UNESCO-IHE Institute for Water Education

Universidad del Valle

Evaluation of a MBR for treating slaughterhouse wastewater in Montevideo, Uruguay

MSc. Thesis

Nicolás Cunha Apatie

UWS-SE CALI 2016-10

April 2015

Evaluation of a MBR for treating slaughterhouse wastewater in Montevideo, Uruguay

Master of Science Thesis
by
Nicolás Cunha Apatie

Supervisor
Prof. Carlos Madera (UNIVALLE)

Mentors
Dr. Hector García (UNESCO-IHE)
Dr. Tineke Hooijmans (UNESCO-IHE)
Dr. Diana Míguez (LATU)

This research is done for the partial fulfilment of requirements for the Master of Science degree at the UNESCO-IHE Institute for Water Education, Delft, the Netherlands

Delft
April 2016

Abstract

In Uruguay, the problem of eutrophication of the rivers is every time more concerning. One of the biggest contributors are slaughterhouses, where they usually have ponds treatment system and do not comply with the discharge Standards, especially regarding to nutrients.

This research aims to evaluate the performance of a pilot scale membrane bioreactor (MBR) for slaughterhouse wastewater treatment, in order to minimize the impact of their effluent discharge in rivers. It was carried out at one of the main slaughterhouses in Uruguay namely Schneck. The MBR consists on an anoxic compartment followed by one aerobic that contains a recirculation pump in order to recycle to the anoxic.

The MBR was placed in order to take its influent from the first step of the treatment plant that was a homogenization basin. After some drawbacks, the MBR was inoculated with a domestic wastewater treatment plant and started operating. Some periods of trials were necessary until it reached a steady state, where it was operated with a recirculation ratio of 4 and an average dissolved oxygen of 3 mg/L, with aeration always on. The MLSS during this period was maintained between 10 and 12 g/L, with a waste flow of around 50 L/d. With these conditions, a total nitrification was achieved, with an average NH_4 of 0.74 mgNH_4-N/L, while the National discharge Standard limits this value at 5 mgNH_4-N/L. Regarding to this parameter, the actual treatment plant was obtaining effluent values between 8 and 79 mgNH_4-N/L. The COD and BOD removals in the MBR where higher than 95% with effluent values of BOD below the Standard limit. The only parameter above the Standard was the TP, which average was 14.7mg/L and the limit is 5mg/L (a chemical phosphorous removal should be carried out adding e.g. Ferric Chloride to the MBR). The Nitrate average in the effluent was 24 mg/L and the TN removal was 57.6%, meaning that the denitrification was not completed. Because of that, another trial conditions were investigated, with the same control parameters as the last one except the dissolved oxygen. The aeration was intermittent, turned "on" for 5 minutes and "off" for 15 minutes. The denitrification was enhanced and the total nitrogen removal efficiency reached a value of 78%. However, the NH_4 increased to 6.2 mgNH_4-N/L.

Furthermore, a BioWin model for estimating the optimal location for the MBR at the existing ponds system treatment plant was carried out, considering the N-removal potential in relation to the COD/N influent ratio. The results shows that the best place to situate the MBR inlet is before the homogenization tank, where the COD/TN ratio is 14.0 and the removal TN efficiency is 83.7 %. The second best point for the MBR is after the homogenization tank (COD/TN=11.1), with an efficiency of 72.8 % . For the other points of the treatment plant (after each treatment pond), the COD/N ratio decreases below 6, and the TN removal was reduced at values below 53 %.

Keywords:
Membrane bioreactor, slaughterhouse wastewater treatment, nutrient removal, COD/N ratio, BioWin.

Acknowledgements

I would like to express my gratitude to my mentors: Dr. Diana Míguez, Prof. Tineke Hooijmans, Dr. Hector Garcia, and to my supervisor Prof. Carlos Madera for their continuous contributions and guidance during my Thesis research.

I would like to acknowledge the financial and technical support of LATU that provided every material needed for the research.

I would also like to thank Schneck, for allowed me to carry out the fieldwork in their place, and for their technical support.

I would like to thank Florencia Arón and Alejandra Szabo for helping me with the startup of the reactor.

My special thanks for the IMFIA institute from the Faculty of Engineering in Montevideo, especially to Elizabeth González and Nicolás Rezzano for the encouragement and comprehension during this period.

In addition, I would like to thank my family and friends from Uruguay for being part of this process by the distance and providing me support.

I would like to extend my gratitude to ANII and Bill and Melinda Gates Foundation for granting me the opportunity to perform my master studies.

Finally, I would like to thank my new friends from Univalle, UNESCO-IHE and TU-Delft for the very special moments shared during this process.

Table of Contents

List of Figures

List of Tables

CHAPTER 1 - Introduction

1.1. Background

One of the major environmental problems in Uruguay is the pollution of the Santa Lucia River Basin, which is the main source of drinking water of the country. The most important source of pollution of the Basin is the food processing industries.

Slaughterhouse represent a significant part of the food processing industries. Meat is the second most important product exported. There are around 40 slaughterhouses in the country, most of them having ponds system for wastewater treatment. Their effluents do not comply with the national standards, especially with respect to carbon and nutrients (*Industrial effluents report*, 2014). Furthermore, slaughterhouses have a very big water consumption, around 2 m^3 per animal processed. In Uruguay, each slaughterhouse processes between 200 to 5000 animals per week (INAC, 2015), generating a big amount of effluent that in addition of the excess of nutrients and organic matter, a big load of pollutants are discharged in the rivers.

1.2. Problem statement

The main effluent contributor of the industrial sector in Montevideo is the agroindustry, consisting in slaughterhouses and meat by-products processing industries. After that, it is situated the leather, refinery and milk industries. Regarding the Ammonia content, the main contributors in the city are the meat industries, discharging 481 kg/d NH_4, followed by refineries with 205 kg/d and the malting with 9 kg/d (*Industrial effluents report*, 2014).

Focusing on Schneck Slaughterhouse, a big contributor of the agroindustry, the average effluent discharge is Q=380 m^3/day (*Industrial effluents report*, 2014) and the effluent parameters are summarized in Table 1. According to the table, during the year 2015 the TSS, fat and oil, NH_4, Total P and Total Coliforms Standards were not achieved. The parameter that stands out is the NH_4, in which even the minimum result of the analysis from the year 2015 exceeds the maximum allowed by the National Standard (“Decreto 253/79,” 1979), and the average value is 8 times bigger.

Table 1: Schneck effluent discharge. Summary of measures during the year 2015 by DINAMA[1]

Parameter	Unit	Min.	Max.	Average	Max. allowed (Decreto 253/79[2])
Temperature	**ºC**	10	26	20	30
pH		7.6	8.6	8.0	6.0 to 9.0
Dissolved Oxygen	**mg/L**	2.8	3.3	3.1	-
BOD_5	**mg/L**	30	60	40	60
COD	**mg/L**	40	360	230	-
TSS	**mg/L**	10	220	106	150
Fat and Oil	**mg/L**	20	130	58	50
NH_4	**mgN/L**	8	79	38	5.0
NO_3	**mgN/L**	0.6	3.5	1.5	-
Total N	**mgN/L**	20	86	50	-
Total P	**mgP/L**	3.0	8.6	5.7	5.0
Fecal Coliforms	**CFU/ 100mL**	1900	7000	3700	5000

1.3. Justification

Slaughterhouses are largely contributing to the pollution of rivers in Uruguay. They produce a big amount of effluent every day, which in addition of the breach of the standard limits, generates very high load of nutrients and organic matter discharged at rivers. This brings problems such as eutrophication and deoxygenation of the water bodies. The focus of the research is on one particular slaughterhouse and meat processing industry, namely Schneck, which is one of the most important of the country.

The evaluation of the slaughterhouse effluent treatment by a MBR is important for the industry. They can have fines due to the current discharge in the river or, even worse, they could be ordered to close the factory. Furthermore, applying a new technology for their wastewater treatment and obtaining very good results can improve their image among the population, visitors, etc. In addition to that, as one of the most important slaughterhouse and meat processing industry in Uruguay, Schneck wants to be an example of slaughterhouses for the country. Their vision is: "We want to be a leader in the sector, based on known quality brands both domestically and internationally, betting on a permanent basis for innovation and technology, complying fully with business ethics and social and committed to preserving the environment" ("Schneck web page," 2015).

Moreover, if the reuse of the MBR effluent in some parts of the industry (e.g. cleaning the cattle shed, the dirty zone) is feasible, the water consumption could be decreased.

[1] DINAMA: "Dirección Nacional de Medio Ambiente", is the National Environmental Agency
[2] Decreto 253/79: Parameters to avoid water pollution. The values presented in the table are for effluent discharge in water bodies

1.4. Research questions

The next questions are going to be answered throughout the report:

- How efficient is a MBR as a Slaughterhouse wastewater treatment?

- Does the treatment reach the required Standards?

- Considering the actual slaughterhouse treatment plant consisting on ponds system (anaerobic, aerobic and facultative), where is the best place to incorporate the MBR in order to obtain best removal efficiencies? How does the influent COD/N ratio affect the N-removal?

CHAPTER 2- Research Objectives

2.1. General objective

The main objective of this research is to evaluate the performance of a membrane bioreactor treating slaughterhouse wastewater in Uruguay.

2.2. Specific objectives

The specific objectives of the research are:

- Evaluate the performance, in special for nutrient and organic matter removal, of a pilot MBR in one of the most important slaughterhouse in Uruguay namely Schneck.
- Develop a BioWin[3] model for estimating the optimal location for the MBR at the existing treatment plant, considering the N-removal potential in relation to the COD/N influent ratio.

[3] BioWin is a wastewater treatment process simulator that ties together biological, chemical, and physical process models, used to design, upgrade, and optimize wastewater treatment plants. It was developed by EnviroSim Associates Ltd (webpage: http://envirosim.com).

CHAPTER 3- Literature review

2.1. Situation of slaughterhouses

Global situation

- **Slaughterhouse wastewater (SWW) composition**

The meat processing industry is one of the major consumers of freshwater, among food and beverage processing facilities, which makes slaughterhouses a significant producer of wastewater effluent. A slaughterhouse plant is classified as a meat processing facility that may consume between 2.5 and 40 m3 of water per metric tons of meat produced. Common slaughterhouse wastewater characteristics are summarized in Table 2. The specific amounts of wastewater and pollutant loads vary depending on the animals slaughtered and processed that are different among the meat processing industries. Nevertheless, they usually contain a considerable amount of total phosphorus (TP), total nitrogen (TN), total organic carbon (TOC), chemical oxygen demand (COD), total suspended solids (TSS), and biochemical oxygen demand (BOD). SWW is in general considered detrimental due to its complex composition of fats, proteins, and fibres from the slaughtering process. The major part of the contamination is caused by blood and by stomach and intestinal mucus. Furthermore, it contains high levels of organics, pathogenic and non-pathogenic microorganisms, and detergents and disinfectants used for cleaning activities (Bustillo-Lecompte & Mehrvar, 2015).

Table 2: General characteristics of slaughterhouse wastewater (Bustillo-Lecompte & Mehrvar, 2015)

Parameter	Range	Mean
TOC (mg/L)	70 -1200	546
BOD_5 (mg/L)	150 - 4635	1209
COD (mg/L)	500 - 15900	4221
TN (mg/L)	50 - 841	427
TSS (mg/L)	270 - 6400	1164
pH	4,90 - 8,10	6,95
TP (mg/L)	25 - 200	50
Orto-PO_4 (mg/L)	20 - 100	25
Orto-P_2O_5 (mg/L)	10 - 80	20
K (mg/L)	0.01 - 100	90
Color (mg/L Pt scale)	175 - 400	290
Turbidity (FAU)	200 - 300	275

- **Slaughterhouse wastewater treatment technologies**

The selection of a particular technology depends on the characteristics of the wastewater, the available technology, and the compliance with regulations.

Bustillo-Lecompte & Mehrvar (2015) presented a questionnaire distributed to 128 slaughterhouses licensed by the Ontario Ministry of Agriculture and Rural Affairs (OMAFRA), in order to gather information on the current characteristics of the actual SWW, type of animals processed, and the type of treatment, storage, or disposal methods used in Ontario, Canada. It was found that 51% of the slaughterhouses do not treat their wastewater onsite; 17% use aerobic treatment, i.e. DAF; 32% utilize passive systems such as storage tanks to settle solids; and only 2% utilize grease trap for fat separation and blood collection.

SWWs have been considered as an industrial waste in the category of agricultural and food industries and classified as one of the most harmful wastewaters to the environment by the United States Environmental Protection Agency (US EPA). SWW discharge may cause deoxygenation of rivers and contamination of groundwater. Typically, anaerobic treatment is used because of the high organic concentrations present in SWWs. Nevertheless, a complete degradation of organic matter present in SWW is not conceivable using anaerobic treatment alone. For that reason, either anaerobic or aerobic processes should not be used as the sole treatment alternative. It is suggested that the combination of anaerobic and aerobic processes minimizes the total cost of the direct aerobic process, in which it requires excessive cost of aeration and sludge disposal due to its high COD level (Cao & Mehrvar, 2011).

SWW treatment may include preliminary, primary, secondary, and even tertiary treatment. The methods after preliminary treatment are various, but they can be divided into five major subgroups: land application, physicochemical treatment, biological treatment, AOPs, and combined processes. Land application usually involves direct irrigation of the SWW onto agricultural land. Physicochemical treatment involves the separation of the SWW into various components, typically the separation of solids from the liquor by sedimentation or coagulation/flocculation, and removal of pollutants using electrocoagulation (EC) and membrane technologies. Biological treatment is divided into anaerobic and aerobic engineered systems as well as constructed wetlands (CWs). Aerobic systems are more common since they commonly operated at a higher rate than anaerobic systems; whereas, anaerobic systems require less complex equipment since no aeration system is required. AOPs (Advance Oxidation Processes) are diverse and include UV/H_2O_2 and UV/O_3 for the oxidation and degradation of organic and inorganic materials present in SWW through reactions with hydroxyl radicals (·OH). Finally combined processes are cost-effective with high removal efficiencies that can lead to a reduction in O&M costs compared to individual processes. Table 3 summarizes the combination of different treatments and their efficiency in the main parameters (Bustillo-Lecompte & Mehrvar, 2015).

Table 3: Comparison of different technologies and their combination for slaughterhouse wastewater treatment (Bustillo-Lecompte & Mehrvar, 2015)

Processes[a]	HRT[b] (h)	TOC_{in}[c] (mg/L)	COD_{in}[c] (mg/L)	BOD_{in}[c] (mg/L)	TN_{in}[c] (mg/L)	TOC removal (%)	COD removal (%)	BOD removal (%)	TN removal (%)	Reference
AeP-RO	8–36	–	5300	2900	557	–	99.80	99.83	99.77	Bohdziewicz and Sroka (2005)
AnaP	24–2160	3500	1820–12,790	–	1176	–	71.51–94.31	–	–	Caldera et al. (2005)
AnaP	360	–	5800–11,600	4524–8700	11–11,150	–	–	20.20–95.60	–	Chávez et al. (2005)
AnaP-AeP	23–91	–	1190–2800	610–1150	150–260	–	93.00	97.00	69.00	Del Pozo and Diez (2005)
AeP	49	–	5000–5098	–	349–370	–	95.00–96.00	–	86.00–88.00	Filali-Meknassi et al. (2005a)
AeP	48	–	5155–5675	–	369–431	–	96.00	–	97.00–99.00	Filali-Meknassi et al. (2005b)
AnaP-AeP	249	–	3000	–	–	–	90–92	–	–	Kuşçu and Sponza (2005)
AnaP	24–48	–	7083	–	547	–	93.9	–	–	Masse and Massé (2005)
AnaP	18–27	–	1400–3600	–	13–179	–	70.60–92.60	–	–	Miranda et al. (2005)
CC	–	–	10,226–15,038	5042–8320	–	–	32.20–63.60	34.70–67.80	–	Satyanarayan et al. (2005)
AOP	0.13	–	–	–	–	–	10.70	23.60	–	Wu and Doan (2005)
EC	0.42	–	2600–2900	10,000–12,000	–	–	60.00–93.00	–	–	Bayramoglu et al. (2006)
EC	0.42	–	2600–2900	12,000–10,000	–	–	60.00–93.00	–	–	Kobya et al. (2006)
AnaP-AeP	249	–	3000	–	70–147	–	80.00–99.00	–	77.40	Kuşçu and Sponza (2006)
AnaP-AeP	24	–	6000–14,500	–	300–1000	–	99.00	–	46.00	Ahn et al. (2007)
AnaP	–	–	3102	–	186	–	–	–	–	Amorim et al. (2007)
AnaP	69	–	2360–4690	1190–2624	147–233	–	57.00–67.00	48.50–63.00	36.00–40.00	Del Nery et al. (2007)
AnaP	30–80	–	7148–20,400	3501–8030	–	–	62.00–96.40	93.96	–	Saddoud and Sayadi (2007)
CW	–	–	3188	2452–2500	494–500	–	97.40	99.90	78.20	Soroko (2007)
AeP	3.0–8.0	–	431	1320	5.6	–	72.00	99.00	–	Al-Mutairi et al. (2008)
EC	1.0–1.5	–	1290–1670	2700–3100	–	–	82.00	86.00	–	Asselin et al. (2008)
AnaP	–	–	1913–5157	1559–2683	–	–	21.00–58.00	14.00–64.00	–	De Nardi et al. (2008)
GR	–	–	–	3860	–	–	–	38.65–85.75	–	Melo et al. (2008)
AeP	42	–	6400–8320	–	260–306	–	95.00	–	97.00	Lemaire et al. (2008)
AeP	8.0	–	2850–4700	1000–2900	250–350	–	97.00	–	94.00	Li et al. (2008)
AnaP	10–3600	1030–3000	3000–4800	750–1890	109–325	15.00–86.00	18.00–80.00			Rajakumar and Meenambal (2008)
AnaP	60	–	4200–9100	–	565–785	–	72.20–98.60	–	45.90–63.70	Debik and Coskun (2009)
AeP-AOP	0.50	–	2800–3000	1400–1600	–	–	80.30–97.60	70.30–95.70	–	De Sena et al. (2009)
AnaP	48	–	5800–6100	–	530–810	–	80.00–92.00	–	–	Gannoun et al. (2009)
AnaP	48–240	–	2100–2425	–	250–260	–	88.00–99.00	–	76.00–78.00	Kabdaşl et al. (2009)
AnaP	10	–	2373–2610	900–2000	78–457	–	96.00–97.00	95.58–97.88	52.00–93.00	Kist et al. (2009)
AnaP	42	–	7460–9300	–	271–317	–	95.00	–	97.00	Lemaire et al. (2009)
AOP	5	–	–	–	–	–	18.00–95.00	–	–	Luiz et al. (2009)
CC-AdP	2	–	6605	5703	–	–	91.10–96.80	93.50–96.80	–	Mahtab et al. (2009)
AeP	29	–	9040	5242	–	–	89.03	89.73	–	Pabón and Gélvez (2009)
CC-AeP	0.33	–	2000–3000	–	100–200	–	80.00	–	90.00	Wang et al. (2009)
AeP	104	–	2800–3500	–	220–350	–	98.00–99.00	–	91.00–95.00	Zhan et al. (2009)
AeP	–	–	24,000	1198	139	–	90.00	–	–	Al-Mutairi (2010)
AnaP-AeP-CC	16–72	–	6363–11,000	5143–8360	46.6–138	–	50.10–97.42	97.76–98.92	73.48–92.72	López-López et al. (2010)
AnaP	30–97	–	8450–41,900	21,000	–	–	18.60–56.90	–	–	Marcos et al. (2010)
UF	–	–	3610–4180	1900–2200	–	–	94.52–94.74	97.80–97.89	–	Yordanov (2010)
EC	1.2	–	2171	1123	–	–	75.00–90.00	–	–	Bayar et al. (2011)
AnaP-AOP	76–91	80–950	2110–2305	1020–1143	80–334	89.90–95.00	97.70	96.60	1.00–6.00	Cao and Mehrvar (2011)
AnaP-AeP-UV	12	–	23–70	0.0–5.0	2.0–21	85.00	–	–	79.00	De Nardi et al. (2011)
AnaP-AeP	16	–	876–1987	12,000	84–409	–	90.60–97.60	–	81.50–95.60	Fongsatitkul et al. (2011)
UF	720–1344	50–328	114–1033	–	82–127	75.00–96.00	83.00–97.00	–	27.00–44.00	Gürel and Büyükgüngör (2011)
AeP	–	–	298–1115	–	–	–	53.65	84.32	–	Mees et al. (2011)
AnaP	12–48	–	6500	2900	–	–	75.00–83.00	–	–	Méndez-Romero et al. (2011)
AnaP	–	–	3437	2646	218	–	76–90	–	8.20–10.10	Mijalova Nacheva et al. (2011)
AnaP	12	–	3000–4800	750–1890	109–325	–	70.00–78.00	–	–	Rajakumar et al. (2011)
EC	0.83	–	–	–	–		62.00–93.00	66.00–97.00	56.00–84.00	Ahmadian et al. (2012)
AOP	2.5	1000	–	–	–	57.60	–	–	–	Barrera et al. (2012)
EC-CC	25	–	4159–5817	2204–2543	92–137	–	80–98	75–93	75–80	Bazrafshan et al. (2012)

(continued on next page)

Processes[a]	HRT[b] (h)	TOC_{in}[c] (mg/L)	COD_{in}[c] (mg/L)	BOD_{in}[c] (mg/L)	TN_{in}[c] (mg/L)	TOC removal (%)	COD removal (%)	BOD removal (%)	TN removal (%)	Reference
AeP	12–20	–	5220	–	4500	–	–	–	–	Dallago et al. (2012)
AeP	110–583	–	850–1400	–	50–100	–	93.50–97.20	–	–	Hsiao et al. (2012)
AeP-UF	48	–	1764–2244	1529–1705	435–665	91.00	98.00	–	–	Keskes et al. (2012)
AnaP	20–96	–	5659–9238	5571–6288	–	–	92.10–96.60	98.00–98.78	–	Park et al. (2012)
CC	3.0	–	6970	5820	–	–	85.46–92.00	85.40	–	Tariq et al. (2012)
AnaP	8.0–24	–	3000–4800	750–1890	–	–	70.00–86.00	–	–	Rajakumar et al. (2012)
AnaP	794–3948	–	70,673	–	–	–	54.00–98.00	–	–	Affes et al. (2013)
AnaP-AeP	24	–	418	117	169	–	95.00	–	76.00	Barana et al. (2013)
AnaP-AeP-AOP	75–168	941–1009	–	630–650	254–428	89.50–99.90	–	99.70	76.40–81.60	Bustillo-Lecompte et al. (2013)
AeP	240	0.10	150	–	–	–	68.00–77.00	–	–	Carvalho et al. (2013)
AeP	1.0	–	18,200	10,500	–	–	81.31–93.08	–	–	Hossaini et al. (2013)
AeP	48	1152–1312	2052–2296	1529–1705	435–665	–	89	–	–	Keskes et al. (2013)
AOP	0.42	2240	–	–	290	92.60	–	–	76.20	Khennoussi et al. (2013)
AeP-AnaP	8.0	–	6485–6840	3000–3500	1050–1200	–	95.00	–	97.00	Kundu et al. (2013)
AeP	23	–	5590–11,750	3450–4365	214–256	–	74–94	–	–	Louvet et al. (2013)
AnaP	39–72	–	1040–24,200	–	296–690	–	30	–	–	McCabe et al. (2013)
AnaP	172	–	1790–4760	834–3186	90–196	–	79.00–89.00	84.00–94.00	–	Nery et al. (2013)
CW	–	–	293–3141	79–87	52–64	–	28.28–75.03	9.27–71.40	5.20–25.40	Odong et al. (2013)
AnaP	24–36	–	2273–20,073	–	570–1603	–	51.00–72.00	–	3.50–21.60	Siqueira et al. (2013)
EC	1.0	–	2171	1123	148	–	69.00–83.00	–	–	Bayar et al. (2014)
AnaP-AeP-AOP	41–76	100–1200	–	610–4635	50–841	75.22–99.98	–	–	–	Bustillo-Lecompte et al. (2014)
EC	1.5	–	840	–	–	–	90.00	–	–	Eryuruk et al. (2014)
EC	–	–	–	–	–	–	55.00–60.00	–	–	Hernández-Ramírez et al. (2014)
AeP	3.0–96	–	6185–6840	–	1950–3400	–	9.42–80.11	–	8.81–93.22	Kundu et al. (2014)
AeP-AnaP	888	–	1400–2500	–	200–250	–	30.20–98.68	–	22.40–96.16	Li et al. (2014)
AnaP	24	–	49–137	30–76	6.1–27	–	13.90	11.30	42.30–77.20	Manh et al. (2014)
AnaP	46–72	–	12,000–15,800	–	–	–	60.00	–	–	Martinez et al. (2014)
AnaP	48–72	–	1014–12,100	1410–7020	–	–	83.62	94.23	–	McCabe et al. (2014)
AOP	0.04–1.0	–	3337–4150	1950–2640	–	–	76.70–90.70	–	–	Ozyonar and Karagozoglu (2014)
AeP	12–3360	1435	6057–6193	4214–4240	547–576	–	97.80–98.20	–	97.70	Pan et al. (2014)
AeP	12–16	–	356–384	–	143–175	–	–	–	80.76–91.09	Mees et al. (2014)
AnaP	24–480	–	88	–	–	–	67.00–80.00	–	90.00	Stets et al. (2014)
AnaP	2640	–	18,600	–	5200	–	–	–	28.00–65.80	Yoon et al. (2014)
MF	–	183	480	–	115	44.81	90.63	–	45.22	Almandoz et al. (2015)
AnaP-MF	48–168	470–2778	2084–13,381	–	108–295	86.36–95.11	97.17–98.90	–	78.00–90.00	Jensen et al. (2015)

[a] AC, activated carbon; AdP, adsorption process; AeP, aerobic process; AnaP, anaerobic process; AOP, advanced oxidation process; CC, chemical coagulation; CW, constructed wetland; EC, electrocoagulation; GR, gamma radiation; MF, microfiltration; RO, reverse osmosis; UF, ultrafiltration; UV, ultraviolet light.

