario two) and of another current with 1,000 m^3/day flow and concentration of 180 mg/L (maximum value for disposal in receiving bodies according to the *Deliberação Normativa Conjunta* COPAM/CERH-MG 01/2008) (scenario 1) were valued in accordance with Molinos-Senante *et al*. (2010). These authors proposed a price of US$ 0.1312 per kg of COD that ceases to be disposed of in water bodies. The Euro exchange rate of R$ 3.08 was considered (exchange rate in 23/11/2013). It is worthy of note that Molinos-Senante and co-workers (2010) also showed in their study suggestions of valuation for total nitrogen, phosphorus, and suspended solids loads which are ceased. However, it was not possible to consider them in this study due to lack of reference data. Thus, it is important to emphasize that if a more complete analyses were made, the environmental valuation would provide results even higher than shown here.

Since the revenue from the savings in water purchase and effluents discharge were more significant, a sensitivity analysis was completed for the rate of treated water and effluent discharge, aiming to confirm how changes in these variables would affect the economic evaluation of the system. For this, rates of R$ 2.00, R$ 4.00, R$ 6.00, R$ 8.00, R$ 10.00, and R$ 12.00 per m^3 of water were considered, along with a membrane lifespan fixed at five years. The effluent discharge rate was considered to be 90% of the rate charged per m^3 of treated water, according to the tool on the website of the water provider, COPASA (COPASA, 2013 b). The value of the multiplication factor K was maintained constant, in accordance with the values shown in Table 1. The NPV and the IRR were calculated for each condition.

RESULTS

Technical Feasibility of the Reuse of Treated Wastewater

Figure 3 presents the results of the combined MBR and NF route for wastewater treatment from dairy industry.

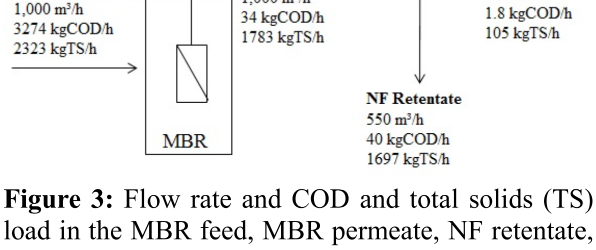


Figure 3: Flow rate and COD and total solids (TS) load in the MBR feed, MBR permeate, NF retentate, and NF permeate.

The results show that MBR efficiently removes organic matter contained in the feed effluent. This is due to its ability to operate with higher biomass concentrations than conventional systems, proving better biodegradation of the organic compounds in the effluent. Moreover, the presence of the membrane ensures complete removal of suspended solids and also partial retention of compounds with low biodegradability, either from the effluent itself or generated by the microorganisms, that remain in the reactor longer than the average for TDH and may thus be degraded by the biomass (Bernhard *et al*., 2006; Andrade *et al*., 2013).

However, the total solids of the MBR permeate, predominantly composed of dissolved solids, were still high and had to be further removed to provide a treated effluent with quality for industrial water reuse. This was achieved by post-treating the MBR permeate with NF, which showed elevated retention of solids and residual COD, as well as color, alkalinity and sodium. As can be seen in Table 2, the overall system efficiencies are quite high for all the parameters evaluated.

Table 2: Removal efficiency of MBR, NF, and the combination of both processes.

	Dairy effluent	MBR Permeate[a]	NF Permeate[a]	Global system efficiency
COD (mg/L)	3274	34 (99%)	4 (88%)	100%
Color (Hu)	2163	35 (98%)	15 (58%)	99%
TS (mg/L)	3366	1783 (47%)	233 (87%)	93%
Alkalinity (mg/L)	641	1167 (-82%)	166 (86%)	74%
TN (mg/L)	115	12 (89%)	7 (40%)	94%
Sodium (mg/L)	606	600 (1%)	69 (89%)	89%
pH	7.72	9.05	8.99	-

[a] Values in parentheses correspond to the removal efficiencies of MBR and NF
TN – Total nitrogen
TS – Total solids

No other studies were found that report on the use of MBR and NF for treatment of dairy wastewater for reuse. However, some authors used NF alone as a treatment system for this type of effluent (Vourch *et al*., 2005; Fernandéz *et al*., 2010; Luo *et al*., 2010). It was found that the final permeate concentrations obtained in the current study were lower than the ones found by other authors, probably due to the high level of pollutant removal by MBR, that generates a final permeate with a high quality.

To verify the possibility of the NF permeate reuse, its physicochemical properties were compared with quality standards of cooling and boiler water, as show in Table 3.

Table 3: Standards for cooling and boiler water and values obtained for the NF permeate.