[b] HRT, Hydraulic retention time.

[c] TOC_{in}; COD_{in}; BOD_{in}; TN_{in}, influent concentration of total organic carbon, chemical oxygen demand, biochemical oxygen demand, and total nitrogen, respectively.

Situation in Uruguay

The meat processing in Uruguay plays a very important role. It is reflected in Figure 1, where it can be seen that during the year 2014, meat was the second main product exported, representing 15% of the whole exports, after soy (16%). Considering only the frozen and refrigerated meat, the total amount exported was U$S 1467 millions. If to this number, it is added the by-products of the meat, the meat processing industry becomes the main export industry exceeding the soy. In addition to this, in Figure 2 it is easy to see that the meat export is increasing during the last fourteen years. (*Exports and imports of Uruguay. Annual report*, 2014).

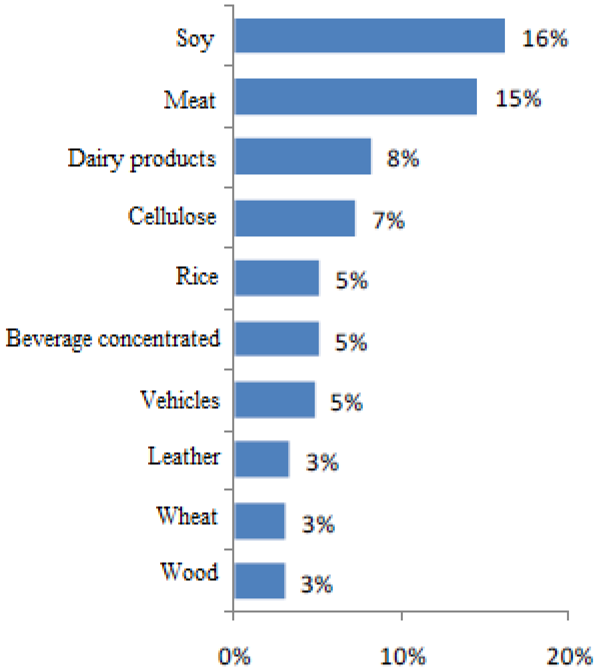


Figure 1: Main exported products of the year 2014. Uruguay

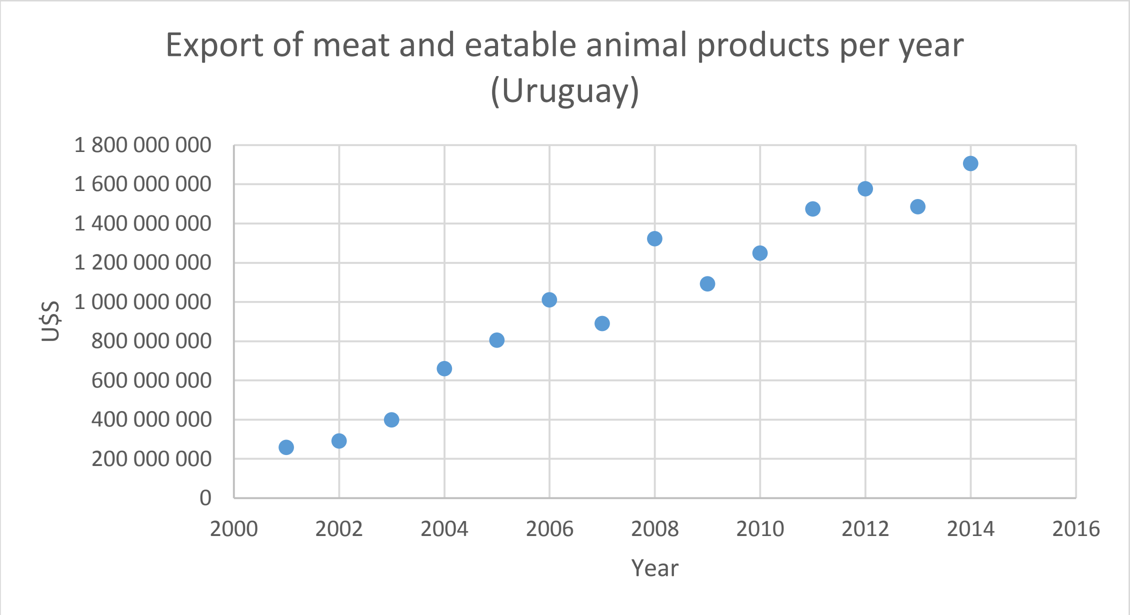


Figure 2: Total year export of meat and its products from Uruguay

- **Slaughterhouse wastewater (SWW) composition**

In Uruguay, there are around 40 slaughterhouses, contributing to a significant part of industrial wastewater effluent production. The water consumption is around 2 m^3 per animal processed (*Environmental report summary for Ontilcor slaughterhouse*, 2011). In the capital city, Montevideo, the effluent flow and loads from the slaughterhouses are summarized in Table 4.

Table 4: Slaughterhouse wastewater discharge in Montevideo, Uruguay (Industrial effluents report, 2014)

Industrial Activity	**Average of industries from Montevideo**					
	Flow (m^3/día)	Fat and oil kg/día	BOD_5 kg/día	TSS kg/día	NH_4 kg/día	Total P kg/día
Slaughterhouse	487	13	13	0.1	40	11

In Appendix A, there is an example of the concentration of the discharging effluent from Schneck slaughterhouse during the year 2015.

2.2. Schneck slaughterhouse

General information

Schneck is one of the most recognized names in the processing and manufacturing of further processed and beef products in Uruguay. It was founded by Mr. Carlos Schneck and his wife Maria Pydd, in June of 1936. At the beginning, they only carried out the manufacturing process; beef cattle was purchased from "Frigorífico Nacional", a national cattle slaughterhouse facility. In 1962, Schneck built its own slaughtering facility in order to become self sufficient in its demand for beef at its processing facility.

Processes

In the slaughterhouse, animals are received and kept in pens for around one day. There they are watered and then stunned (making them immobile and unconscious, without killing them). The wastewater of this zone comes from the pens cleaning, which contains the manure from the cattle. Before going to the ponds system treatment, the green solid part is separated in a press.

After this step, the animals are driven to the slaughtering area where the following activities take place:

- Suspension from an overhead rail by the hind legs.
- Bleeding over a collecting channel, where the blood is collected.
- Leather removal.
- Decapitation.
- Opening and washing of the carcass.

All the preceding activities take place in a dirty zone, where the wastewater comes mainly for cleaning the zone, which has a big content of blood. This effluent has a blood clots separation previous to the ponds system.

The next activity is the evisceration (removal of intestines and internal organs). In this process, a green effluent comes from the rumen of the animal. The partially digested food is estimated to be from 27 to 40 kg per cattle (FAO, 2015).

The final activities are the splitting and cutting of the carcass and final wash.

All the effluent from the wash of the dirty zone and the carcass wash is gathered with the rainwater from the opening area and convey to a grease separator. After that, it is combined with the green effluent that comes from the pens wash and rumen content in a homogenization basin of 880 m^3. The effluent from there is pumped to the ponds system.

The process flow diagram is shown in Figure 3.

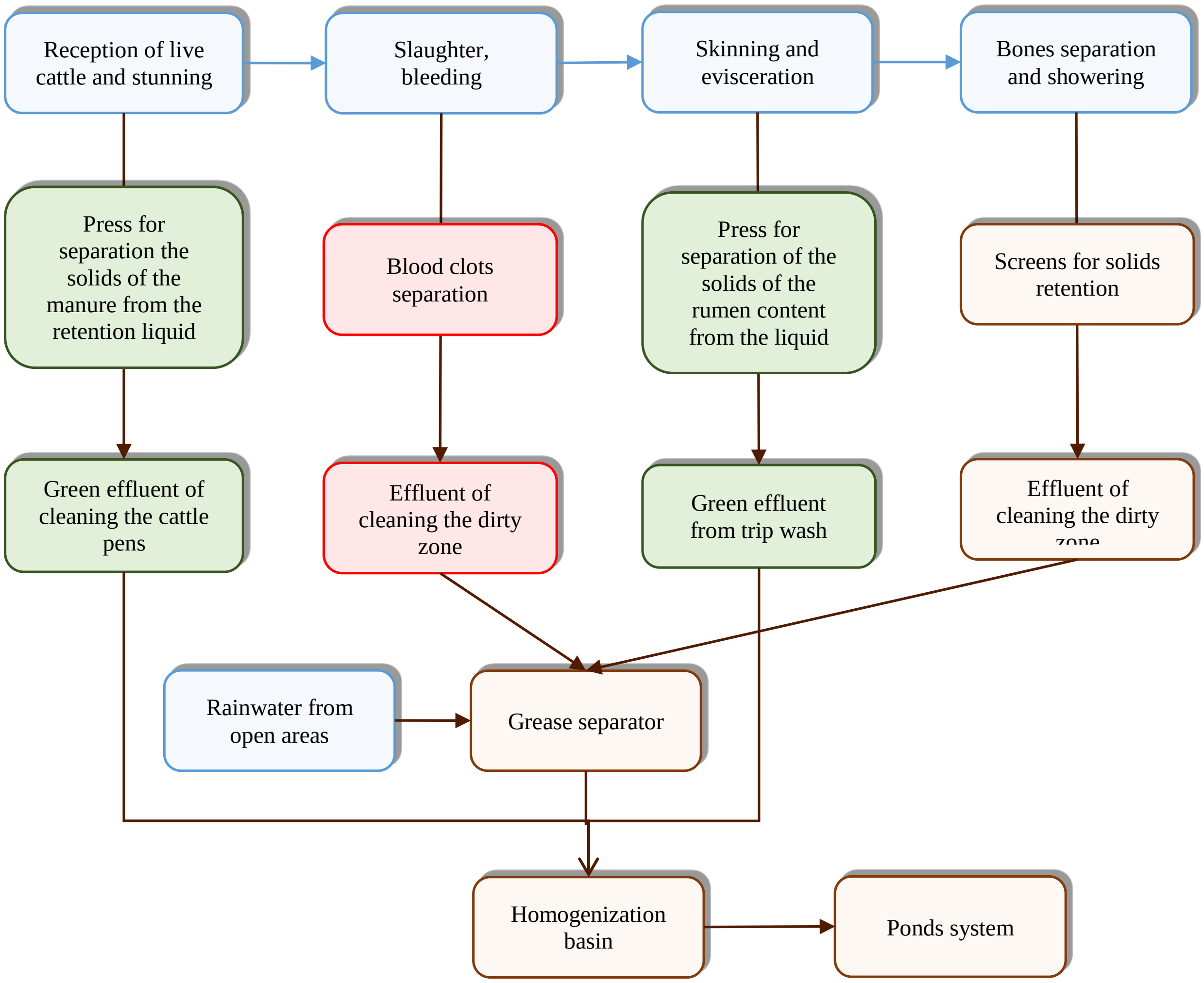


Figure 3: Schneck slaughterhouse process flow diagram

Current wastewater treatment

At the moment, the slaughterhouse has a ponds system for the wastewater treatment. The effluent that comes from the different processes of the slaughterhouse and from the rainwater is gathered in a homogenization basin (Figure 4). After that, is pumped to an anaerobic pond, following by another anaerobic, an aerobic and a facultative pond, which discharges into a little stream (Figure 5) that finishes in the Miguelette Creek (Figure 6). The Miguelete Creek is an important water body for the city of Montevideo as it cross almost the whole city, but has the defect of being highly polluted. The system layout of the actual treatment plant is shown in Figure 7.

Figure 4: Homogenization basin

Figure 5: Facultative pond effluent discharge in a small stream that finishes in the Miguelete Creek

Figure 6: Aerial view of the Miguelete Creek

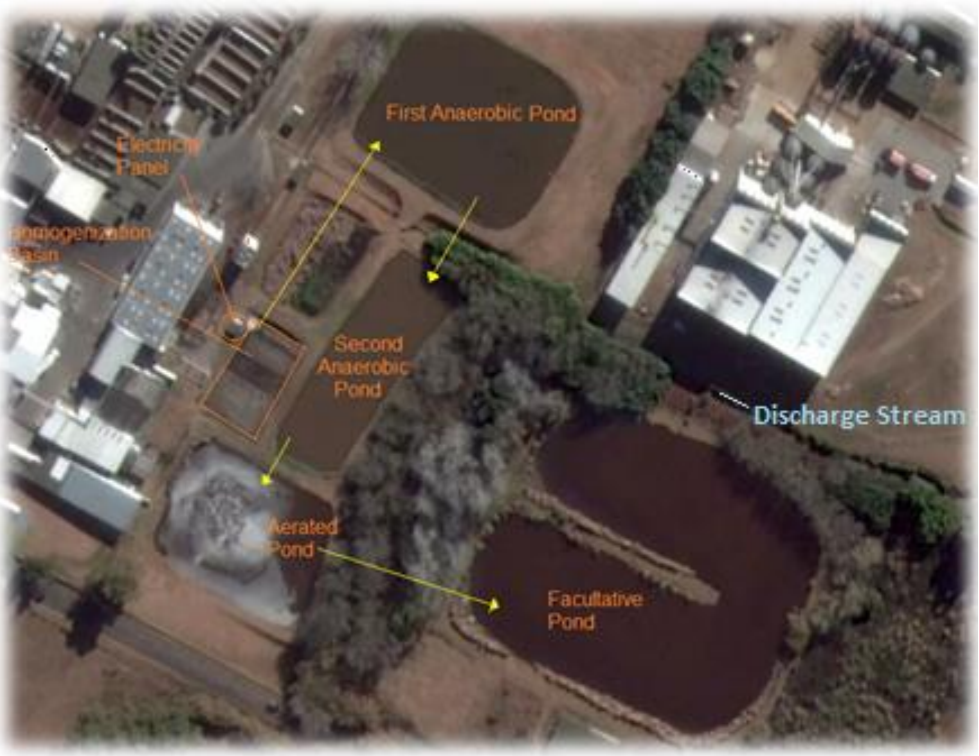


Figure 7: Ponds treatment system for Schneck slaughterhouse

Effluent parameters from the different steps of the current treatment plant

In Table 5 is presented an analysis realized by an external company (Estudio Pittamiglio) in the year 2015. It shows the relevant parameters of the influent and after each intermediate step of the treatment plant.

Table 5: Analysis of the effluent from the different steps of the treatment plant (Estudio Pittamiglio, 2015)

Date	Place	pH	BOD_5 mg/L	COD mg/L	TSS mg/L	Fats and oil mg/L	NH_4-N mg/L	TN mg/L	NO_3^- mg/L	Total P mg/L
14/05/2015	Green influent	6,8	3100	8500	7400	430	134	318	129	116
14/05/2015	Red influent	6,7	2100	3000	250	100	190	196	6,8	61
28/04/2015	Homogenization tank effluent	7,0	930	2500	890					
3/02/2015	First anaerobic pond effluent	7,6	110	550	260					
28/04/2015		7,4	110	420	200					
24/06/2015		7,1	200	710	220	60				
29/07/2015		7,3	150	660	160					
15/09/2015		7,5	180	430	180					
19/02/2015	Second anaerobic pond effluent	7,4	120	550	175					
28/04/2015		7,7	70	540	240					
3/02/2015	Aerated pond effluent	8,3	50	190	110					
28/04/2015		7,8	60	570	220					

Taking the average of the information in Table 5 for the intermediate steps and in Table 1 from the discharge, the graph of Figure 8 was generated to create a better visualization of the results.

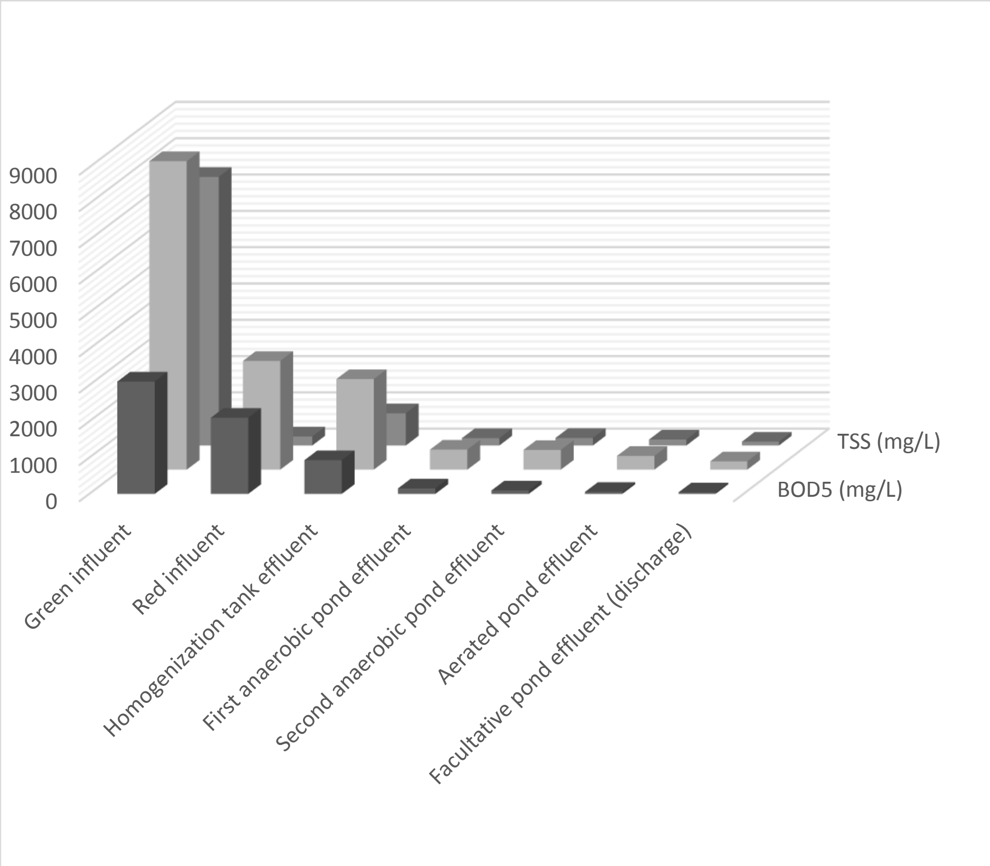


Figure 8: BOD5, COD and TSS analysis in the different steps of the ponds system

It can be seen a big drop in the parameters after the homogenization tank. Still the influent of the ponds system has almost 100 mg/L of BOD_5 and TSS, and 2500 mg/L of COD. The big removal in the ponds system is produced in the first anaerobic pond. It can also be interpreted in Table 6, where is shown the accumulated removal efficiency of the ponds system.

Table 6: Removal efficiency (%) of the ponds respect to the effluent of the homogenization tank

	BOD_5 accumulated removal (%)	**COD accumulated removal (%)**	**TSS accumulated removal (%)**
First anaerobic pond	83.9	77.8	77.1
Second anaerobic pond	89.8	78.2	76.7
Aerated pond	94.1	84.8	81.5
Facultative pond	95.7	90.8	88.1

Discharge parameters

A report of fifteen analysis to the effluent discharge parameters during the year 2015 is presented in Appendix A.

2.3. Membrane Bioreactors

Description of MBRs

A classical MBR comprises a conventional activated sludge process coupled with membrane separation to retain the biomass. Since the effective pore size of the membrane can be below 0.1μm, the MBR effectively produces a clarified and substantially disinfected effluent. In addition, it concentrates up the biomass and, in doing so, reduces the necessary tank size and also increases the efficiency of the biotreatment process. MBRs thus tend to generate treated waters of higher purity with respect to dissolved constituents such as organic matter and ammonia, both of which are removed by biotreatment. Moreover, by removing the requirement for biomass sedimentation, the flow rate through an MBR cannot affect product water quality through impeding solids settling, as is the case for an activated sludge process (Judd, 2006).

There are two main MBR configurations: submerged or immersed (iMBR), and sidestream (sMBR), represented in Figure 9. The difference is based on the position of the membranes relatively to the reactor, if they are inside (submerged) or outside (sidestream) (Judd, 2006).

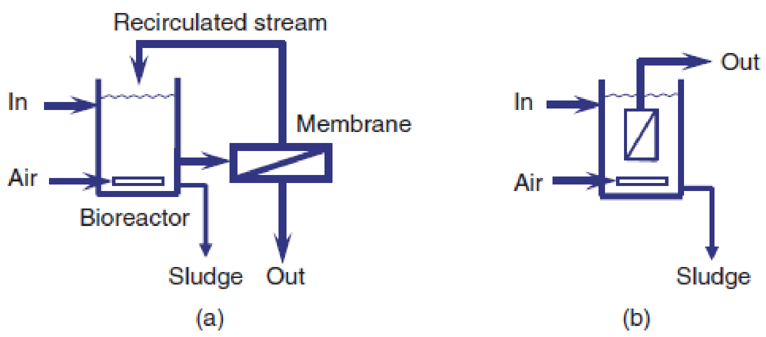


Figure 9: Configurations of MBR: (a) sidestream and (b) immersed

MBR plant does not require nor primary nor secondary sedimentation tank (secondary clarifier). Moreover, MLSS is 3 to 5 times higher than in classical treatment; consequently, the reactor basins are much smaller. Because of that, the area for construction of MBR plant is even 3 times smaller compared to the one necessary for classical biological wastewater treatment plant, thus not affecting the quality of purified water (almes-eko, 2015).

This technology has some advantages and disadvantages (Garcia, 2015). The main advantages are:

- As MBR combines biological aerobic treatment with membrane separation, the effluent is clarified and disinfected, resulting with low turbidity, bacteria, TSS and organic content.
- Has smaller footprint than a conventional activated sludge treatment.
- Bulking problems become less relevant as none sedimentation step is required.
- It operates with longer SRTs with less sludge production.

Those advantages lead MBRs to be a main candidate of wastewater recycling technology.

On the other hand, MBRs have some limitations:

- Membrane surface fouling.
- Clogging of membrane channel.
- High capital cost.
- High operational cost.

MBR performances used in slaughterhouses

Gürel & Büyükgüngör (2011) evaluated ultra-filtration membrane bioreactor to treat slaughterhouse wastewater. TOC and COD removal efficiencies of this system were found to be 96 and 97%, respectively. Removal performances for TN, TP, and NH_4–N were 44, 65, and 99%, respectively. The nitrate concentration of slaughterhouse wastewater varied in the range of 0.253–1.938 mg/L and reached 39.25 and 80.52 mg/L at the end of the treatment studies. Only high nitrate concentrations in treated effluent were a problem in this process. This happened because it was a one-stage MBR process. To overcome this problem, adding an anoxic reactor for denitrification may be the solution.

Yordanov (2010) analysed the performance of a MBR for a poultry slaughterhouse. The results obtained are presented in Table 7. The gap of this analysis is the lack of investigation of nutrients removal.

Table 7: Parameters of wastewater from a poultry slaughterhouse after treatment by ultrafiltration (Yordanov, 2010)

Parameter	Raw wastewater (mg/L)	After ultrafiltration process (mg/l)	Removal efficiency (%)
BOD_5	1900	40	97.89
	2178	48	97.80
	2200	48	97.82
COD	3610	198	94.52
	4140	220	94.69
	4180	220	94.74
TSS	2360	22	99.07
	2446	22	99.10
	2280	20	99.12
Fat	289	3	98.96
	380	4	98.95
	389	4	98.97

Influence of COD/N ratio and dissolved oxygen on nutrient removal in membrane bio reactors

Fu et al. (2009) studied the relation of the COD/N ratio for nutrient removal in a MBR. They used high strength synthetic water as influent of an Anoxic-Aerobic MBR. Their results showed that above 95.0% removal efficiencies of organic matter were achieved irrespective of COD/N ratio. On the other hand, the average removal efficiencies of total nitrogen (TN) and phosphate (PO_3^{-4}–P) with a COD/N ratio of 9.3 were the highest at 90.6% and 90.5%, respectively. When COD/N ratios were decreased to 7.0 and 5.3, TN removal efficiencies in steady states were 69.3% and 71.2%, respectively.

Effect of COD/N ratio and aeration rate on performance of continuously operated internal circulation membrane bioreactor (ICMBR) was also investigated by Fan et al. (2014) using synthetic domestic wastewater. The results showed that COD and total nitrogen (TN) removal efficiencies were improved with the increase of COD/N ratio under certain conditions. However, the high C/N ratio required adding more carbon sources, which increased operating cost. Therefore, a suitable C/N ratio was found at a relation 6:1. When C/N ratio was 6:1 and aeration rate was $0.15 m^3/h$, average removal rates of COD, NH_4, and TN reached 98.5, 97.4, and 52.6%, respectively. Additionally, the improvement in activity of denitrifying bacteria decreasing the aeration rate, increased TN removal. Under the optimal operation parameters

(COD/N ratio of 6:1 and aeration rate of 0.05m^3/h), the high average removal efficiencies of COD (96.0%), NH_4 (96.4%), and TN (81.0%) were obtained.

The effects of chemical oxygen demand and nitrogen (COD/N) ratio and dissolved oxygen concentration (DO) on simultaneous nitrification and denitrification (SND) were investigated by Qingjuan et al. (2008) using an internal circulation membrane bioreactor with synthetic wastewater. The results showed that the nitrification and denitrification rates reached equilibrium and resulted in nearly complete SND when the COD/N ratio was controlled at 10.04. With this COD/N ratio, nitrogen and organic carbon were both optimally removed. Furthermore, the authors mentioned that the optimum range of DO concentration for SND was 0.75–1.0 mg/L. Either low or high DO concentration could restrict SND.

Ćurko et al. (2012) treated synthetic wastewater in two membrane bio reactors, focusing on the removal of total nitrogen through nitrification and denitrification. In the first one, the best results in the experiment were achieved when the aeration regime was set to 60 minutes aeration and 120 minutes without aeration, resulting in the reduction of total nitrogen from 45 mg/L to about 12 mg/L. In the second MBR, the best results were with the same aeration regime, with a total nitrogen removal of 90%.

Capodici et al. (2015) states that the alternating oxic/anoxic process with the automatic control of the intermittent aeration (IA) might be a suitable and effective strategy to adopt as a solution for improving the efficiency of nutrient removal and reducing energy costs.

CHAPTER 4- Materials and methods

2.4. Pilot scale membrane bioreactor

Description of the MBR pilot plant

The pilot-scale membrane bioreactor was built by a Croatian company named almes-eko (almes-eko, 2015). It was brought to Uruguay in 2013, in order to be part of a study research for a Master thesis, installed in a dairy industry called Conaprole. After the research was finished, the MBR was taken to a laboratory named LATU, site where the start up of this study took place.

The reactor contains an anoxic compartment followed by one aerobic, where is situated the submerged membranes, a diffusor and a recirculation pump. Finally it has one permeate compartment for the clean water. The treatment capacity of the reactor is around 1 m^3/d. Figure 10 shows the components of the MBR.

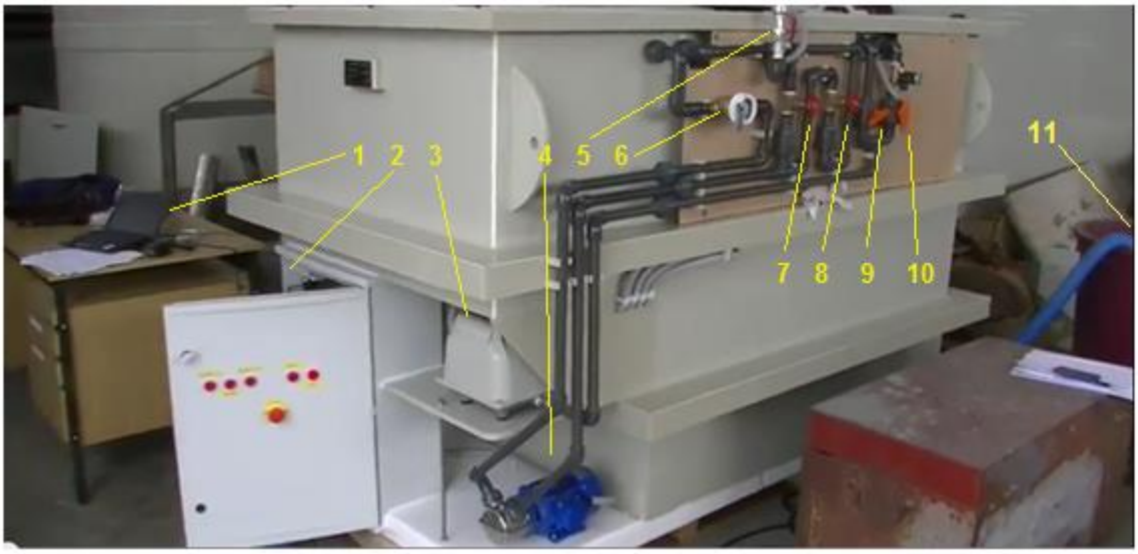


Figure 10: Pilot scale MBR components. 1: Computer connected to the PLC; 2: PLC (Programmable Logic Controller); 3: Compressor; 4: Reversible pump; 5: Pressure sensor; 6: Flow measure; 7: Backwash valve; 8: Inlet flow valve; 9: Aeration valve for cleaning the membranes; 10: Aeration valve for diffusors, 11: Influent pump

The MBR pilot scale process is shown in Figure 11. The influent to be treated is taken by a pump (Figure 12) and led to the denitrification zone (Anoxic tank, Figure 13). The effluent of this compartment overflows to the aerobic zone, where are situated the fine bubble diffuser, the membranes for the effluent filtration and the pump for recirculation to the anoxic tank (Figure 14). After the membrane filtration, the effluent is sucked out by the reversible pump shown in Figure 10 and convey to the permeated basin (Figure 15) where the clean water is situated. The clean water is then discharged by a hose when the permeate tank is full. The reversible pump (Figure 10) also takes the permeate influent to make the backwash of the membranes.

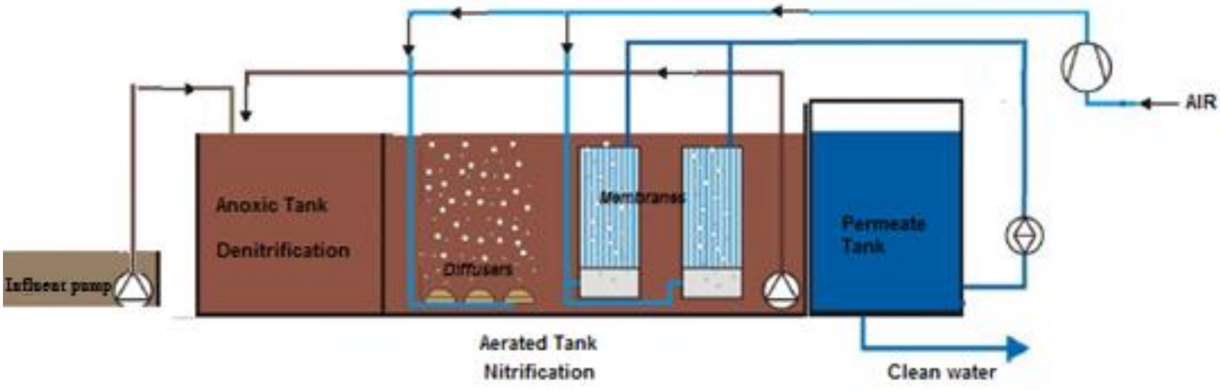


Figure 11: Process diagram of the MBR pilot scale plant (almes-eko, 2010)

Figure 12: Influent pump

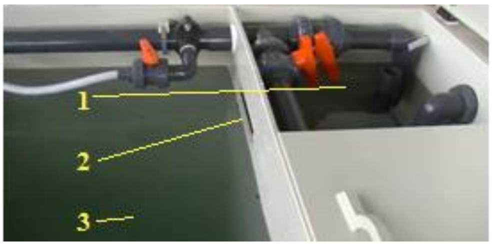


Figure 13: Anoxic tank (1). After this compartment, the effluent reaches the aerobic zone (3) by an overflow (2)

Figure 14: Aerobic tank, with immersed membranes (1), a diffuser for providing air (2) and a recirculation pump (3)

Figure 15: Clean water (permeated) basin

Operation of the MBR pilot plant

The control of the plant operation and monitoring data is achieved through a local PLC (Programmable Logic Controller) device (Figure 16), which is via modem connected to personal computer and SCADA system (Supervisory Control And Data Acquisition System), which integrates measurement control and data storage. All electromotor devices are controlled via local PLC. The plant can be operated manually to carry on the start up. Then, after adjusting all valves and introducing in the computer the parameters necessary for the operation of the plant (e.g. suction time of a cycle, backwash time, blower working time, recirculation pump working time), the MBR can be completely self-guided (working automatically).

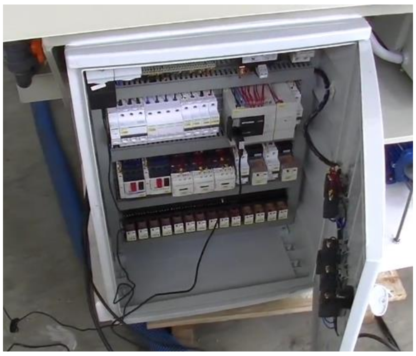


Figure 16: PLC device

2.5. Parameters measured

During the operation of the MBR in Schneck slaughterhouse, some parameters were measured in order to control the performance of the MBR. Those were:

- In the influent and permeate: pH, Chemical Oxygen Demand (COD), Biological Oxygen Demand after 5 days (BOD_5), Total Suspended Solids (TSS), Nitrate (NO_3^-), Nitrite (NO_2^-), Ammonia (NH_4), Total Kjeldahl Nitrogen (TKN), Total Nitrogen (TN) and Total Phosphorous (TP).

- Inside the MBR: Temperature, DO, Mixed Liquor Suspended Solids (MLSS) and Mixed Liquor Volatile Suspended Solids (MLVSS).

Moreover, in order to make a model in BioWin it was necessary to add the measures of COD filtrated with a 1.2 μm glass fibre filter (COD_{GF}), COD micro filtrated with 0.45 μm (COD_{MF}), filtrated BOD (BOD_{GF}), phosphate (PO_4), Calcium, Magnesium and Acetate.

The analyses of COD (total, filtrated and micro filtrated), NO_3^-, NO_2^-, NH_4, TP and PO_4 were carried out with a colorimeter (Spectroquant Move 100, shown in Figure 17) and its test kits, provided by LATU. The solid's analyses were done following the "Standard Methods for the Examination of Water and Wastewater", using an oven, a muffle and an analytical balance. The rest of the analyses were taken either to the LATU's laboratory or to another laboratory namely ECOTECH.

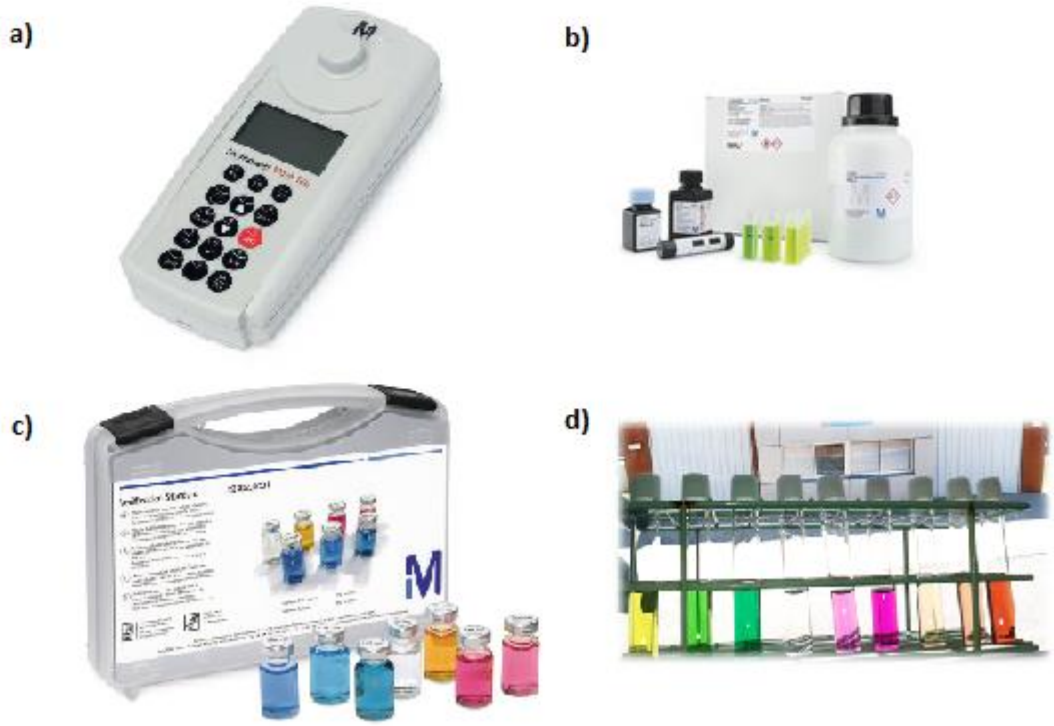


Figure 17: a) Spectroquant Move 100 Colorimeter. b) Kit to measure NH_4. c) Verification Standard for calibrating d) Samples from Schneck prepared to be measured in the colorimeter.

2.6. Methodology

MBR check and start up

The first step before installing the MBR in the slaughterhouse was checking the conditions of all the parts included in the pilot plant and the start-up of the MBR with tap water. This activity was carried on in October at the LATU laboratory, with the help of the laboratory staff from the electrical and mechanical sector. It consisted on checking the pumps performance, the pipes condition (if there are some for replace), and the membranes.

As membranes were not in good condition, it was necessary to make a chemical cleaning. The first step was to take out the membranes from the cassettes in order to insert them into a tank.

This one was filled with water and was aerated through an air compressor. Soon after, Citric Acid was added until the pH reached a value of 3. The membranes were then placed into the tank for 1 hour (Figure 18). After this step, they were taken out and washed. The next step was to follow the same procedure as before, but adding Sodium Hypochlorite instead of the Acid, until pH reached a value of 10.

Figure 18: Membranes submerged into a tank with Citric Acid for chemical cleaning

Furthermore, the recirculation pump was not working and it was replaced. After that, all pipes were connected and the MBR was filled with tap water in order to do the start-up, checking that the membranes were permeating at a flow of around 1 m^3/d with a suction pressure of less than 40 mbar (maximum pressure allowed for the membranes).

.

Location of MBR

After checking in LATU that the MBR was working properly, it was transported to Schneck Slaughterhouse.

The MBR equipment was placed next to the room for electric panel, as shown in Figure 19, in a shelter with a roof, constructed by Schneck staff. The inlet pump was placed inside the homogenization pond, taking the effluent from there to the anoxic basin of the reactor. This configuration is presented in Figure 20.

Figure 19: Inlet from homogenization basin (1); MBR (2); Room for electric panel (3)

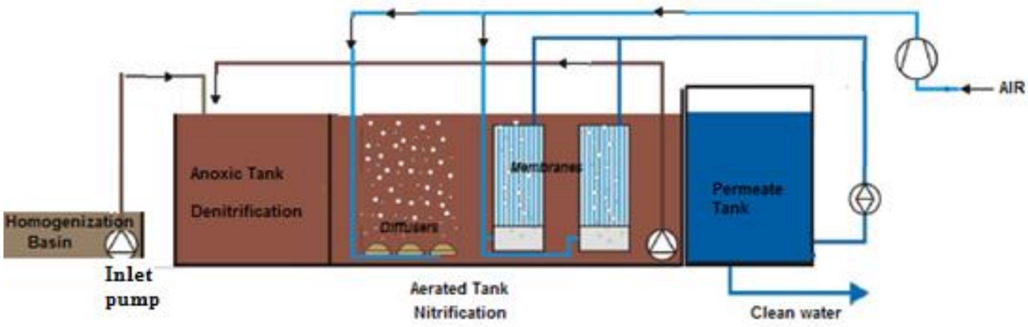


Figure 20: Configuration of the equipment

Set-up and operation of the MBR

The MBR was initially inoculated on November/2015 in order to obtain microorganisms acclimatized.

The first option was to make it with sludge from the aerated pond of the Schneck treatment system, but after a solids analysis it results of having less than 500 mgTSS/L, which would take so much time to let them increase the MLSS inside the reactor until 10 g/L.

The inoculation was finally done with sludge from the aerated tank of an activated sludge treatment plant, which treats domestic wastewater (Canelones treatment plant), with an initial concentration of 2.3 gTSS/L. This procedure was carried out through a rented sludge vacuum truck.

The MBR was operated aiming to maintain a mixed liquor suspended solids (MLSS) of between 10 and 12 g/l, and adjusting the control parameters of the MBR (recirculation ratio, aeration intensity, time of permeation and backwash) in order to enhance its performance.

Characterization of the effluent in current ponds system

A characterization of the wastewater parameters in the different steps of the current ponds system was done in order to analyse the optimal location for the MBR at the existing treatment plant, , in order to make a model in BioWin to evaluate the best scenario of placing the MBR, considering the efficiency of the COD and Nitrogen removal. The parameters measured are shown in Table 8.

Table 8: Parameters to measure for modeling in BioWin

Parameter	Code	Unit	Comment
Total Suspended Solids	TSS	mg/L	20 μm coarse paper filtered, oven dried (105 °C)
Inorganic Suspended Solids (Ash)	ASH	% of TSS	Incineration (550 °C) of filtered and dried TSS
pH	pH		
Alkalinity	Alk	$mgCaCO_3/L$	
Calcium	Ca	mg/L	
Magnesium	Mg	mg/L	
Dissolved Oxigen	DO	mgDO/L	
Total Phosphorous	TP	mgP/L	Total sample (solids and liquid)
Ortho-phosphate	PO_4	mgP/L	1,2 μm glass-fibre filtered (soluble fraction)
Total COD	TCOD	mgCOD/L	Total sample (solids and liquid)
COD glass-filtered	COD_{GF}	mgCOD/L	1,2 μm glass-fibre filtered (soluble fraction)
COD micro-filtered	COD_{MF}	mgCOD/L	0,45 μm (membrane) filter (soluble fraction)
COD as VFA	VFA	mgCOD/L	Acetate + propionate, No poly-acetate filters or vacuum filtration
Acetate	Hac	mgCOD/L	Do not use poly-acetate filters or vacuum filtration
BOD_5	BOD	mgBOD/L	Total sample (solids and liquid)
BOD_5 glass-filtered	BOD_{GF}	mgBOD/L	1,2 μm glass-fibre filtered (soluble fraction)
Total Kjeldahl nitrogen	TKN	mgN/L	Total sample (solids and liquid)
Ammonium	NH_4	mgN/L	1,2 μm glass-fibre filtered (soluble fraction)
Nitrate and Nitrite	NO_x	mgN/L	1,2 μm glass-fibre filtered (soluble fraction)

BioWin modelling

Some models simulating the MBR treatment process were carried out in BioWin. In the simulation, the MBR was placed after each pond of the actual treatment system in order to evaluate the different results.

2.7. Drawbacks during the research

The main issue was that one of the membranes was broken. This fact was unnoticed while the MBR was operated at LATU with tap water because the problem of solids passing to the permeate water tank was undetectable. After starting working with wastewater, solids started to be noticed in the permeate tank (Figure 21).