Parameter	NF Permeate	Cooling water*	Steam generation*	
			< 10 bar	10 to 50 bar
TDS (mg/L)	233	500	700	500
Alkalinity (mg/L)	166	350	350	100
pH	8.99	6.9 to 9.0	7.0 to 10.0	8.2 to 10.0
COD (mg/L)	4.0	75	5.0	5.0
Calcium (mg/L)	0.44	50	+	0.40
Magnesium (mg/L)	0.041	0.5	+	0.25
Copper (mg/L)	0.04	+	0.5	0.05
Zinc (mg/L)	<0.1	+	+	0.01
Iron (mg/L)	0.05	0.5	1.0	0.30

TDS – Total Dissolved Solids
+ Accepted as received as long as other standards are met
* Reference: Fiesp; Asano (2007)

It was observed that the quality of the NF permeate meets the water standards for cooling and low pressure boilers, and can be reused for such applications, as well as for washing floors, outside areas, and trucks, which have lower water quality requirements. In addition, the only parameters that do not meet the standards for medium pressure boilers are alkalinity and calcium. Thus, if there is interest in reusing the effluent in boilers that operate with pressure greater than 10 bar, one could evaluate options such as the implementation of a subsequent degassing unit to remove dissolved CO_2 and reduce the alkalinity, replacement of nanofiltration by reverse osmosis, or the implementation of a final polish treatment with ion exchange. Moreover, although the majority of organic and inorganic compounds and microorganisms are removed by NF, Asano and co-authors (2007) emphasize that disinfection of the permeate should be performed before reuse to ensure system security in case of failure or damage to the membranes.

The COD concentration of NF retentate was 73 mg/L and the pH 9.0. According to *Deliberação Normativa Conjunta* COPAM/CERH-MG nº 01, of May 05, 2008, which establishes the quality required to discharge effluents in superficial water bodies in the state of Minas Gerais, the discharge standards for COD and pH are 180 mg/L and 6.0-9.0. It was found that the NF retentate meets the legislative parameters and can be directly released into rivers. Another possibility would be to reuse the retentate for applications that have lower water quality requirements, such as garden irrigation, after a disinfection process.

Table 4 shows the BRM and NF performance in terms of operational flux and critical flux.

Maximum flux values reported on the literature for submerged BRM modules treating industrial effluents lie between 5 and 15 L/h.m² (Cornel and Krause, 2008). In this work, the operational flux was 15.9 L/h.m² near the upper limit reported in the literature. However, system operation was stable and did not need frequent chemical cleaning. According to the literature, critical flux is one of the parameters that most influences membrane fouling (Bacchin *et al*., 2006). Although fouling during sub-critical operations has been reported (Pollice *et al*., 2005), it has been proved that BRMs operating above the critical flux have higher fouling rate (Bacchin *et al*., 2006). Thus, the operation of BRMs below the critical flux, as conducted in this work, is essential to fouling control and good system performance.

Up to a permeate flux of 25 L/h.m² no critical behavior was observed for the NF system. This result, quite positive, indicates the low fouling of NF membrane.

Table 4: Main operational flux and critical flux for the MBR and NF.

Parameter	MBR	NF
Mean operational flux (L/h.m²)	15.9	18.5
Critical flux (L/h.m²)	21.6	>25.1

Economic Feasibility of Reuse of Treated Wastewater

Figure 4 presents the annual operational costs and the percent of these costs associated with membrane replacement as a function of the lifespan of the modules. It was show that the operational costs become progressively smaller as the lifespan of the membranes increases. This effect is significant when the duration of the modules passes from one to two years and becomes a little less important after it becomes larger than four years. Thus, it is worthwhile to highlight the importance of adopting operational procedures for module maintenance and increasing the lifespan of membranes, avoiding actions that could damage the membrane structure and lead to the need for frequent replacements.

Table 5 shows the price of treated wastewater in R$/m^3. The costs for the initial investment, labor, electricity, maintenance, purchase of chemicals for cleaning the membranes, and treatment and disposal of excess sludge from MBR are equal for all the situations evaluated since they are not influenced by the membrane lifespan.

Once again, one may note the importance of maintaining the integrity of the modules in order to reduce costs and influence the economic feasibility of the membrane system. If the modules were replaced annually, the total cost for treatment and reuse of wastewater through the proposed system would be R$ 9.99/m^3, with 40% of the costs due to purchase of replacement modules. On the other hand, if the modules were well maintained and could be used for seven years, the total treatment cost would be reduced by 32%, and the purchase of modules would correspond to only 8% of the total expenditures.