Figure 21: Problem of solids passing to the permeate tank

The first thought was that pipe connections were not watertight. In consequence, the membranes were taken out of the reactor and all the connections were sealed. Nevertheless, after inserting them again inside, the issue of solids continued appearing. After removing once again the membranes, it was observed that one of them had a hole at the bottom of the cassette (Figure 22).

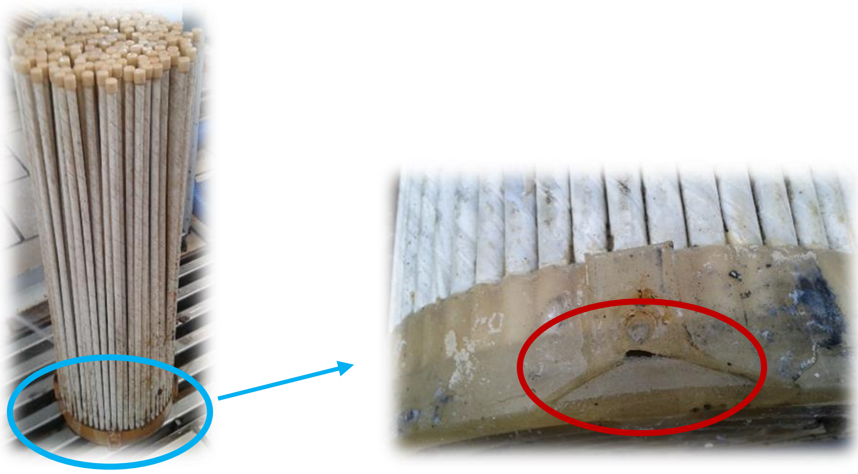


Figure 22: Hole in one of the old membranes

After becoming aware of the situation, immediately a new pair of membranes was ordered from Germany. Meanwhile they arrived, it was used a spared pair of membranes that were overdosed with Ferric Chloride last year during a thesis research (Figure 23). Before placing them inside the reactor, a chemical cleaning was done. The consequence was that the permeate flow was so low that was almost negligible, as the membranes were too clogged.

The last try was to fix the hole with silicone and operate again with the old membranes, but the analysis of the permeate water after this trial resulted of having 9 mg/L of solids, when they should be 0 mg/L.

Figure 23: Spare membranes that were clogged because an overdose of Ferric Chloride

Soon after the previous issues, the new pair of membranes arrived. The MBR was emptied and inoculated again on 28/01/2016 with 300 L of the same wastewater treatment plant as before.

CHAPTER 5- Results and discussion

2.8. Introduction

This section describes the results obtained during the operation of the pilot scale MBR treating wastewater from Schneck slaughterhouse, and an evaluation in BioWin of placing it after different steps of the actual treatment plant.

Firstly, specifies the operational conditions of the MBR during the studying period, such as permeability, aeration, recirculation ratio and mixed liquor suspended solids. Afterwards, an evaluation of the removal of different parameters of interest is done. Later, a comparison of the MBR and the actual treatment with the Standards is carried out. Finally, the results of modelling the MBR in BioWin after each pond of the actual treatment system is presented.

2.9. Operational conditions

Control parameters

In order to evaluate the performance of the MBR, some parameters were adjusted during the study period. As described before, the MBR has valves to modify the permeate flow and the suction pressure. With the relation of these parameters and the membranes area, the operational parameters flux and permeability can be calculated. Other important regulation valves for the control of the MBR are the aeration valve, which is related with the dissolved oxygen inside the MBR, and the one that regulates the recirculation of the sludge from the aerated tank to the anoxic tank. Furthermore, it is important to check the suspended solids inside the reactor as they are related with the actives bacteria.

Flow and Permeability:

The average permeate flow of the whole period was 1.3 m^3/d. Figure 24 shows the mean flow of each day of operation.

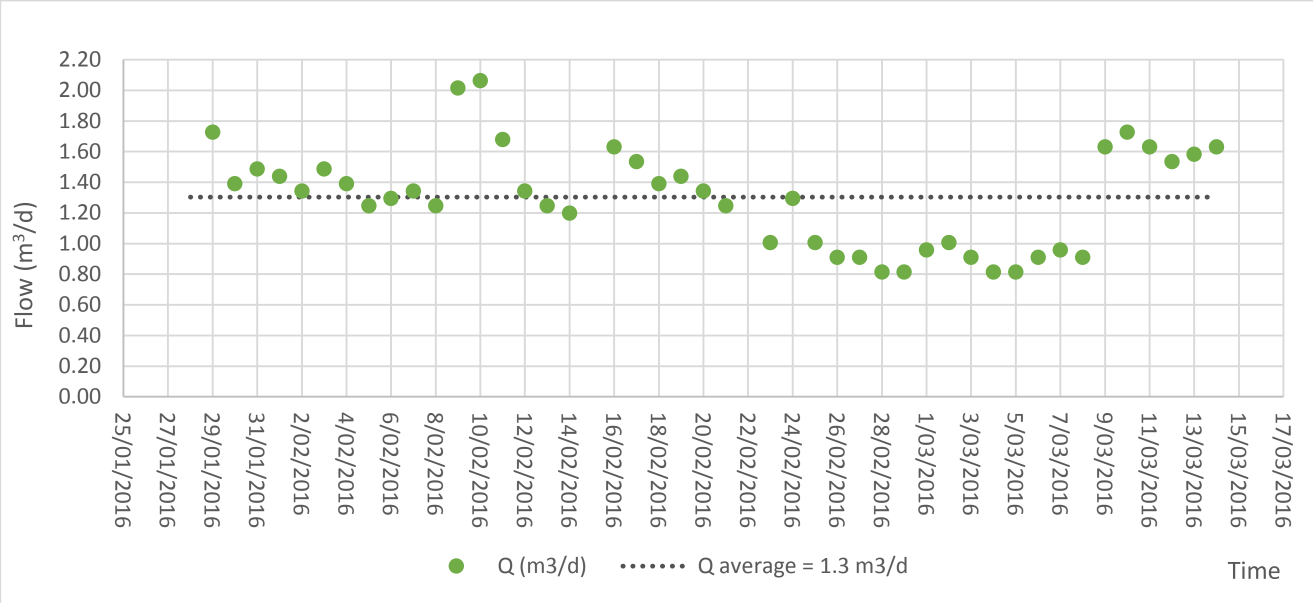


Figure 24: Mean daily permeate flow during the period of operation

The MBR was connected to a computer, where the data of suction pressure and permeate flow (permeated volume as function of time) was collected every day. Moreover, the suction and backwash time per cycle can be set. In the whole period, it was set as 480 seconds (8 minutes) of suction and 30 seconds of backwash.

An example during 30 minutes of operation is illustrated on Figure 25. It can be seen that the suction pressure every time is more negative until a backwash is implemented. The maximum suction pressure that can hold these membranes without being damage is -0.40 bar. When this value is reached, the permeate pump automatically turns off and an alarm turns on. In that moment, a membranes cleaning is carried out, backwashing them with Sodium Hypochlorite solution at a concentration of 500 ppm.

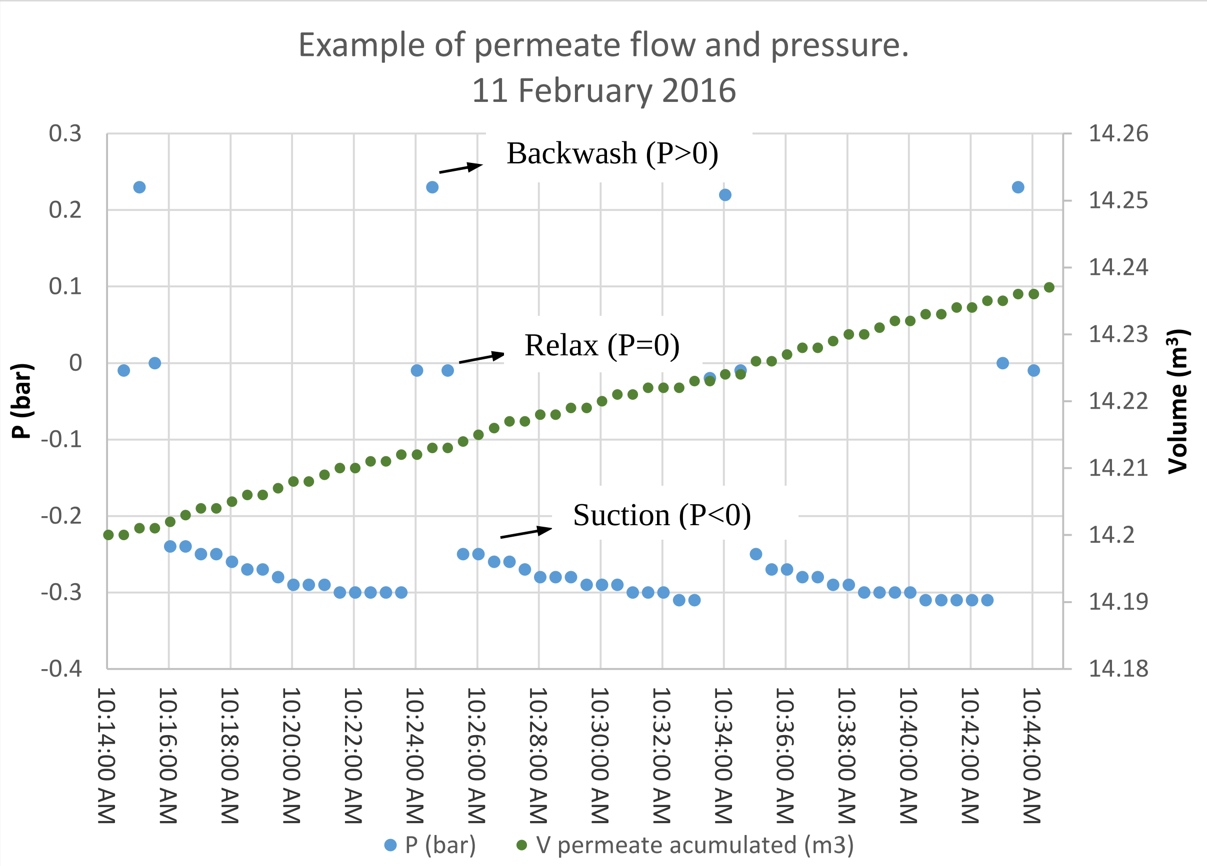


Figure 25: Permeate flow and pressure during 3 cycles of permeate. Example taken from 11/02/16.

Figure 26 shows the permeability and the maximum pressure reached during the day in the period studied. Something to highlight is that every time the pressure was near -0.40 bar, or the permeability decrease too much, a membrane cleaning was implemented. In consequence, the suction pressure decreases and the permeability increases. A complete table of these calculations is presented in Appendix D.

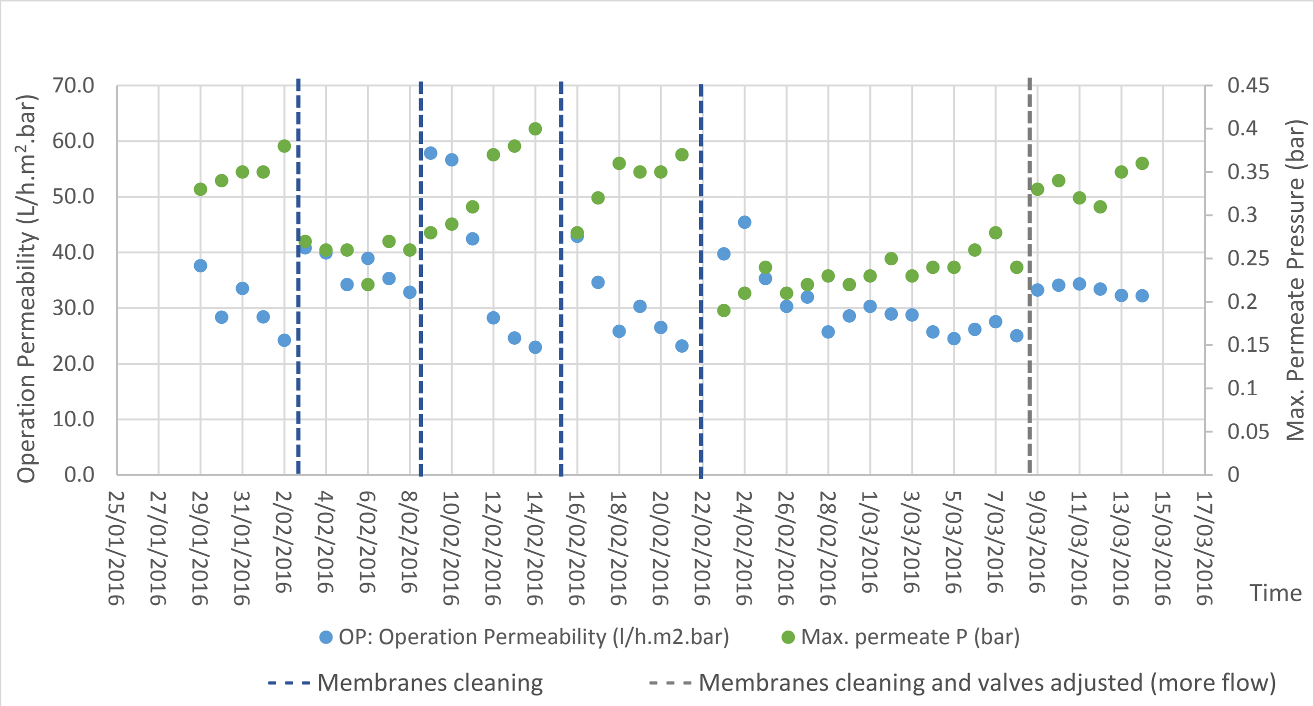


Figure 26: Membranes permeability and maximum suction pressure of each day during the studied period

<u>Recirculation and aeration:</u>

The aeration time and intensity, and the recirculation from the aerated to the anoxic tank were modified during the studied period. Therefore, six groups of similar conditions were established as shown in Table 9.

Table 9: Groups established with similar conditions of aeration and recirculation

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Start date	3/02/2016	8/02/2016	14/02/2016	19/02/2016	26/02/2016	11/03/2016
Finish date	7/02/2016	13/02/2016	18/02/2016	25/02/2016	10/03/2016	14/03/2016
Rec. Ratio	2	2	2	2	4	4
Aeration	Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min; with air valves a quarter opened	Aeration "ON" the whole day, with valves a quarter opened	Aeration "ON" the whole day, but with valves barely open because sludge started to go out from the MBR due to high mixed liquor solids concentration	Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min; with air valves a quarter opened	Aeration "ON" the whole day, with valves full opened	Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min, with valves full opened
DO aerat., Median	0.50	1.29	0.91	0.98	3.04	0.64[4]
DO anoxic, Median	0.00	0.00	0.00	0.00	0.04	0.00

MLSS and MLVSS

The MBR was inoculated on 28/01/2016 with 300 L of sludge from a domestic wastewater treatment plant. Immediately after this, the suspended solids inside the MBR (MLSS) were around 2 g/L. The higher the solids, the better is in terms of efficiency as the volatile suspended solids (MLVSS) are related to the active microorganisms presents inside the MBR. However, the membranes can be clogged operating with suspended solids higher than 12 g/L. Because of that, the ideal operation of the MBR is with between 10 g/L and 12 g/L of MLVSS. Figure 27 illustrates the evolution of MLSS and MLVSS during the first half of February.

[4] Measure carried out at the laboratory and not directly in the MBR because the portable DO meter was broken.

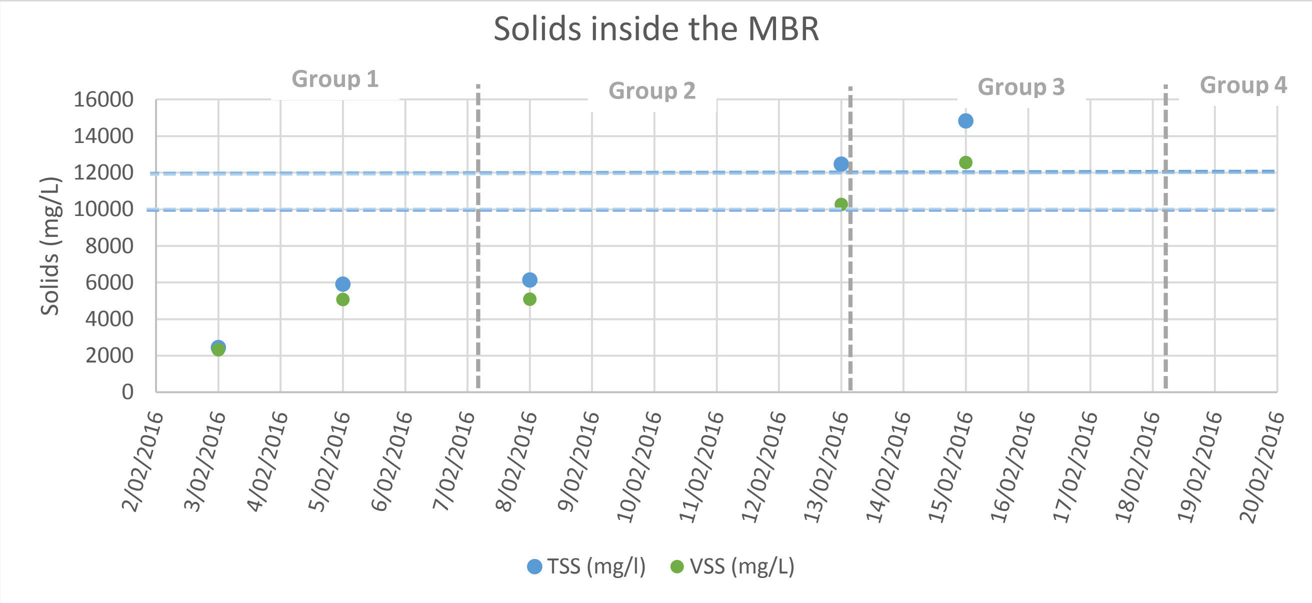


Figure 27: Evolution of MLSS and MLVSS during the first half of February

On 20 of February, sludge was wasted from the reactor because of the elevated concentration of solids. The issue here was that too much was wasted. Therefore, the MLSS fell to a value of about 2 g/L. Nevertheless, because of the high temperature in the summer of Uruguay, they reached 12 g/L in about one week. After reaching this value on 27 of February, the sludge was wasted every day at a rate of around 50 L/day, and the MLSS started to be maintained between 10 g/L and 12 g/L. With these conditions, the sludge retention time can be calculated as: SRT = $V/Q_w = 1.3m^3/(0.05m^3/d) = 26$ days. It is worthy to highlight that during the period of Group 5 and Group 6 conditions, the solids inside the MBR were maintained almost constant between 10 g/L and 12 g/L.

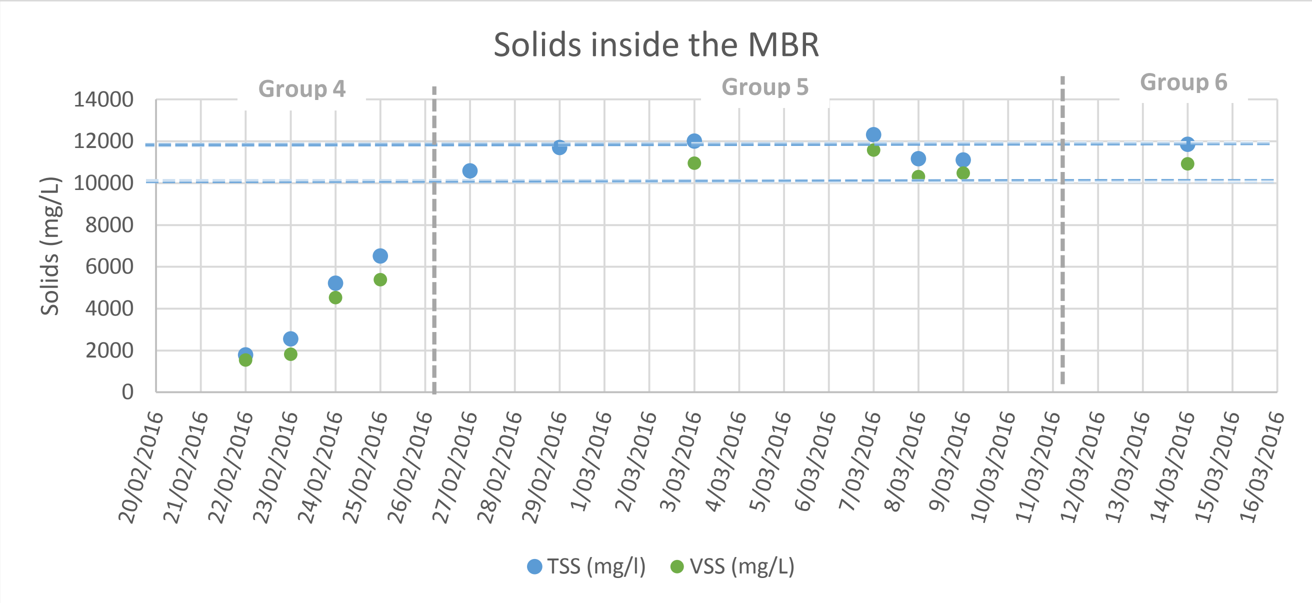


Figure 28: Evolution of MLSS and MLVSS during the second half of February until the end of the studied period

The most important conditions analysed are from Group 5, where the volatile solids were established between 10 and 12 g/L and the aeration was at the maximum possible, with the higher values of dissolved oxygen, improving the nitrification. Another important group was the sixth. Despite having only one result during this last week of operation, it was a trial of enhancing the denitrification process, with the aeration turned on and off. In Groups 1, 2 and 4, the solids were not yet established around 10 g/L, they were rising starting from 2 g/L, and the operational conditions of aeration and recirculation were not the best. In group 3 the solids inside the MBR where too high, making the sludge more dense and starting falling outside the MBR when it was aerated. Because of that, the aeration was maintained very low, hence the nitrification was not benefited.

2.10.Evaluation of the removal efficiency

In order to evaluate the performance of the MBR treating the slaughterhouse wastewater, analyses of organic matter, nitrogen, phosphorous and coliforms were performed in the influent and effluent.

Generally, Schneck processes are every week the same, with the slaughter process every Tuesday and Thursday, and the others days the meat is separated from the bones and is prepared to export to meat processing facilities.

An analysis of the influent of the MBR during a week was done in order to define the sample frequency and dates. Figure 29 shows the COD (as a measure of organic matter) and NH_4 (as a measure of Nitrogen) of the influent of the MBR, during the week from 3/02/16 to 10/02/16. The values obtained for this week are not totally representative of the feed of the MBR as they were taken in the very first seconds of the MBR inlet, where a big amount of solids that were accumulated inside of the pump shelter were taken, providing higher values of COD and

Nitrogen. Nevertheless, it is worthy to show the analysis done in order to highlight the variation of COD and Nitrogen in the influent.

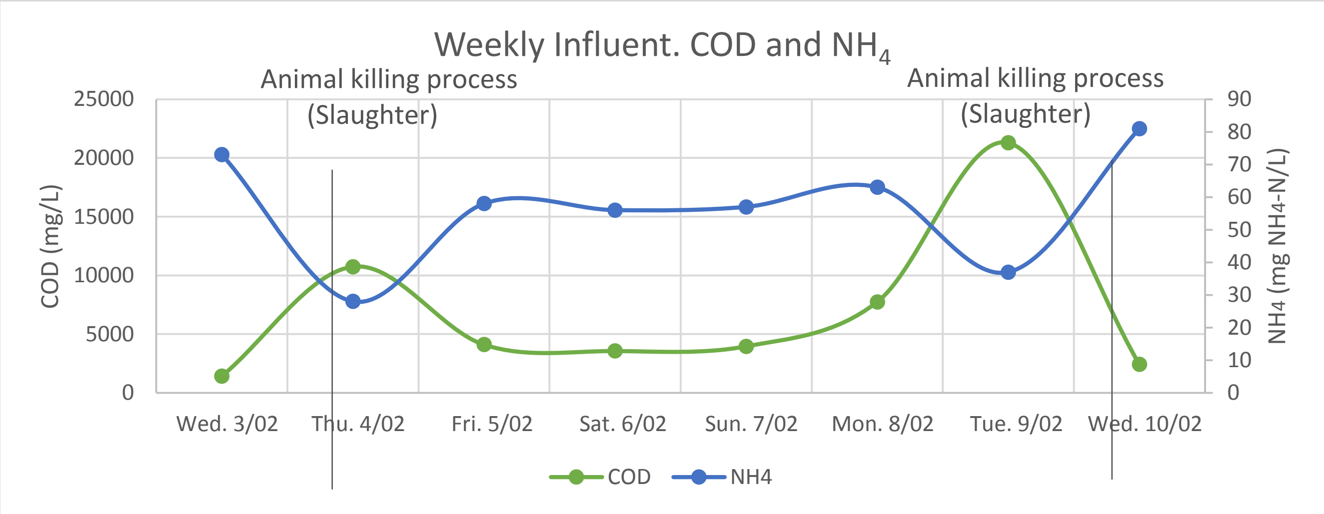


Figure 29: Weekly COD and NH_4 of the influent. Week considered from 3/02/16 to 10/02/16. Samples not representative of the daily feeding of the MBR.

The characterization of the influent and effluent could not be done every day of the week due to a high time and money consumption. Looking at Figure 29, the variation of COD and NH_4 from Sunday to Monday is not so high. However, the days that the slaughter takes place, the COD rises and the NH_4 decreases. The opposite happens on Wednesday. As a result, the characterization of the influent and effluent was planned to be done two times a week: Tuesdays (during one slaughter of the week, when the COD in the influent is higher) and Wednesdays (The COD in the influent has the lowest value, but the NH_4 is high). Full characterization data is presented in Appendix E.

Organic Matter

During the studied period (from 3/02/2016 to 14/03/2016), the influent and effluent COD of the MBR were analysed. The results are shown in Figure 30 and Figure 31 respectively.

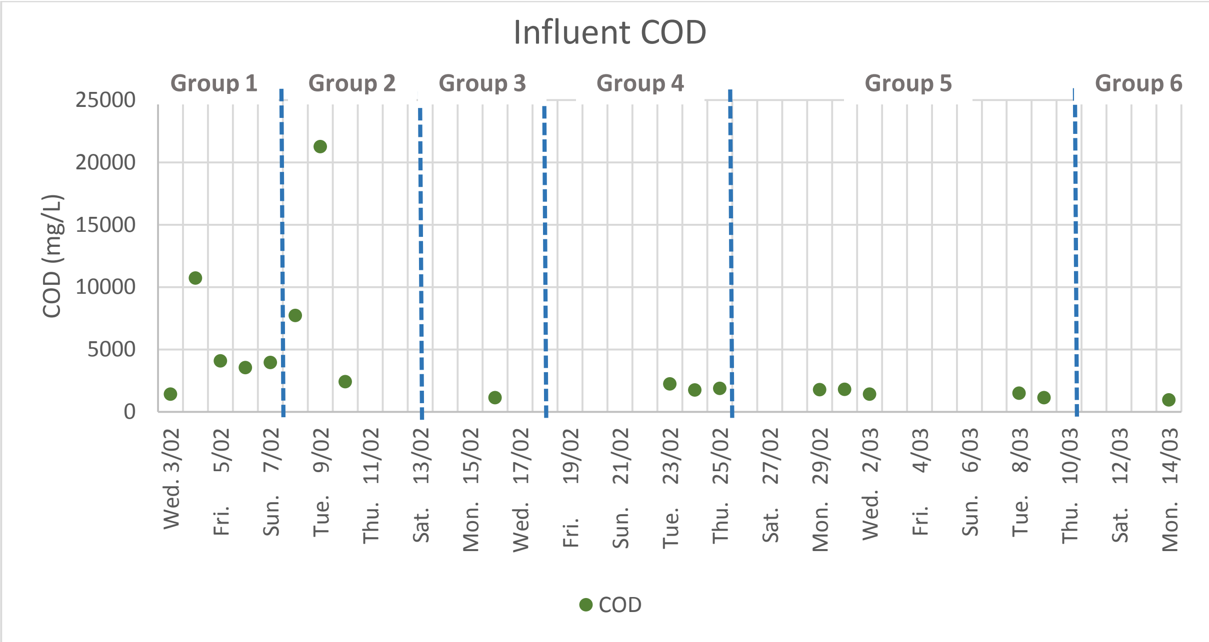


Figure 30: Influent COD during the whole studied period. First week not representative

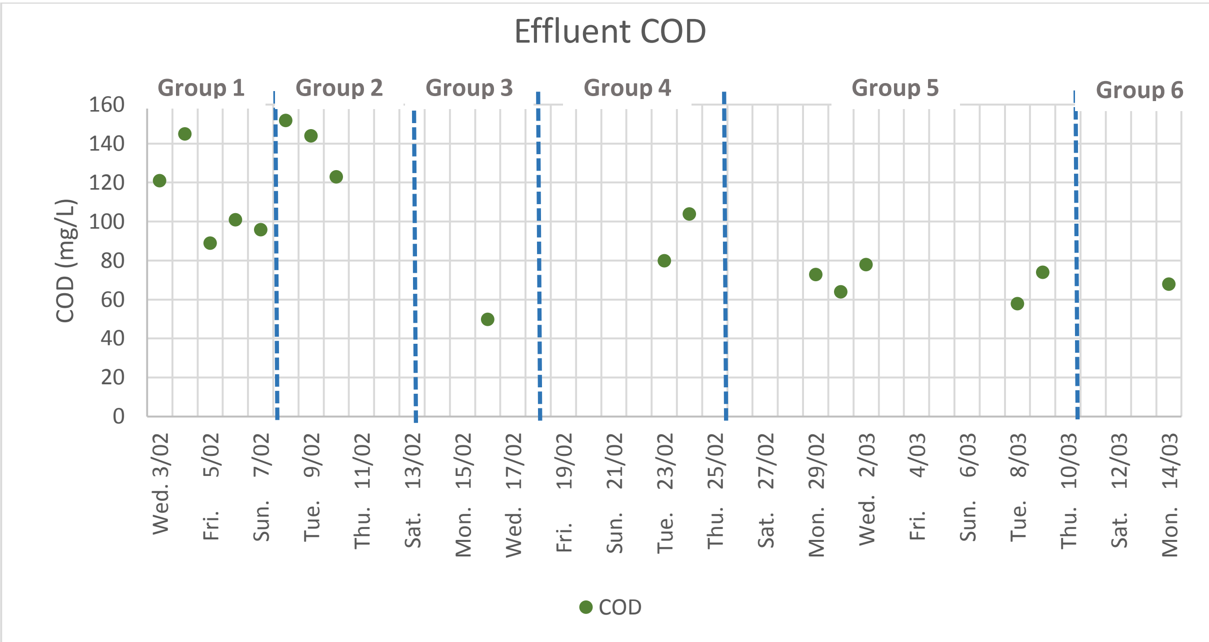


Figure 31: Effluent COD during the whole studied period. First week not representative

As commented before, the first week of the studied period was not representative of the MBR influent due to a sample error. Therefore, in Figure 32 and Figure 33 the first week of analysis was skipped in order to visualize better the differences of the values in the influent.

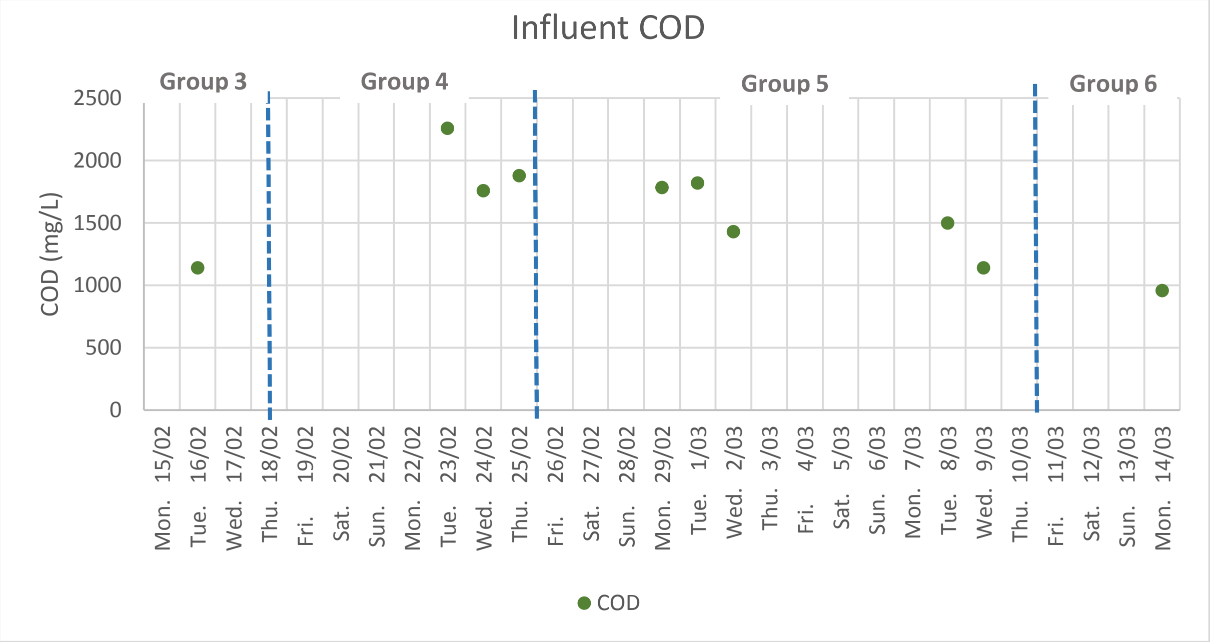


Figure 32: Influent COD during the studied period, excluding the first week

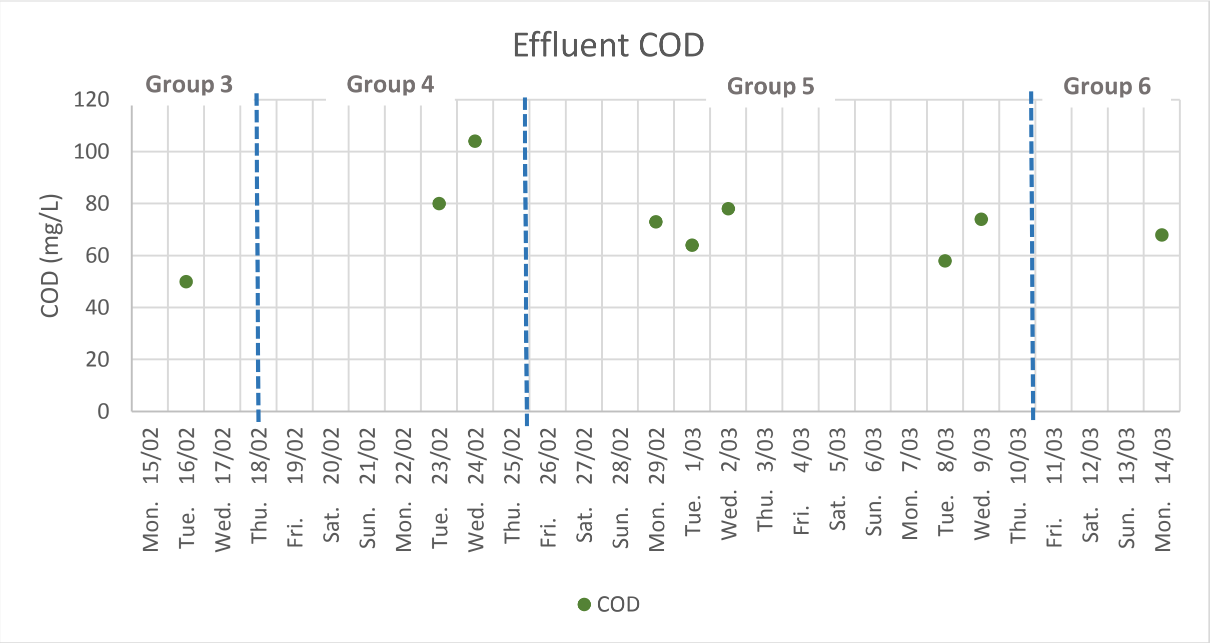


Figure 33: Effluent COD during the studied period, excluding the first week

Figure 34 and Figure 35 represents the average, maximum and minimum value of COD in the effluent and the removal efficiency, for each group of similar conditions of operation.

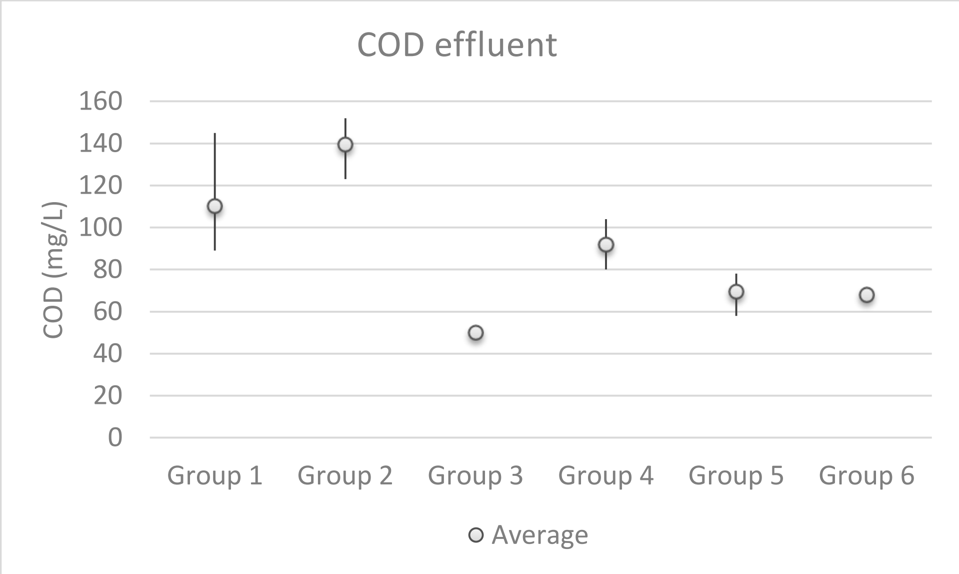


Figure 34: COD in the effluent. Average, maximum and minimum of each group of similar conditions of operation

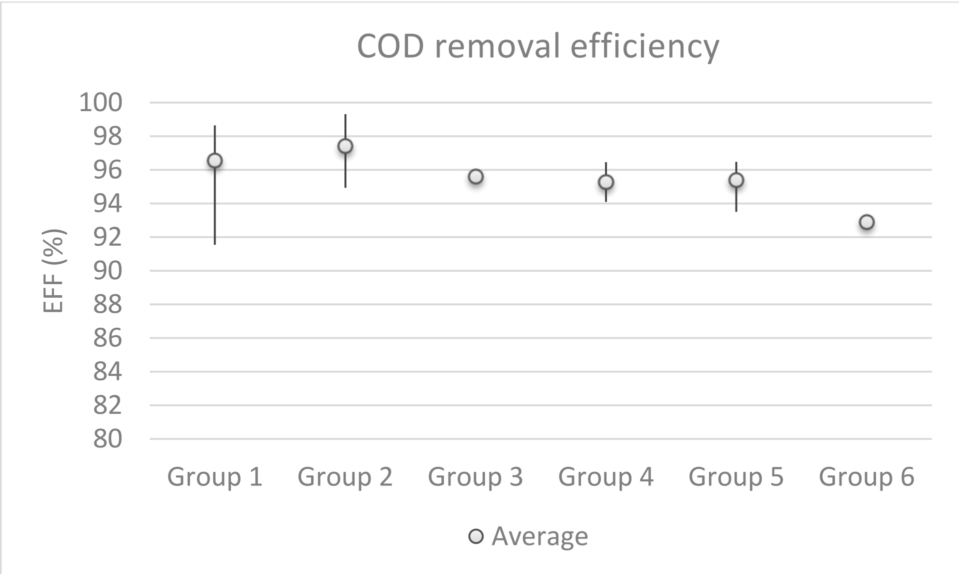


Figure 35: COD removal efficiency. Average, maximum and minimum of each group of similar conditions of operation

The removal COD efficiency is always higher than 92%. The National Standard from Uruguay ("Decreto 253/79," 1979) does not limit the COD as organic matter discharge, but restricts the BOD_5 as a maximum value for water bodies discharge of 60 mg/L. For this reason, the BOD_5 was measured once in each Group period as presented in Table 10. The values for Groups 5 and 6 were reported as less than 30 from the laboratory and not the exactly number, but widely complies the Standard.

Table 10: BOD of influent and effluent, and removal BOD efficiency from each group of similar conditions of operation

	BOD_5 (mg/l) influent	BOD_5 (mg/l) effluent	Removal efficiency (%)
Group 1	816	56.3	93.1
Group 2	819	47.8	94.2
Group 3	330	39	88.2
Group 4	686	43.0	93.7
Group 5	577	<30	>94.8
Group 6	380	<30	>92.1

Nitrification and denitrification

The nitrogen removal from the wastewater can be carried out biologically by the processes of nitrification and denitrification (Metcalf & Eddy Inc. et al., 2002).

The first one occurs in aerobic conditions. Through this process, the Ammonium (NH_4^+) present in the wastewater is transformed to Nitrate (NO_3^-) in two steps: First, the NH_4^+ is oxidized to Nitrite (NO_2^-) mainly by Nitrosomonas and Nitrosococcus bacteria. The second step (oxidation of nitrite into nitrate) is done mostly by bacteria of the genus Nitrobacter and Nitrospira. The denitrification takes place in anoxic conditions (without dissolved oxygen), where the Nitrate is converted into N_2 gas (also passing through Nitrite before), removing the Nitrogen from the effluent to the atmosphere. The bacteria that are able to denitrify are heterotrophics, as they need organic matter as a carbon source.

In order to evaluate the nitrogen removal performance of the MBR in the slaughterhouse, measurements of NH_4, NO_3, NO_2 and Total Nitrogen (TN) were carried out. The results are shown in Figure 36 and Figure 37.

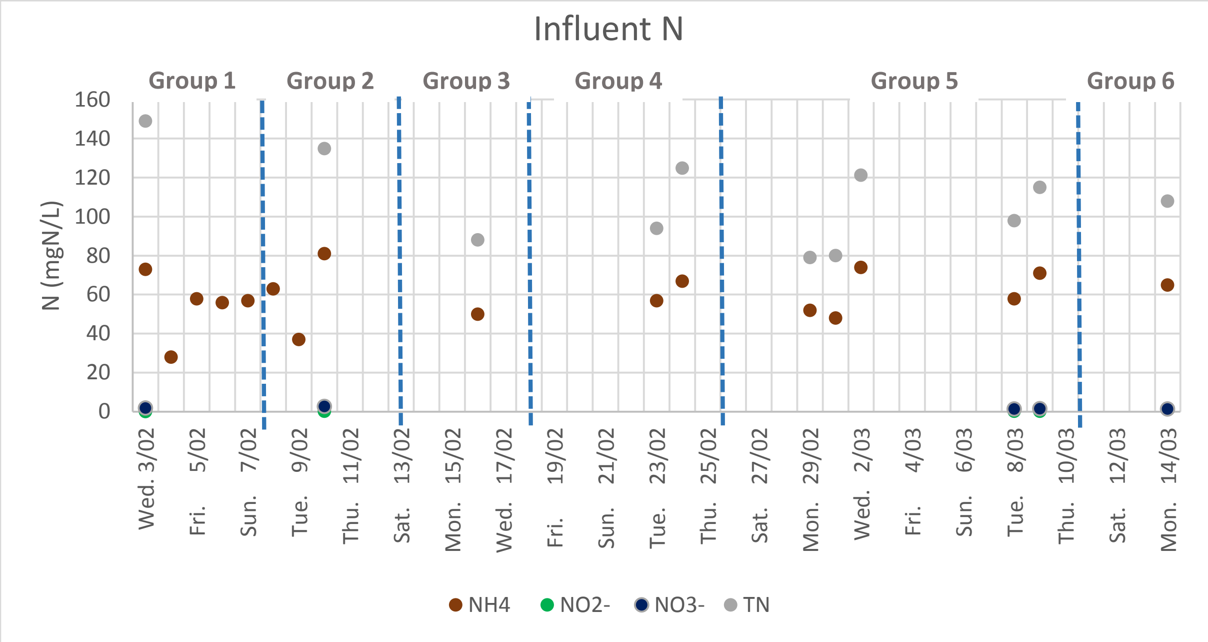


Figure 36: Influent Nitrogen (TN, NH_4, NO_3, NO_2) during the studied period

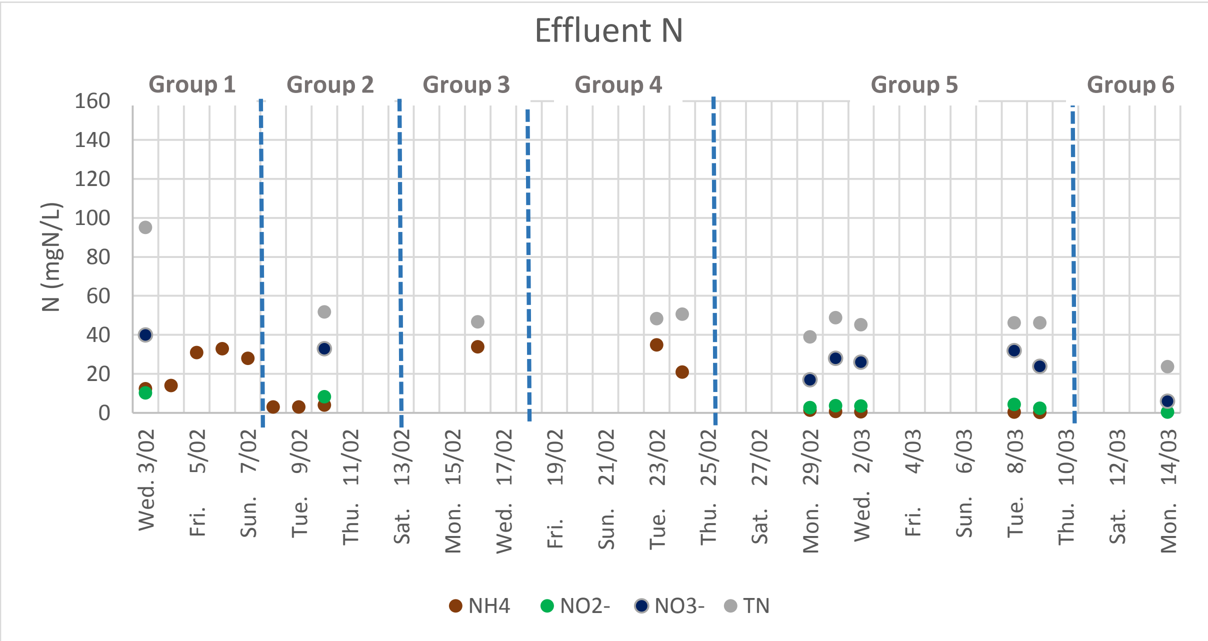


Figure 37: Effluent Nitrogen (TN, NH_4, NO_3, NO_2) during the studied period

Focusing on the nitrification process, the average, maximum and minimum value of NH_4 in the effluent for each group of similar conditions of operation is presented in Figure 38. Furthermore, the NH_4 removal efficiency is shown in Figure 39. From this graphs, it can be verified that the nitrification in Group 5 was achieved, with NH_4 values less than 1 mg/L and an average efficiency of 98.8 mg/L. Moreover, in Group 2 despite of not having the valves completely opened and having the solids still growing, the nitrification efficiency reached a value of 94.1 %.