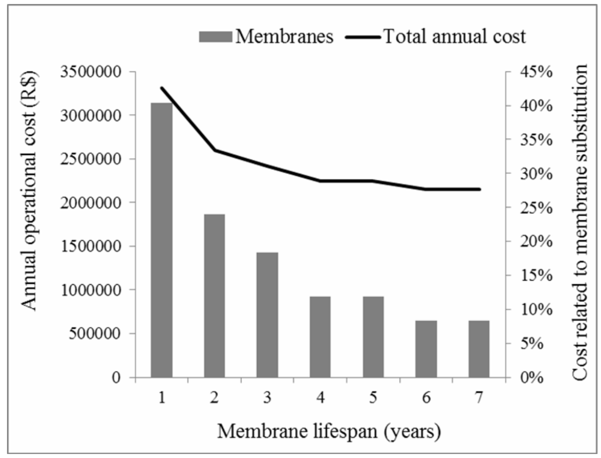


Figure 4: Annual operational costs and percent of cost associated with substitution of modules.

Table 5: Price of treated wastewater (R$/m³) in total and for each expense.

	Lifespan of membrane modules (MF and NF)						
	1 year	**2 years**	**3 years**	**4 years**	**5 years**	**6 years**	**7 years**
	Cost (R$/m³ of treated wastewater)						
Initial Investment	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Labor	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Electricity	3.46	3.46	3.46	3.46	3.46	3.46	3.46
Maintenance	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Chemicals	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Sludge	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Membranes	3.66	1.71	1.22	0.73	0.73	0.49	0.49
Total	9.99	8.03	7.55	7.06	7.06	6.82	6.82

It was also shown that the cost of electricity is rather significant, corresponding to approximately 38% of the total cost in the case of annual replacement of membranes and 59% in the case of replacement every seven years.

Figure 5 shows the values of NPV for the implementation and operation of the MBR and NF wastewater reuse system as a function of the opportunity cost for the investor and the lifespan of the membrane modules.

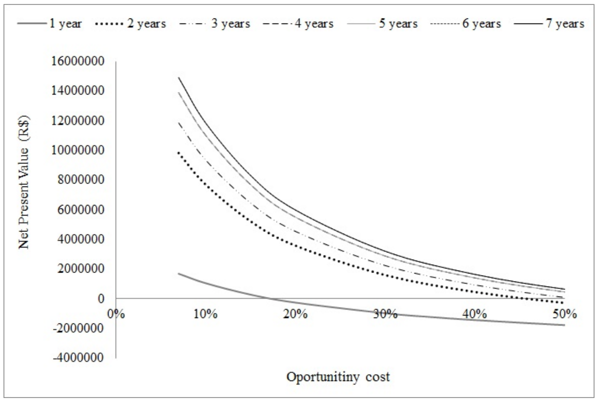


Figure 5: NPV of the system as a function of opportunity cost and lifespan of the membrane modules.

It was found that the NPV is positive, for opportunity cost of 10%, even when membrane lifespan is only 1 year, indicating profit with the implementation of the system. For an opportunity cost of 15%, considering membrane replacement every two years, the PLV is R$ 5,234,100.70, a value that could be considered quite high and attractive. On the other hand, in the case that the modules are well conserved and can be replaced every seven years, the NPV, considering an opportunity cost of 15%, would be 60% greater and equal to R$ 8,325,773.11. Thus, it is demonstrated that, as the lifespan of the membranes increases, the NPV also grows.

The internal rate of return calculated for various lengths of membrane lifespans are found in Table 6.

Table 6: Internal rate of return and payback period for different lifespans of membrane modules.

Membrane lifespan (years)	IRR (% per year)	Payback (years)
1	17.5	4
2	45.8	2
3	51.4	<1
4	56.7	<1
5	56.7	<1
6	59.3	<1
7	59.3	<1

It can be observed that the IRR is extremely attractive under each set of conditions, even with frequent membrane replacement. Rates of return of 17% are considered very interesting in the financial market, especially when dealing with an investment of low risk, such as the case analyzed in this study. The internal rates of return rise with the increase of the interval between membrane replacements, and this increase is more significant for lower membrane lifespans, specifically between one and four years. Except for the annual exchange of membrane modules, under all other conditions evaluated, the payback period was one year or less, since the income from the first year of unit operations already compensated for the initial investment.

Since the profit from the implementation of the reuse system is derived principally from the savings in the purchase of treated water from the local utility companies and from the disposal of the wastewater in the sewage collection system, the variable "cost of water" has a large influence on the final economic results. Thus, to verify the effects of the price of treated water on the economic assessment of the system, a sensitivity analysis was performed for this variable. Rates of R$ 2.00, R$ 4.00, R$ 6.00, R$ 8.00, R$ 10.00 e R$ 12.00 per m^3 of water, consistent with typical Brazilian water prices, were considered. For the sensitivity analysis, the membrane lifespan was fixed at five years, the rate for wastewater disposal was considered to be 90% of the rate of treated water, and the multiplication factor K was maintained constant, corresponding to the values in Table 1, for all conditions. The NPVs calculated as a function of these different rates and different opportunity costs are presented in Figure 6.