The only Nitrogen value limited at the National Standard from Uruguay ("Decreto 253/79," 1979) is theNH_4, with a maximum value for water bodies discharge of 5 mg/L. However, it is worthy to consider as well the total nitrogen removal (Figure 40 and Figure 41). In order to obtain good results in total nitrogen efficiency, not only the nitrification must take place, but also the denitrification. The removal of the NO_3 produced in the Nitrification process was not so efficient until Group 6, despite of having an MBR with an anoxic compartment. One reason could be that when the nitrification process was being successful, the dissolved oxygen was high. According to Fan et al. (2014) and Qingjuan et al. (2008) simultaneous nitrification and denitrification can be affected either when too low or too elevated value of DO is presented in the MBR. Furthermore, Capodici et al. (2015) and Ćurko et al. (2012) point out that the alternating aerated/anoxic process with the automatic control of the intermittent aeration (IA) might be a suitable and effective strategy to adopt, as within a typical IA cycle, an ''aerated'' and a ''non-aerated'' phase can be define, improving the simultaneous nitrification and denitrification. During the days of Group 6, the aeration valves were turned "on" and "off" automatically, with a cycle defined as 5 minutes of aeration and 15 minutes without aerating. With this conditions, the NO_3 present in the effluent decreased more than four times, reaching a value of 6 mg/L. Though the NH_4 removal efficiency decreased respect to the Group 5 operation, its value was still high (90.5 %) but not enough to reach the Standard's limits, as the effluent NH_4 was 6.2g/L. As a result, the average TN decrease from 42.3 in Group 5 to 23.8 in Group 6 conditions.

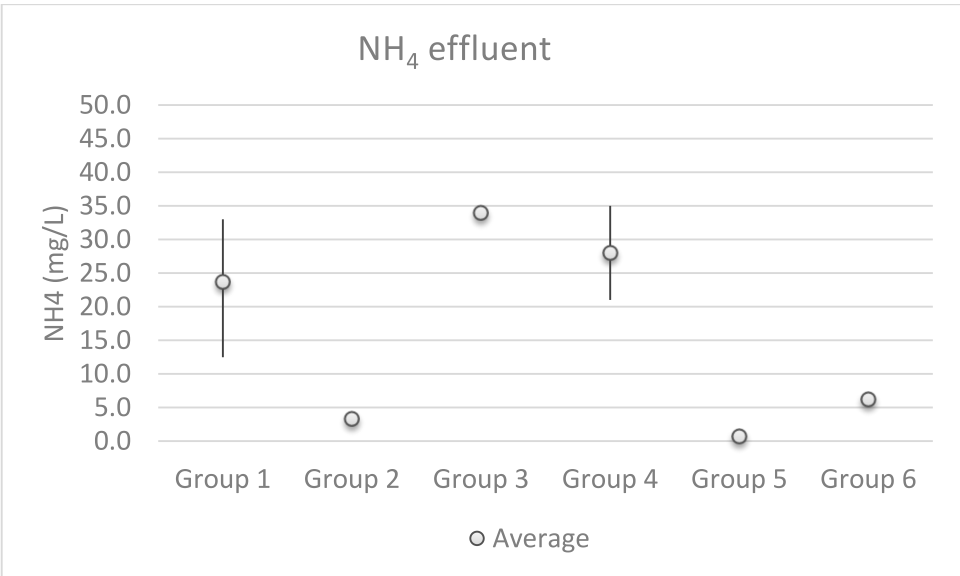


Figure 38: NH_4 in the effluent. Average, maximum and minimum of each group of similar conditions of operation

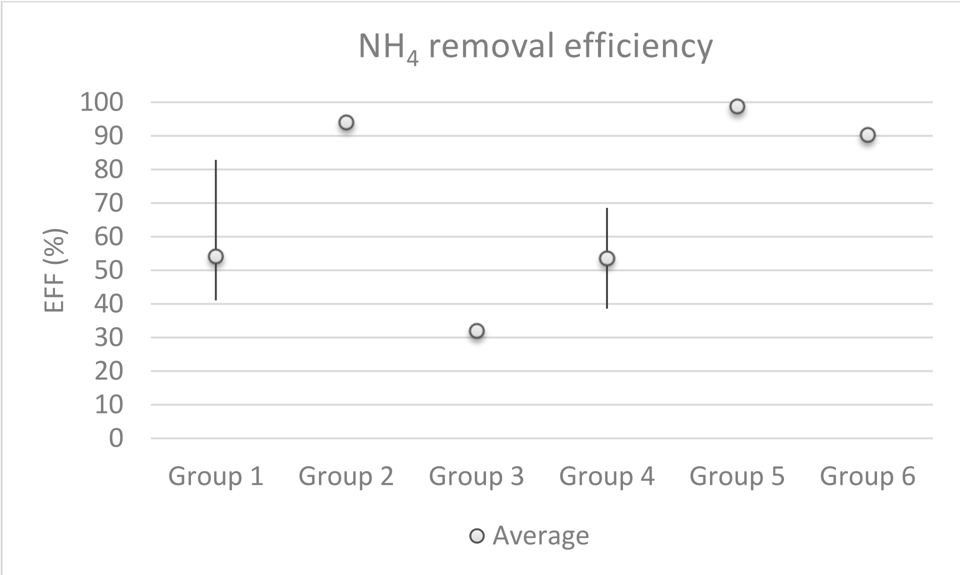


Figure 39: NH_4 removal efficiency. Average, maximum and minimum of each group of similar conditions of operation

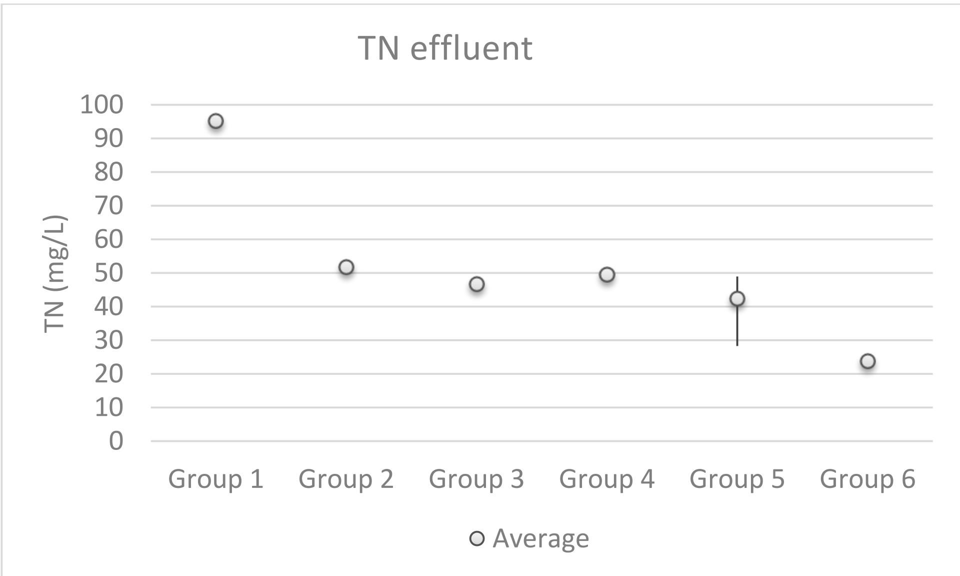


Figure 40: TN in the effluent. Average, maximum and minimum of each group of similar conditions of operation

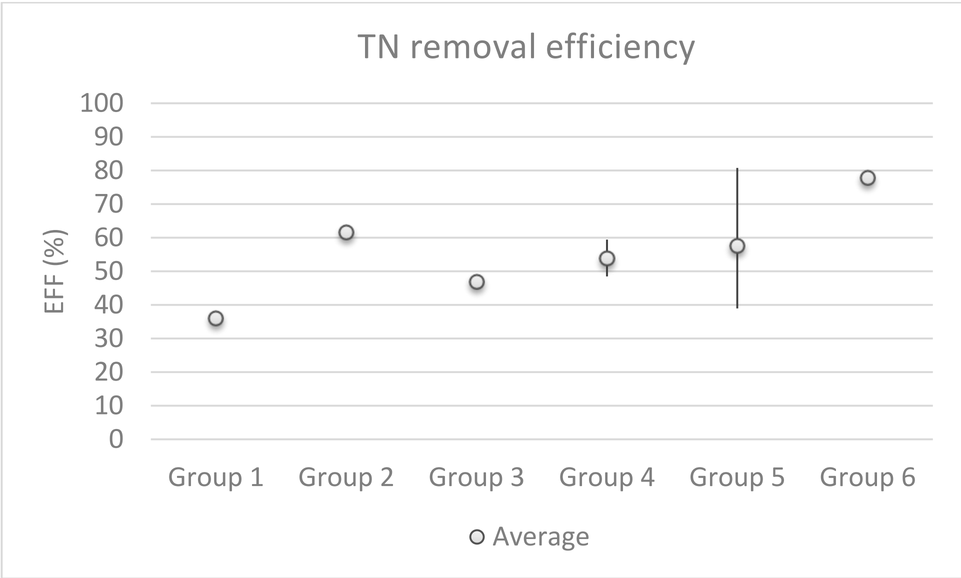


Figure 41: TN removal efficiency. Average, maximum and minimum of each group of similar conditions of operation

Phosphorous

The total phosphorous removal efficiency was measured in Groups 5 and 6, as presented in Table 11. The Uruguayan National Standard for discharges in water bodies ("Decreto 253/79," 1979), sets the limit value as 5 mgP/L, which could not be achieved with the MBR process. In order to reach a value of less than 5 mgP/L in the effluent, a chemical phosphorous removal could be done, where phosphorus is removed introducing salts of aluminium, calcium or iron (e.g. ferric chloride) to the MBR tank, creating Phosphate precipitates (Metcalf & Eddy Inc. et al., 2002) which doesn't pass through the membrane pores and is then removed with the sludge.

Table 11: P_T averages of influent, effluent and removal efficiency from Group 5 and Group 6

	P_T (mg/l) Average infl.	P_T (mg/l) Average effl.	Average removal efficiency (%)
Group 5	22.0	14.7	33.8
Group 6	23.1	15.2	34.2

Faecal Coliforms

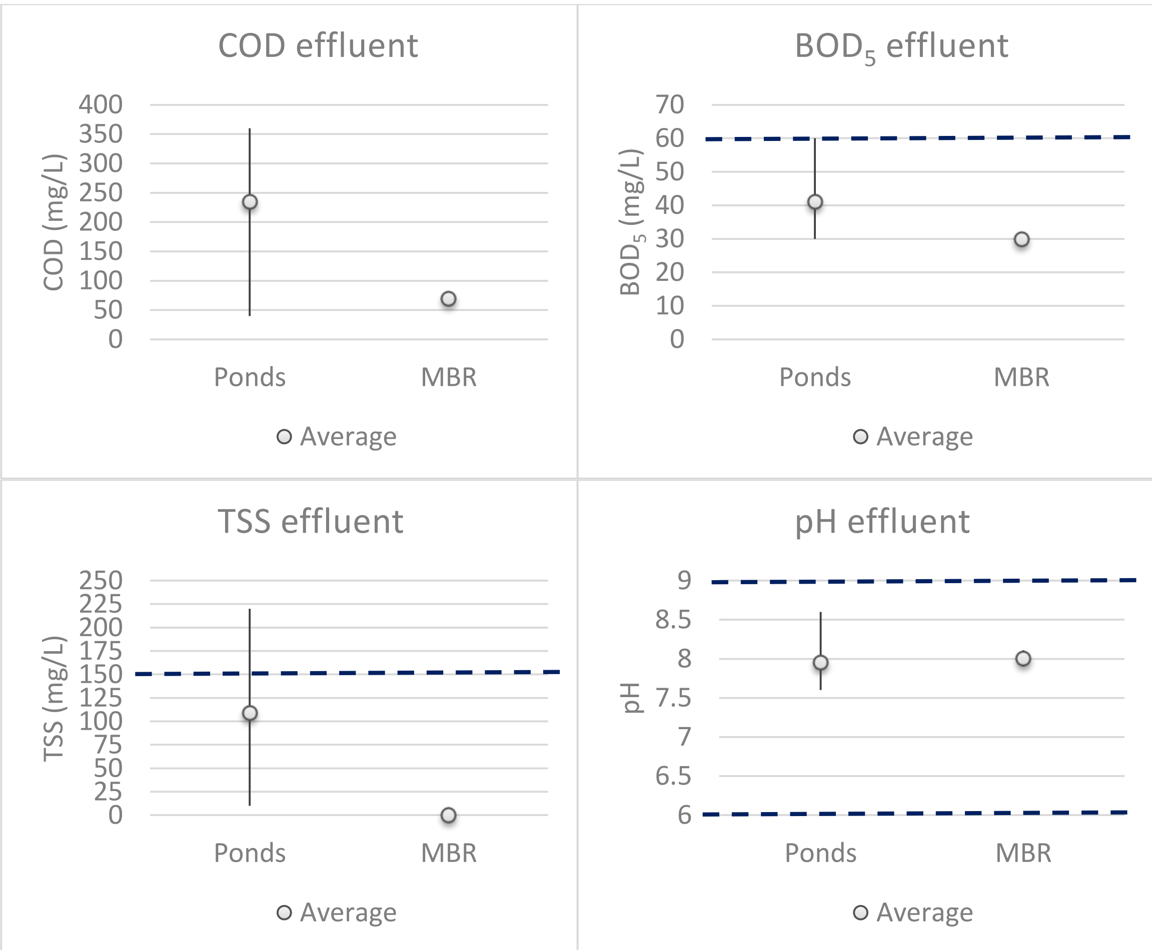
The maximum value of Faecal Coliforms allowed to discharge in water bodies according to the Uruguayan National Standard ("Decreto 253/79," 1979), is 5000 CFU/100mL. Table 12 shows the values obtained for remotion of Faecal and Total coliforms. The removal efficiency was high, and the Coliforms were below the Standard, but ideally the effluent should be free of bacteria as the membrane's pores size are so small that does not allow bacteria to pass through the membranes.

Table 12: Total and Faecal Coliforms averages of influent, effluent and removal efficiency from the studied period

	Average infl. (CFU/100mL)	Average effl. (CFU/100mL)	Removal Efficiency
Faecal Coliforms	$7.0x10^7$	527	3 to 5 Log. removal units
Total Coliforms	$1.4x10^8$	2067	3 to 5 Log. removal units

2.11. Comparison with current discharge

A comparison of the actual ponds treatment system and the MBR taking the influent from the homogenization pond is illustrated in Figure 42. The dashed blue line represents the National Standards limits for discharging in water bodies ("Decreto 253/79," 1979). The circles in the graphs shows the effluent averages, and the straight lines the maximum and minimum values. The values for the analysis of the actual ponds system were taken from the measures during the year 2015 made by DINAMA[1], presented in Appendix A, and the characterization done for modelling. The MBR effluent data was taken from the Group 5 characterization presented in Figure 33 and Figure 37.



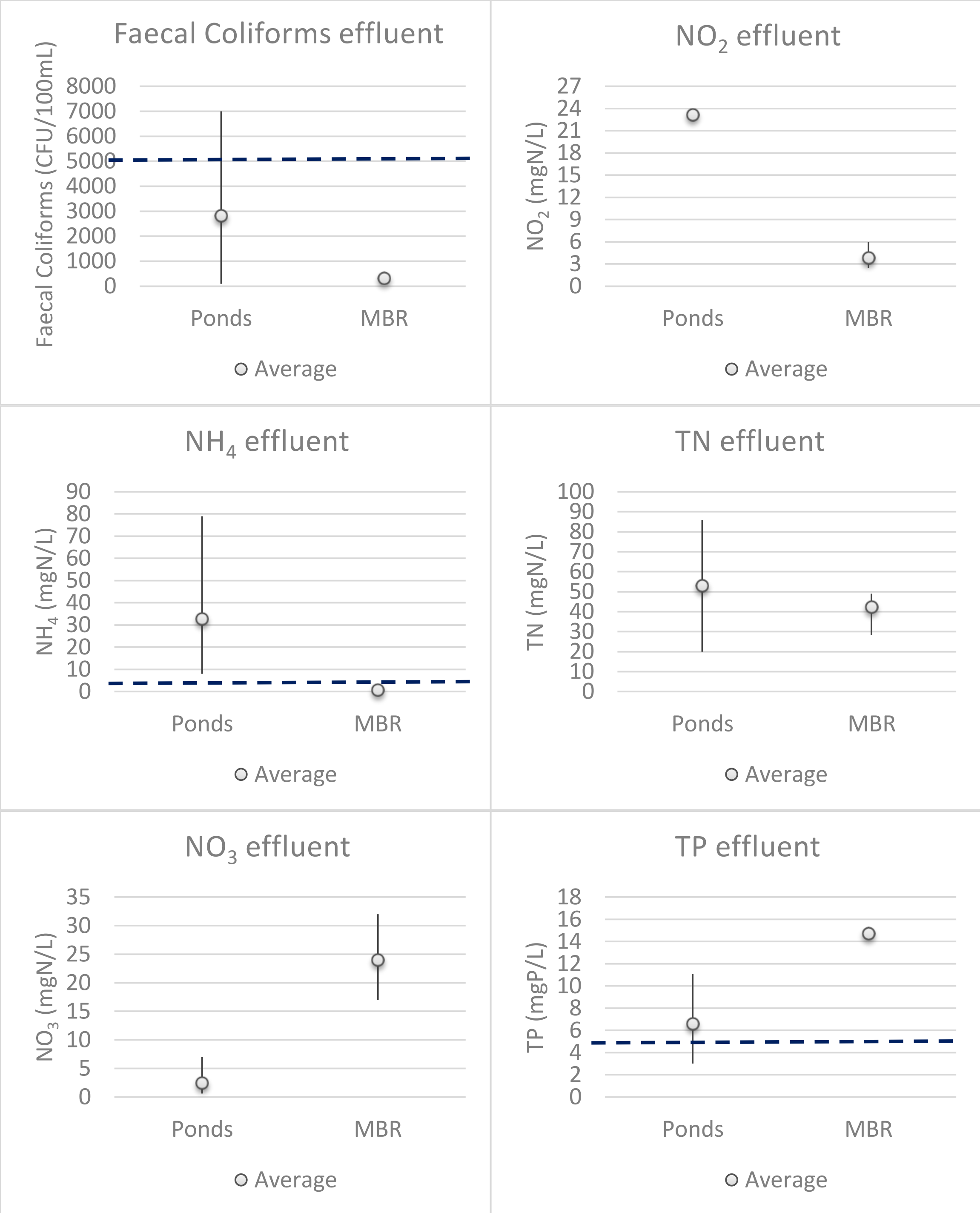


Figure 42: Comparison of actual ponds treatment system vs. MBR (as Group 5 operational conditions). Dashed blue line represents the National Standards limits for discharging in water bodies. The circles shows the effluent averages and the straight lines the maximum and minimum values.

Considering the National standards for discharging to water bodies, the only parameter of the MBR effluent that is above the maximum value allowed is the Total Phosphorous. As mentioned before, this parameter could be removal by the addition of as instance Ferric Chloride.

Comparing with the actual ponds system, the main difference is in the NH_4. Whereas the MBR process produces an effluent with less than 1 mg/L, the pond's average is 33 mgNH_4-N/L (more than 6 times the maximum allowed) and a maximum value of 79 mgNH_4-N/L (around 16 times more). The actual system sometimes do not comply the Standard regarding the Suspended Solids, while the MBR brings a solids free effluent. Faecal coliforms could also be higher than the standard for the ponds system. Other parameters that the ponds system is not as effective as the MBR are the COD (in average is four times bigger) and the Total Nitrogen. However, it is important to highlight that the NO_3 in the MBR effluent is around 5 times more than in the ponds system because of the low efficiency in the denitrification process. With the study of turning the aeration on and off as Group 6 conditions, a better denitrification could be achieved, but have to be careful with the ammonia growing.

2.12.Possibility of reuse

Because of the meat in the slaughterhouse is always in contact with the water, the Standard that the slaughterhouse must meet is the drinking water Standard (OSE, 2008). Some of these parameters are presented in Table 13. In order to define whether it is possible or not to reuse the water treated inside the industry, a tough microbial, chemical and physical characterization should be done. Meanwhile, it can be said that at least a disinfection step after the MBR treatment is recommended if the water is wanted to be reused. Something to highlight is that in the slaughterhouse there are some big dirty zones that are necessary to clean every slaughter day, and they are not in contact with the meat (e.g. separation zone of the solid/liquid phase of the cows rumens). These places are the most suitable to use the water treated.

Table 13: Uruguay National Standard for drinking water quality (OSE, 2008)

		Standards Drinking Water Quality (OSE, Uruguay)	**MBR effluent, operating at Group 5 conditions.**
Colour	**(Esc.Pt-Co)**	15	
Heterotrophics	**(CFU/ml)**	500	
Fecal Coliforms	**(CFU /100ml)**	Absence in 100 ml	320
Total Coliforms	**(CFU /100ml)**	Absence in 100 ml	1400
Enterococci	**(CFU /100ml)**	Absence in 100 ml	
Escherichia coli	**(CFU /100ml)**	Absence in 100 ml	
Sulfite-reducing clostridium	**(CFU /100ml)**	Absence in 100 ml	
Pseudomonas Aeruginosas	**(CFU /100ml)**	Absence in 10 ml	
pH		6.5-8.5	8.0
Turbidity	**(NTU)**	1	
Hardness	**(Mg$CaCO_3$/L)**	500	
Chlorides	**(mgCl/L)**	250	
NO_3-	**(mgNO_3/L)**	50	24
NO_2-	**(mgNO_2/L)**	3	3.8

Ammonia	**($mgNH_4/L$)**	1.5	0.7
Fe	**(mgFe/L)**	0.3	
Aluminium	**(mgAl/L)**	0.2	
Mercury	**(mgHg/L)**	0.001	
Cyanide	**mgCN/L**	0.1	
Sulfate	**($mgSO_4$)**	400	
Sodium	**mgNa/L)**	200	
Chrome	**(mgCr/L**	0.05	
Manganese	**(mgMn/L)**	0.1	
Lead	**(mgPb/L)**	0.03	
Arsenic	**(mgAs/L)**	0.05	
Zinc	**(mgZn/L)**	5	
Fluoride	**(mgF/L)**	1.5	
Total chloramines	**(mg/L)**	3	
Free chloride	**(mg/L)**	2.5	
Dibromochloro methane	**(mg/L)**	0.06	
Chloroform	**(mg/L)**	0.2	
Dissolved total solids	**(mg/L)**	1000	

2.13. Biowin model

Best location for the MBR in terms of efficiency

The characterization of the actual treatment plant was carried out as shows in Figure 43 in order to obtain the data necessary for the BioWin inputs. The results are presented in Table 14.

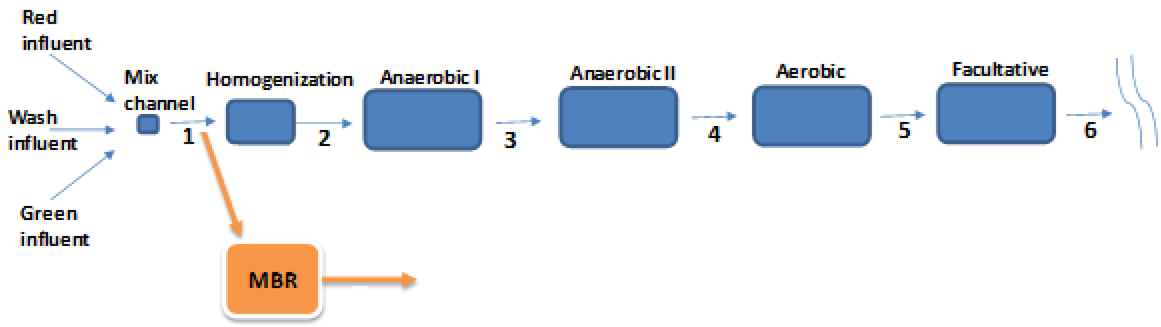


Figure 43: Points of sample for characterization of the actual treatment plant, to be used as MBR influent in BioWin modelling

Table 14: Actual treatment plant characterization

Sample taken from point:	COD (mg/L)	COD_{GF} (mg/L)	COD_{MF} (mg/L)	BOD (mg/L)	BOD_{GF} (mg/L)	NH_4 (mg NH_4-N/L)	NO_3^- (mg NO_3-N/L)	NO_2^- (mg NO_2-N/L)
1	3320	1430	840	2060	891	162	2.3	0.25
2	1640	380	230	577	98	84	1.5	0.084
3	535	213	157	141	62	74	1.1	0.057
4	411	192	156	85.5	38	62	1.3	0.061
5	380	162	99	67.5	<30	23	17.6	8.82
6	283	117	90	47	<30	8	7	23.2

Table 14 (Continue): Actual treatment plant characterization

Sample taken from point:	TKN (mg/L)	TN (mg/L)	TP (mg/L)	PO_4^- (mg/L)	TSS (mg/L)	VSS (mg/L)	ISS (mg/L)
1	234	236.6	48.7	42	1273	1195	78
2	146	147.6	21.4	18.8	778	656	122
3	132	133.2	24.8	21.5	231	184	48
4	109	110.4	22.9	19.4	203	183	20
5	43	69.4	16.8	13.1	188	177	11
6	37.8	68.0	11.1	8	145	138	7

Table 14 (Continue): Actual treatment plant characterization

Sample taken from point:	pH	Alkalinity (mg $CaCO_3$/L)	Ca (mg/L)	Mg (mg/L)	Acetate (mg/L)
1	7.03	772.8	64.2	22.3	268
2	7.25	916.3	79.6	29.2	12.3
3	7.83	949.4	71.4	26.6	20.4
4	7.69	982.6	68.7	26	23.2
5	8.24	982.6	62.7	26.4	11
6	8.33	828.0	55.9	27.3	23.9

A model in BioWin was implemented considering different scenarios. Each simulation represents the MBR placed in the actual treatment plant, taking the influent for the different six points presented in Figure 43. Moreover, the COD, nitrogen and phosphorous fractions that are set as default for domestic wastewater treatment, were calculated (as in Appendix B) and changed in the model (results are presented in Appendix C). Furthermore, the dimensions of the anoxic and aerobic tank and membranes characteristics were added. The scheme of the simulation produced is presented in Figure 44, with the reactor divided into the anoxic and aerated part, with the recirculation and the wasted sludge.

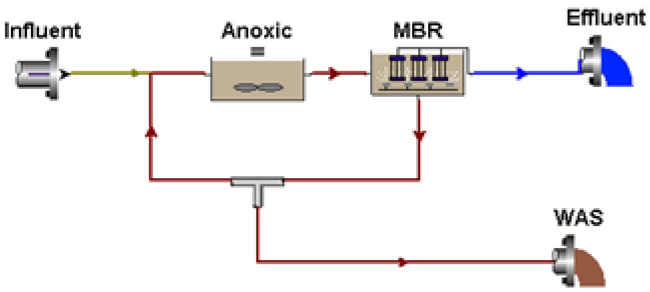


Figure 44: Modelling scheme of the MBR in BioWin

The analysis was done with the MBR data as if it was operating with similar conditions as Group 5, with a dissolved oxygen concentration of 3,0 mg/L, recirculation ratio ($Q_{recirculation}/Q_{influent}$) = 4, and wasted sludge flow = 50L/day. The results obtained by the program are presented in Table 15.

Table 15: Results obtained by the BioWin simulation, with dissolved oxygen concentration of 3,0 mg/L, recirculation ratio (Qrecirculation/Qinfluent) = 4, and waste flow = 50L/day (similar operating conditions as Group 5)

MBR placed after point:	Effluent									
	NH_4 (mg NH_4-N/L)	NO_3^- (mg NO_3-N/L)	NO_2^- (mg NO_2-N/L)	TKN (mg/L)	TN (mg/L)	TP (mg/L)	TSS (mg/L)	COD (mg/L)	BOD (mg/L)	pH
1	0.74	31.95	0.16	6.55	38.67	6.14	0	76.75	0.95	6.68
2	0.68	35.07	0.15	4.86	40.08	10.58	0	68.6	0.95	7.34
3	0.69	90.07	0.15	5.53	95.75	21.13	0	68.67	0.88	7.21
4	0.69	74.93	0.15	5.78	80.85	20.07	0	68.58	0.83	7.4
5	0.68	38.98	0.15	3.31	42.44	13.96	0	68.92	0.9	7.65
6	0.68	27.07	0.15	4.79	32.01	9.14	0	68.93	0.91	7.64

Focusing on the Nitrogen, it can be noticed that the NH_4 in the effluent is always slow, independently of the MBR placement in the treatment plant. This occurs because of the high DO concentration inside the aerated part of the MBR. The same happens with the NO_2 and the TKN. The big differences are in the NO_3^- which affects the TN effluent value. Table 16 shows the influence of the influent COD/TN regarding to the TN removal efficiency displayed by the modelling. With the MBR placed immediately after the mixed channel, without any treatment or homogenization tank before (Point 1), the TN removal efficiency reaches the highest value of 83.7 %. In this case, the influent COD/TN ratio is 14.0. Following this value is situated the Point 2 as inlet from the MBR (actual situation), with an efficiency of 72.8 % and COD/TN=11.1. For the other points of study (MBR placed after anaerobic, aerated or facultative pond), where the influent COD/TN ratio decreases at values below 6, the TN removal efficiencies is reduced to between 27 and 53 %. These results are consistent with the studies of Fu et al. (2009) and Fan et al. (2014), where the TN removal increased with the COD/N ratio because the denitrification decreases.

Table 16: Influence of the influent COD/TN relation in the TN removal efficiency. Results obtained by modelling the MBR as situated in the different steps of the actual treatment plant.

MBR placed after point:	COD/TN influent	TN effluent	TN removal (%)
1	14.0	38.7	83.7
2	11.1	40.1	72.8
3	4.0	95.8	28.1
4	3.7	80.9	26.7
5	5.5	42.4	38.9
6	4.2	32.0	52.9

Regarding the organic matter removal, the BOD effluent is always slow, and the COD almost the same except after the first point, where it is higher than the rest in the effluent because of the elevated influent COD. Concerning the TP removal, the best place to situate the MBR is the point 1, where the acetate value is around 10 times higher than in the rest points, stimulating the phosphorous removal.

Table 17 shows a comparison of the BioWin effluent results with the real characterization of the pilot MBR effluent, both taking the influent of the homogenization pond (Point 2) and operating with similar conditions (Group 5 conditions).

The results shows that there are not big differences between the modelling results and the parameters measured in the MBR effluent situated in the slaughterhouse. The NH_4, TN, and COD effluent values have less than 10% of difference between the modelling and the reality. The TSS are not present in any of them as the MBR efficiency removing them is 100 %. The TP has not a big difference either. One big difference is in the TKN, which is the sum of organic nitrogen plus the ammonia. As the ammonia content is similar in the modelling and the reality, the variation is on the organic nitrogen. The deviation of the NO_3 and NO_2 from the modelling to the reality is not so big, as in the Table 17 are presented only average results, but sometimes the values were similar to the model as observed in Figure 37. About the BOD_5 measured value, it is only known that is less than 30 mg/L because of limits in the BOD test, so can not be really compared to the model.

Table 17: Comparison of the BioWin effluent results with the real characterization of the pilot MBR effluent. Both taking the influent of the homogenization pond and operating with similar conditions. (Group 5 conditions)

	Effluent									
	NH_4 (mg NH_4-N/L)	**NO_3^- (mg NO_3-N/L)**	**NO_2^- (mg NO_2-N/L)**	**TKN (mg/L)**	**TN (mg/L)**	**TP (mg/L)**	**TSS (mg/L)**	**COD (mg/L)**	**BOD (mg/L)**	**pH**
Modelling: MBR after point 2 (Homogenization pond), with Group 5 values.	0.68	35.1	0.15	4.9	40.1	10.6	0	68.6	0.95	7.3
Reality: Average results of pilot MBR effluent situated after homogenization pond, during GROUP 5 operational conditions	0.74	24	3.8	14.5	42.3	14.7	0	69.5	<30	8.1

Table 18 shows a comparison of the BioWin effluent results with the real characterization of the pilot MBR effluent, both taking the influent of the homogenization pond (Point 2) and operating in the same conditions (Group 6 conditions). The "Modelling I" was performed with the dissolved oxygen value of Group 6 measured only one day and in the laboratory instead of in the slaughterhouse due to the DO meter was broken, so it is an approximated value. Besides, turning the aeration on and off, provides a big variation of dissolved oxygen inside the reactor. The ideal simulation for comparing results should be with the DO variable inside the MBR after making several measures of both conditions (when the air is introduced and when it is not).

The BioWin results of "Modelling I" shows a drop in NO_3 respect to Group 5 conditions, but not as much as the measured decay of NO_3 in the pilot MBR. Trying a model with less average DO concentration inside the reactor ("Modelling II", DO = 0.39 mg/L), the consequence is that the values of NO_3 and TN obtained for the effluent are more similar to the ones measured.

Table 18: Comparison of the BioWin effluent results with the real characterization of the pilot MBR effluent. Both taking the influent of the homogenization pond and operating with similar conditions. (Group 6 conditions)

	Effluent									
	NH_4 (mg NH_4-N/L)	**NO_3^- (mg NO_3-N/L)**	**NO_2^- (mg NO_2-N/L)**	**TKN (mg/L)**	**TN (mg/L)**	**TP (mg/L)**	**TSS (mg/L)**	**COD (mg/L)**	**BOD (mg/L)**	**pH**
Modelling I: MBR after point 2, with DO=0.64 mg/L (DO measured in Group 6)	1	22.4	0.44	5.2	28.0	10.6	0	68.6	0.94	7.4
Modelling II: MBR after point 2, with DO = 0.39 mg/L	1.4	9.1	7.6	5.6	22.3	10.5	0	68.7	0.97	7.4
Reality: Average results of pilot MBR effluent situated after homogenization pond, during GROUP 6 operational conditions	6.2	6	0.4	17.4	23.8	15.2	0	68	<30	8.1

CHAPTER 6– Conclusions and recommendations

Conclusions

In this study, a pilot scale MBR was operated treating wastewater from a slaughterhouse situated in Uruguay, where the actual treatment consists in a ponds system (two anaerobic, followed by one aerated and one facultative pond), discharging in a small stream. The results showed that by placing the membrane bio reactor before the ponds treatment (taking the influent from an homogenization basin), it is more efficient than the actual system treatment, which means that the hole treatment plant could be replaced for a compact MBR, avoiding mainly land wasting, but also birds and ducks that were always present and excess of mosquitos, which could transmit diseases.

Furthermore, the current treatment plant was not achieving some Standard parameters for discharging in water bodies (TSS, Faecal Coliform, NH_4 and TP). The worst one is the NH_4 effluent value, which was between around 2 and 16 times higher than the 5 mgN/L admissible. On the other hand, the only Standard limit that MBR effluent did not satisfy was the TP. This parameter could be removed by adding Ferric Chloride inside the MBR, precipitating the phosphorous.

Six different operational MBR conditions were tried (named Group 1 until Group 6). From Group 1 to Group 4 were just failed trials, but Group 5 and 6 were was the ones with high removal efficiencies and operational steady conditions (the MLSS were maintained constant at between 10 and 12 g/L).

The average effluent values and removal efficiencies for Group 5 (DO = 3.0 mg/L; recirculation ratio = 4; MLSS between 10 g/L and 12 g/L) were the ones presented in Table 19:

Table 19: Average effluent values and removal efficiencies for Group 5 conditions

	Effluent average (mg/L)	Average removal efficiency (%)
COD	69.5	95.4
NH_4	0.74	98.8
TN	42.3	57.6

In the National Standard ("Decreto 253/79," 1979), the only form of nitrogen limited is the NH_4 with a maximum value of 5 mgN/L, which in this case is widely achieved. The organic matter parameter limited is the BOD_5 = 60mg/L. With this operational conditions, it was always below 30 g/L (the exact number is not presented because of a limited value of 30g/L in the BOD test).

As it was observed in the literature review, by intermittent aeration and decreasing the dissolved oxygen, the Nitrate could decrease, having the risk of increasing the ammonia, but if it is well operated and the times are well decided, the TN should decrease. Because of that, Group 6 conditions were carried out with cycles of intermittent aeration: 15 minutes off and 5 minutes on. The results were the next:

Table 20: Average effluent values and removal efficiencies for Group 6 conditions

	Effluent average (mg/L)	**Average removal efficiency (%)**
COD	68.0	92.9
NH_4	6.2	90.5
TN	23.8	78

It can be inferred that the TN removal efficiency increased with the intermittent aeration, but the NH_4 reaches a value a little bit higher than the Standard limit. The ideal condition to remove both NH_4 and TN, should be determined by analysing the optimal intervals of aeration and no aeration.

Some models in BioWin were carried out, simulating the MBR inlet as before and after the homogenization tank and also from the effluent of each pond of the actual treatment system. The simulations were done with the operational conditions of Group 5 (DO = 3 mg/L). Regarding the organic matter removal, the effluent BOD and COD were similar no matter where the MBR was placed. The same happened to the effluent NH_4, that was always low because the high aeration improves the nitrification, transforming the NH_4 into NO_3 in aerobic conditions through autotrophic bacteria (without the need of organic matter). The big differences were in the NO_3. After the nitrification step, the NO_3 is formed and can be released from the water as N_2 gas, what makes a decrease in TN. In order to occur this, it is necessary anoxic conditions (no presence of dissolved oxygen) and also organic matter as the denitrifying bacteria are heterotrophic. The results shows that the best place to situate the MBR inlet is before the homogenization tank, where the COD/TN ratio is 14.0 and the removal TN efficiency is 83.7 %, reaching a value in the effluent of 38.7 mgTN/L. The second best point for the MBR is after the homogenization tank (COD/TN=11.1), with an efficiency of 72.8 % and effluent TN concentration of 40.1 mgTN/L. For the other points of the treatment plant (after each pond), the COD/N ratio decreases below 6 and the TN removal is reduced at values below 53 %. As a result, from the modelling, the best place to situate the MBR in the ponds system is when treating directly the effluent of the slaughterhouse, without any previous treatment. However, this should be good when the influent characteristics are constant, but in the case of this slaughterhouse is not the case. The effluent taken to do the simulation was during one day of slaughter, but the other days is more diluted. The second option, and with not big difference in TN removal efficiency was after the homogenization tank, which is the best idea due to there is not a big variation in its effluent parameters.

Recommendations

It is highly recommended to continue with the study of the cycles of intermittent aeration inside the MBR and its efficiency in simultaneous nitrification and denitrification, defining the most suitable interval of aeration “on” and “off”.

A strict control in the Faecal Coliforms should be implemented, and in case they continue appearing, a disinfection step should be design in order to reuse the water. Moreover, a full microbiological, chemical and physical analysis of the MBR effluent should be carried out.

It is recommended to perform a chemical phosphorous removal analysis in order to define the concentration, dose and kind of coagulant to add.

An economic evaluation of a full scale MBR would be interesting to perform, as it is not a cheap technology but produces very good effluent quality, which could save the industry of having fines or even worse, to be closed by the authorities because of the breach of the Standards.

References

almes-eko. (2010). *MBR plants from watewater treatment*.

almes-eko. (2015). Almes-eko membranes bioreactor. Retrieved from http://www.almes.hr/mb-reactor

Bustillo-Lecompte, C. F., & Mehrvar, M. (2015). Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances. *Journal of Environmental Management*, *161*, 287–302. http://doi.org/10.1016/j.jenvman.2015.07.008

Cao, W., & Mehrvar, M. (2011). Slaughterhouse wastewater treatment by combined anaerobic baffled reactor and UV/H2O2 processes. *Chemical Engineering Research and Design*, *89*(7), 1136–1143. http://doi.org/10.1016/j.cherd.2010.12.001

Capodici, M., Di Bella, G., Di Trapani, D., & Torregrossa, M. (2015). Pilot scale experiment with MBR operated in intermittent aeration condition: analysis of biological performance. *Bioresource Technology*, *177*, 398–405. http://doi.org/10.1016/j.biortech.2014.11.075

Ćurko, J., Matošić, M., Korajlija Jakopović, H., & Mijatović, I. (2012). Nitrogen removal in submerged MBR with intermittent aeration. *Desalination and Water Treatment*, *24*(1-3), 7–19. http://doi.org/10.5004/dwt.2010.1118

Decreto 253/79. (1979). Retrieved from http://www.ciu.com.uy/innovaportal/v/30555/10/innova.front/decreto_253_79_y_modificativos:_control_de_las_aguas.html

Environmental report summary for Ontilcor slaughterhouse. (2011). Retrieved from mvotma.gub.uy/contacto/item/download/1057_213b5f73360ead8c3ad06b828a8f3d4b.html

Exports and imports of Uruguay. Annual report. (2014). Montevideo, Uruguay. Retrieved from http://www.uruguayxxi.gub.uy/exportaciones/informes-comerciales/

Fan, X., Li, H., Yang, P., & Lai, B. (2014). Effect of C/N ratio and aeration rate on performance of internal cycle MBR with synthetic wastewater. *Desalination and Water Treatment*, *54*(3), 573–580. http://doi.org/10.1080/19443994.2014.884942

FAO. (2015). Slaughterhouses. Retrieved from http://www.fao.org/wairdocs/lead/x6114e/x6114e04.htm

Fu, Z., Yang, F., Zhou, F., & Xue, Y. (2009). Control of COD/N ratio for nutrient removal in a modified membrane bioreactor (MBR) treating high strength wastewater. *Bioresource Technology*, *100*(1), 136–41. http://doi.org/10.1016/j.biortech.2008.06.006

Garcia, H. (2015). *Lecture notes. Module 8: Modeling of wastewater treatment plants*. Delft, Netherland.

Gürel, L., & Büyükgüngör, H. (2011). Treatment of slaughterhouse plant wastewater by using a membrane bioreactor. *Water Science & Technology*, *64*(1), 214. http://doi.org/10.2166/wst.2011.677

INAC. (2015). Parte Semanal de Faenas. Retrieved from http://www.acg.com.uy/faenas.php

Industrial effluents report. (2014). Retrieved from http://www.montevideo.gub.uy/sites/default/files/Informe UEI 2014.pdf

Judd, S. (2006). *The MBR Book: Principles and Applications of Membrane Bioreactors in Water and Wastewater Treatment*.

Meijer, S., & Brdjanovic, D. (2012). *A Practical Guide to Activated Sludge Modelling*. Delft, Netherland.

Metcalf & Eddy Inc., Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2002). *Wastewater Engineering: Treatment and Reuse*.

OSE. (2008). UNIT 833 Standard. Retrieved from www.ose.com.uy/descargas/clientes/reglamentos/unit_833_2008_.pdf

Qingjuan, M., Fenglin, Y., Lifen, L. I. U., & Fangang, M. (2008). E ff ects of COD / N ratio and DO concentration on simultaneous nitrification and denitrification in an airlift internal circulation membrane bioreactor, *20*(2), 933–939.

Schneck web page. (2015). Retrieved from http://www.schneck.com.uy/

Yordanov, D. (2010). PRELIMINARY STUDY OF THE EFFICIENCY OF ULTRAFILTRATION TREATMENT OF POULTRY SLAUGHTERHOUSE WASTEWATER, *16*(6), 700–704.

Appendices

Appendix A Historical analysis of effluent. Year 2015

Table 21: Schneck effluent discharge parameters. Meassures during the year 2015 by DINAMA[1]

Parameter	Unit	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	Max. allowed Decreto 253/79
Temperature	**ºC**	-	24		25	25		26	21		20	20	-	-	13	10	30
pH		8,4	8,1		8,6	8,3		7,9	7,6		7,6	7,8	-	7,6	7,8	7,8	6,0 to 9,0
Dissolved Oxygen	**mg/L**	3,3	-		-	-		-	2,8		-	-	-	-	-	-	-
BOD_5	**mg/L**	50	30		35	30		30	60		30	50	-	40	50	40	60
COD	**mg/L**	270	40		140	150		110	250		260	360	-	280	320	350	-
TSS	**mg/L**	60	50		50	85		10	100		220	190	-	150	130	120	150
Fat and Oil	**mg/L**	40	<20		40	30		60	120		130	<20	-	40	20	115	50
NH_4	**mgN/L**	-	12		-	8		-	57		-	33	-	-	-	79	5
NO_3	**mgN/L**	-	0,6		-	1		-	1,2		-	3,5	-	-	-	1,4	-
Total N	**mgN/L**	-	44		-	20		-	58		-	42	-	-	-	86	-
Total P	**mgP/L**	-	8,6		-	6		-	5		-	5,9	-	-	-	3,0	5
Detergents	**mg/L**															< 0,20	4
Fecal Coliforms	**CFU/ 100mL**	-	-	<100	-	-	$1,9x10^3$	-	-	$7,0X10^3$	-	-	$2,3x10^3$	-	-	-	5000

Appendix B BioWin fractions calculations

BioWin COD calculations (Based on (Meijer & Brdjanovic, 2012)**)**

The influent unbiodegradable COD (S_{US}) for systems with a SRT > 3 days is based on the effluent measurement of soluble (glass-filtered) COD according to:

$$S_{US} = COD_{S,EFF} = COD_{GF,EFF}$$

In the current case of implementing a MBR, the effluent is previously filtered by a micro-filter membrane, therefore the $COD_{GF,EFF}$=$COD_{MF,EFF}$=COD_{EFF}.