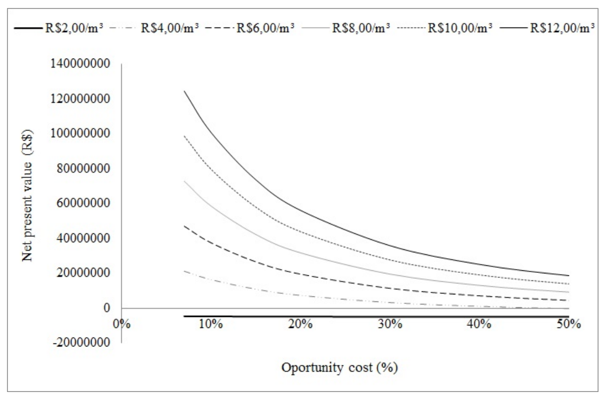


Figure 6: NPV of the system as a function of opportunity cost and of cost of treated water, considering a membrane lifespan of five years.

The large influence of the variable evaluated on the economic result obtained is clearly demonstrated. For a cost of water of R$ 4.00/m^3 and an opportunity cost of 15%, the NPV is R$ 10,957,105.29. On the other hand, if the price of water was R$ 12.00/m^3, the NPV at 15% is almost 7 times larger, equal to R$ 73,716,775.62, indicating a highly attractive investment. It is worth noting that the price of water used is consistent with Brazilian reality since the rates are similar to those offered by SABESP (Basic Sanitation Company of the State of São Paulo). In several municipalities in the metropolitan region of São Paulo, companies that consume more than 50 m^3/ month must pay R$ 12.72 per m^3 of water (SABESP, 2013).

The revenue gained through environmental valuation (R$ 21,900.00 /year) corresponds to only 0.5% of the total annual revenue when the cost of treated water is R$ 4.00/m^3 and 0.2% when the cost is R$ 12.00/m^3. Even though this revenue is insignificant when compared to the others, it is still important to consider the variable environmental value added in economic and environmental feasibility studies since this tool allows the valuation of environmental resources that are not considered in the sphere of market operations. By using methodologies of environmental valuation, it is possible to estimate the willingness of society to pay for the preservation or conservation of resources and environmental services, assisting in decision-making. According to AQUAREC (2006) *apud* Molinos-Senante *et al*. (2012), the weight distribution for assessing the feasibility of wastewater reuse projects should be 50% for economic aspects, 25% for environmental impacts, and 25% for social aspects.

The internal rate of return and the payback period of the investment calculated for each cost of water evaluated, considering a membrane lifespan of five years are shown in Table 7.

Table 7: Internal rate of return and payback period for different costs of treated water.

Rate (R$/m³)	IRR (%)	Payback (years)
2.00	-	-
4.00	48.2	3
6.00	91.7	2
8.00	134.9	<1
10.00	178.2	<1
12.00	221.4	<1

Table 7 once again shows the large impact the variables considered can have on the results of the economic analysis. The implementation of the proposed reuse system appears to be a very interesting investment for locations in which the cost of water is close to R$ 4.00/m^3, which is considered to be a low rate. For consumers who pay rates higher than R$ 6.00/m^3, the investment is extremely attractive, since it results in an IRR greater than 90%, rates rarely obtained in other low-risk businesses. The time to remake the capital spent with the initial investment also is short, and even less than one year for water rates higher than R$ 8.00/m^3, reinforcing the attractiveness of the system.

Thus, considering the data presented, it can be concluded that the results are very promising, although this was only a preliminary economic study, and that the treatment system proposed for the reuse of wastewater from the dairy industry proves quite technically and economically feasible.

CONCLUSION

The treatment process evaluated (MBR combined with NF) permits the production of water for reuse derived from dairy industry wastewater. The NF permeate is of sufficient quality to be used as water to generate steam in low-pressure boilers, for cooling towers, and for good manufacturing practices, such as washing floors and outside areas. Furthermore, the NF retentate complies with legislative parameters for the disposal of wastewater in water bodies.

The economic feasibility of the reuse of the wastewater treated with MBR and NF was also confirmed, mostly in cases when the cost to buy treated water from the utility providers is above R$ 4.00/m^3. From the analyses of NPV, IRR, and payback period, the importance of adequate maintenance of the membrane modules in order to extend the lifespan was demonstrated. The total cost of the treatment by the proposed treatment system ranged from R$ 9.99/m^3 to R$ 6.82/m^3, depending on membrane lifespan.

Although these results are good indicators of the economic feasibility of the proposed reuse system, it is important to emphasize that the cost analysis was based on some assumptions. Moreover, other variables should be included in a systematic economic evaluation prior to the decision about the real implementation of the system.

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