The fraction for unbiodegradable COD is calculated according to:

$$F_{US} = \frac{S_{US}}{TCOD} = \frac{COD_{GF,EFF}}{TCOD_{INF}}$$

Soluble COD includes the colloidal and is expressed as COD_S as the sum of all soluble model fractions. It can be measured from glass-filtered COD according to:

$$COD_S = S_{BSA} + S_{BSP} + S_{BSC} + X_{SC} + S_{US} = COD_{GF,INF}$$

Particulate (non-colloidal) COD (COD_p or COD_X) is the sum of particulate (non-colloidal) COD, particulate unbiodegradable COD and active biomass in the influent (X_{BH} is often assumed to be zero) given by:

$$COD_X = X_{SP} + S_{UP} + X_{BH} \approx X_{SP} + S_{UP}$$

COD_X is calculated by subtracting the total COD and the soluble COD (COD_S) which is calculated based on the glass-filtered COD according to:

$$COD_X = TCOD - COD_S = TCOD_{INF} - COD_{GF,INF}$$

Soluble COD excluding the colloidal is expressed as COD_{MF} and measured by membrane filtering the COD according to:

$$COD_{MF} = S_{BSA} + S_{BSP} + S_{BSC} + S_{US} = COD_{MF,INF}$$

The total soluble readily biodegradable COD (the total of acetate, propionate and complex soluble COD but without slowly colloidal COD) is calculated from the measured micro-filtered fraction COD_{MF} according to:

$$S_{BS} = S_{BSA} + S_{BSP} + S_{BSC} = COD_{MF} - S_{US} = COD_{MF,INF} - COD_{GF,EFF}$$

The fraction of soluble readily biodegradable COD is given by:

$$F_{BS} = \frac{S_{BS}}{TCOD} = \frac{(S_{BSA}+S_{BSP}+S_{BSC})}{TCOD} = \frac{COD_{MF,INF}-COD_{GF,EFF}}{TCOD_{INF}}$$

Influent acetate (+ propionate) is direct measured as VFA:

$$S_{BSA} + S_{BSP} = VFA_{INF}$$

The fraction of readily biodegradable COD (which is acetate-COD) is given by:

$$F_{AC} = \frac{S_{BSA}}{S_{BS}} = \frac{S_{BSA}}{(S_{BSA}+S_{BSP}+S_{BSC})} = \frac{VFA_{INF}}{COD_{MF,INF}-COD_{GF,EFF}}$$

From the difference between the glass and membrane-filtered COD, the colloidal fraction can be calculated according to:

$$X_{SC} = COD_S - COD_{MF} = COD_{GF,INF} - COD_{MF,INF}$$

The last soluble parameter to be calculated is the complex soluble COD S_{BSC} calculated from the measurements according to:

$$S_{BSC} = COD_{MF} - S_{BSA} - S_{BSP} - S_{US} = COD_{MF,INF} - VFA_{INF} - COD_{GF,EFF}$$

The total soluble (readily and slow colloidal) biodegradable COD (S_S) is the total of acetate, propionate, complex soluble COD and colloidal COD (influent methanol is assumed to be zero) given by:

$$S_S = S_{BSA} + S_{BSP} + S_{BSC} + X_{SC}$$

And calculated according to:

$$S_S = COD_S - S_{US} = COD_{GF,INF} - COD_{GF,EFF}$$

The next Figure (Figure 45) shows the division of municipal wastewater Biodegradable COD (S_S) into constituent fractions.

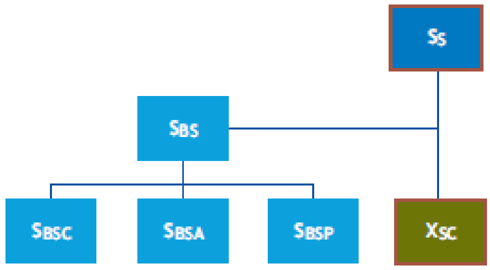


Figure 45: BioWin municipal wastewater soluble biodegradable COD (S_S). The fraction is measured by glass filtering and includes all soluble and colloidal material. Blue fractions are soluble and green fractions (colloidal) particulate.

The last two influent fractions that need to be calculated are related to the solids; particulate biodegradable COD and unbiodegradable COD, as seen before according to:

$$COD_X = X_{SP} + S_{UP} + X_{BH} \approx X_{SP} + S_{UP}$$

These fractions are estimated from the BOD measurements in the influent as explained later.

The BioWin influent tab the fraction of slowly biodegradable influent COD (which is particulate) is given by:

$$F_{XPS} = \frac{X_{SP}}{X_{SC} + X_{SP}}$$

VSS is often calculated from the ISS (Ash) measurement according to:

$$VSS = TSS - ISS$$

BioWin N and P calculations

Ammonia is given by:

$$NH_3 = F_{NA} \times TKN$$

Soluble unbiodegradable organic nitrogen is given by:

$$N_{US} = F_{NUS} \times TKN$$

Nitrogen from organisms present in the influent is calculated by the sum of the products of the various organism concentrations and their respective nitrogen fractions, i.e.:

$$Organisms, N = \sum Zb_x - f_{N,zbx}$$

Unbiodegradable particulate nitrogen is given by:

$$X_{IN} = F_{UP,N} \times F_{UP} \times TCOD$$

The remaining organic nitrogen is broken into particulate and soluble components. Particulate biodegradable organic nitrogen is given by:

$$X_{ON} = (TKN - NH_3 - N_{US} - X_{IN} - Organisms, N) \times F_{NOX}$$

Soluble biodegradable organic nitrogen is given by:

$$N_{OS} = (TKN - NH_3 - N_{US} - X_{IN} - Organisms, N) \times (1 - F_{NOX})$$

Similarly, an explanation of the fractionation of influent phosphorus is as follows. Soluble orthophosphate is given by:

$$PO_4 = F_{PO4} \times TP$$

Phosphorus from organisms present in the influent is calculated by the sum of the products of the various organism concentrations and their respective phosphorus fractions, i.e.:

$$Organisms, P = \sum Zb_x - f_{P,Zbx}$$

Unbiodegradable particulate phosphorus is given by:

$$X_{IN} = F_{UP,P} \times F_{UP} \times TCOD$$

The remaining particulate biodegradable organic phosphorus is given by:

$$X_{OP} = TP - PO_4 - X_{IP} - Organisms, P$$

Appendix C BioWin fractions input

Table 22: BioWin fractions input

Inlet of the MBR from point :	**1**	**2**	**3**	**4**	**5**	**6**
Fbs - Readily biodegradable (including Acetate) [gCOD/g total COD]	0.233	0.099	0.167	0.215	0.083	0.08
Fac - Acetate [gCOD/ g readily biodegradable COD]	0.347	0.076	0.23	0.136	0.381	0.533
Fxsp - Non-colloidal slowly biodegradable [gCOD/ g slowly biodegradable COD]	0.75	0.81	0.69	0.7	0.29	0.56
Fus - Unbiodegradable soluble [gCOD/ g total COD]	0.02	0.04	0.126	0.164	0.178	0.239
Fup - Unbiodegradable particulate [gCOD/ g total COD]	0.09	0.21	0.28	0.33	0.51	0.46
Fna - Ammonia [gNH3-N/gTKN]	0.69	0.575	0.561	0.48	0.535	0.212
Fnox - Particulate organic nitrogen [gN/g organic N]	0.5	0.5	0.5	0.5	0.5	0.5
Fnus - Soluble unbiodegradable TKN [gN/gTKN]	0.02	0.02	0.02	0.02	0.02	0.02
FupN - N:COD ratio for unbiodegradable part. COD [gN/gCOD]	0.035	0.035	0.035	0.035	0.035	0.035
Fpo4 - Phosphate [gPO4-P / gTP]	0.862	0.8	0.82	0.934	0.857	0.811
FupP - P:COD ratio for influent unbiodegradable part. COD [gP/gCOD]	0.011	0.011	0.011	0.011	0.011	0.011

Appendix D **Flux and permeability calculations**

Table 23: Flux and permeability calculations

Date	Q (L/h)	Q (m^3/d)	Mean permeate P. (bar)	Max. permeate P. (bar)	Jp Flux (l/h.m^2)	OP: Operation Permeability (l/h.m2.bar)	*Comments*
28/01/2016							***Inoculation***
29/01/2016	72	1.73	0.29	0.33	10.9	37.6	
30/01/2016	58	1.39	0.31	0.34	8.8	28.3	
31/01/2016	62	1.49	0.28	0.35	9.4	33.5	
1/02/2016	60	1.44	0.32	0.35	9.1	28.4	
2/02/2016	56	1.34	0.35	*0.38*	8.5	24.2	***Membranes cleaning***
3/02/2016	62	1.49	0.23	0.27	9.4	40.8	
4/02/2016	58	1.39	0.22	0.26	8.8	39.9	
5/02/2016	52	1.25	0.23	0.26	7.9	34.3	
6/02/2016	54	1.30	0.21	0.22	8.2	39.0	
7/02/2016	56	1.34	0.24	0.27	8.5	35.4	
8/02/2016	52	1.25	0.24	0.26	7.9	32.8	
9/02/2016	84	2.02	0.22	0.28	12.7	57.9	***Membranes cleaning***
10/02/2016	86	2.06	0.23	0.29	13.0	56.7	
11/02/2016	70	1.68	0.25	0.31	10.6	42.4	
12/02/2016	56	1.34	0.3	0.37	8.5	28.3	
13/02/2016	52	1.25	0.32	0.38	7.9	24.6	
14/02/2016	50	1.20	0.33	*0.4*	7.6	23.0	
15/02/2016							***Membranes cleaning***
16/02/2016	68	1.63	0.24	0.28	10.3	42.9	
17/02/2016	64	1.54	0.28	0.32	9.7	34.6	
18/02/2016	58	1.39	0.34	0.36	8.8	25.8	
19/02/2016	60	1.44	0.3	0.35	9.1	30.3	
20/02/2016	56	1.34	0.32	0.35	8.5	26.5	
21/02/2016	52	1.25	0.34	*0.37*	7.9	23.2	
22/02/2016							***Membranes cleaning***
23/02/2016	42	1.01	0.16	0.19	6.4	39.8	
24/02/2016	54	1.30	0.18	0.21	8.2	45.5	
25/02/2016	42	1.01	0.18	0.24	6.4	35.4	
26/02/2016	38	0.91	0.19	0.21	5.8	30.3	
27/02/2016	38	0.91	0.18	0.22	5.8	32.0	

28/02/2016	34	0.82	0.2	0.23	5.2	25.8	
29/02/2016	34	0.82	0.18	0.22	5.2	28.6	
1/03/2016	40	0.96	0.2	0.23	6.1	30.3	
2/03/2016	42	1.01	0.22	0.25	6.4	28.9	
3/03/2016	38	0.91	0.2	0.23	5.8	28.8	
4/03/2016	34	0.82	0.2	0.24	5.2	25.8	
5/03/2016	34	0.82	0.21	0.24	5.2	24.5	
6/03/2016	38	0.91	0.22	0.26	5.8	26.2	
7/03/2016	40	0.96	0.22	0.28	6.1	27.5	
8/03/2016	38	0.91	0.23	0.24	5.8	25.0	
9/03/2016	68	1.63	0.31	0.33	10.3	33.2	***Membranes cleaning and Valves adjusted (to more flow)***
10/03/2016	72	1.73	0.32	0.34	10.9	34.1	
11/03/2016	68	1.63	0.3	0.32	10.3	34.3	
12/03/2016	64	1.54	0.29	0.31	9.7	33.4	
13/03/2016	66	1.58	0.31	0.35	10.0	32.3	
14/03/2016	68	1.63	0.32	0.36	10.3	32.2	

Appendix E Results tables

Table 24: MBR influent and effluent characterization during Group 1 operational conditions

		Wed. 3/02			Thu. 4/02			Fri. 5/02			Sat. 6/02			Sun. 7/02		
		Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)
Treatment efficiency	COD	1430	121	91.5	10740	145	98.6	4100	89	97.8	3560	101	97.2	3960	96	97.6
	NH_4	73	12.5	82.9	28	14	50.0	58	31	46.6	56	33	41.1	57	28	50.9
	NO_2^-	0.159	10.3													
	NO_3^-	1.9	40													
	TN	149	95.2	36.1												
	BOD (mg/L)	816	56.3	93.1												
	TSS (mg/L)	545	0	100												
	pH	7.1	7.9													
	Total Coliforms (CFU/100mL)	>1.6 x10^6	3500	99.8												
	Fecal Coliforms (CFU/100mL)	>1.6 x10^6	330	99.98												
	TKN	146.9	44.9													
	TP															
	PO_4^-															
Control Parameters	MLSS (mg/l)	2460						5920								
	MLVSS (mg/L)	2340						5080								
	T air (°C)	27			27			28			26			31		
	T inside MBR (°C)	24.2			23.4			24.3			24.2			24.9		
	DO aerated	0.78			0.48			0.40			0.52			0.50		
	DO anoxic	0.00			0.00			0.00			0.00			0.00		
	Recirc. Ratio	2			2			2			2			2		
	Blower on (min)	5			5			5			5			5		
	Blower off (min)	15			15			15			15			15		
	Aeration valve opening	Quarter			Quarter			Quarter			Quarter			Quarter		
Comments		Sample not representative of the feeding of the MBR. It was teken at the first moment of MBR feed with excess of solids			Sample not representative of the feeding of the MBR. It was teken at the first moment of MBR feed with excess of solids			Sample not representative of the feeding of the MBR. It was teken at the first moment of MBR feed with excess of solids			Sample not representative of the feeding of the MBR. It was teken at the first moment of MBR feed with excess of solids			Sample not representative of the feeding of the MBR. It was teken at the first moment of MBR feed with excess of solids		
		Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2		
		Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min; with air valves a quarter opened			Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min; with air valves a quarter opened			Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min; with air valves a quarter opened			Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min; with air valves a quarter opened			Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min; with air valves a quarter opened		
		GROUP 1														

Table 25: MBR influent and effluent characterization during Group 2 operational conditions

		Mon. 8/02			Tue. 9/02			Wed. 10/02			Sat. 13/02		
		Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)
Treatment efficiency	COD	7740	152	98.0	21280	144	99.3	2430	123	94.9			
	NH_4	63	3	95.2	37	3	91.9	81	4	95.1			
	NO_2^-							0.305	8.4				
	NO_3^-							2.8	33				
	TN							135	51.8	61.6			
	BOD (mg/L)							819	47.8	94.2			
	TSS (mg/L)							1125	0	100			
	pH							7.3	8.2				
	Total Coliforms (CFU/100mL)												
	Fecal Coliforms (CFU/100mL)												
	TKN							131.9	10.4				
	TP												
	PO_4^-												
Control Parameters	MLSS (mg/l)	6140									12480		
	MLVSS (mg/L)	5100									10280		
	T air (°C)	28			30			25			27		
	T inside MBR (°C)	24.8			25.2			22.2			24.3		
	DO aerated	0.92			1.12			1.46			1.94		
	DO anoxic	0.00			0.00			0.00			0.00		
	Recirc. Ratio	2			2			2			2		
	Blower on (min)	Whole day			Whole day			Whole day			Whole day		
	Blower off (min)	---------			---------			---------			---------		
	Aeration valve opening	Quarter			Quarter			Quarter			Quarter		
Comments		Sample not representative of the feeding of the MBR. It was teken at the first moment of MBR feed with excess of solids			Sample not representative of the feeding of the MBR. It was teken at the first moment of MBR feed with excess of solids			Sample not representative of the feeding of the MBR. It was teken at the first moment of MBR feed with excess of solids					
		Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2		
		Aeration "ON" the whole day, with valves a quarter opened			Aeration "ON" the whole day, with valves a quarter opened			Aeration "ON" the whole day, with valves a quarter opened			Aeration "ON" the whole day, with valves a quarter opened		
		GROUP 2											

Table 26: MBR influent and effluent characterization during Group 3 operational conditions

		Sun. 14/02			Mon. 15/02			Tue. 16/02			Wed. 17/02			Thu. 18/02		
		Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)
Treatment efficiency	COD							1140	50	95.6						
	NH_4							50	34	32.0						
	NO_2^-															
	NO_3^-															
	TN							88.1	46.7	47.0						
	BOD (mg/L)							330	39	88.2						
	TSS (mg/L)							1483	0	100						
	pH							7.15	8.3							
	Total Coliforms (CFU/100mL)							5.4 x10^5	1300	99.8						
	Fecal Coliforms (CFU/100mL)							5.4 x10^5	930	99.83						
	TKN							88.1	46.7							
	TP															
	PO_4^-															
Control Parameters	MLSS (mg/l)				14830											
	MLVSS (mg/L)				12560											
	T air (^oC)				26			32								
	T inside MBR (^oC)				23.5			25.1								
	DO aerated				0.96			0.85								
	DO anoxic				0.00			0.00								
	Recirc. Ratio	2			2			2			2			2		
	Blower on (min)	Whole day			Whole day			Whole day			Whole day			Whole day		
	Blower off (min)	---------			---------			---------			---------			---------		
	Aeration valve opening	Barely			Barely			Barely			Barely			Barely		
Comments		Solids high			Solids high			Solids high			Solids high			Solids high		
		Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2		
		Aeration "ON" the whole day, but with valves barely open because liquid started to go out from the MBR			Aeration "ON" the whole day, but with valves barely open because liquid started to go out from the MBR			Aeration "ON" the whole day, but with valves barely open because liquid started to go out from the MBR			Aeration "ON" the whole day, but with valves barely open because liquid started to go out from the MBR			Aeration "ON" the whole day, but with valves barely open because liquid started to go out from the MBR		
								No Slaughter this day								
		GROUP 3														

Table 27: MBR influent and effluent characterization during Group 4 operational conditions

		Fri. 19/02			Mon. 22/02			Tue. 23/02			Wed. 24/02			Thu. 25/02		
		Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)
Treatment efficiency	COD							2260	80	96.5	1760	104	94.1			
	NH_4							57	35	38.6	67	21	68.7			
	NO_2^-															
	NO_3^-															
	TN							94.05	48.4	48.5	125	50.7	59.4			
	BOD (mg/L)										686	43	93.7			
	TSS (mg/L)										834	0	100			
	pH										7.5	8.4				
	Total Coliforms (CFU/100mL)															
	Fecal Coliforms (CFU/100mL)															
	TKN								48.4			50.7				
	TP															
	PO_4^-															
Control Parameters	MLSS (mg/l)				1805			2556			5225			6525		
	MLVSS (mg/L)				1560			1825			4533			5392		
	T air (^oC)				29			29			30			22		
	T inside MBR (^oC)				23.5			24.6			24.5			21.0		
	DO aerated				0.82			0.75			1.20			1.13		
	DO anoxic				0.00			0.00			0.00			0.00		
	Recirc. Ratio	2			2			2			2			2		
	Blower on (min)	Whole day			Whole day			Whole day			Whole day			Whole day		
	Blower off (min)	---------			---------			---------			---------			---------		
	Aeration valve opening	Barely			Barely			Barely			Barely			Barely		
Comments		Sludge wasted because a high value of MLSS (More than half of thereactor)			Solids inside the MBR growing			Solids inside the MBR growing			Solids inside the MBR growing			Solids inside the MBR growing		
		Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2			Rec. Ratio = 2		
		Aeration "ON" the whole day, but with valves barely open			Aeration "ON" the whole day, but with valves barely open			Aeration "ON" the whole day, but with valves barely open			Aeration "ON" the whole day, but with valves barely open			Aeration "ON" the whole day, but with valves barely open		
		GROUP 4														

Table 28: MBR influent and effluent characterization during Group 5 operational conditions

		Fri. 26/02			Sat. 27/02			Mon. 29/02			Tue. 1/03			Wed. 2/03		
		Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)
Treatment efficiency	COD							1785	73	95.9	1820	64	96.5	1430	78	94.5
	NH_4							52	1.35	97.4	48	0.82	98.3	74	0.64	99.1
	NO_2^-								2.72			3.8			3.5	
	NO_3^-								17			28			26	
	TN							79.0	39	50.7	80.2	48.9	39.0	121.4	45.2	62.7
	BOD (mg/L)															
	TSS (mg/L)															
	pH							7	7.9							
	Total Coliforms (CFU/100mL)															
	Fecal Coliforms (CFU/100mL)															
	TKN								19.3			17.1			15.7	
	TP															
	PO_4^-															
Control Parameters	MLSS (mg/l)				10600			11710								
	MLVSS (mg/L)															
	T air (°C)				22			23			19			21		
	T inside MBR (°C)				21.1			21.3			21.0			21.1		
	DO aerated				2.45			3.50			3.24			4.80		
	DO anoxic				0.02			0.11			0.08			0.10		
	Recirc. Ratio	4			4			4			4			4		
	Blower on (min)	Whole day			Whole day			Whole day			Whole day			Whole day		
	Blower off (min)	---------			---------			---------			---------			---------		
	Aeration valve opening	Full			Full			Full			Full			Full		
Comments		Solids inside the MBR growing			Solids inside the MBR growing			Sludge wasted 50L/day			Sludge wasted 50L/day			Sludge wasted 50L/day		
		Rec. Ratio = 4			Rec. Ratio = 4			Rec. Ratio = 4			Rec. Ratio = 4			Rec. Ratio = 4		
		Aeration "ON" the whole day, with valves full opened			Aeration "ON" the whole day, with valves full opened			Aeration "ON" the whole day, with valves full opened			Aeration "ON" the whole day, with valves full opened			Aeration "ON" the whole day, with valves full opened		
		GROUP 5														

Table 28 (Continue): MBR influent and effluent characterization during Group 5 operational conditions

		Thu. 3/03			Mon. 7/03			Tue. 8/03			Wed. 9/03			Thu. 10/03		
		Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)	Infl.	Effl.	Effic.(%)
Treatment efficiency	COD	1640	70	95.7				1500	58	96.1	1140	74	93.5			
	NH_4	84	1	98.8				58	0.4	99.3	71	0.2	99.7			
	NO_2^-	1.5	6					0.271	4.46		0.2	2.46				
	NO_3^-	0.1	17					1.5	32		1.6	24				
	TN	147.6	28.3	80.8				98	46.3	52.8	115	46.3	59.7			
	BOD (mg/L)	577	<30	> 94.8												
	TSS (mg/L)	778	0	100												
	pH	7.25	8.11													
	Total Coliforms (CFU/100mL)	2.8 x10^8	1400	99.9995												
	Fecal Coliforms (CFU/100mL)	1.4 x10^8	320	99.9998												
	TKN	146.0	5.3					96.2	9.8		113.2	19.8				
	TP	21.4	14.6	31.8				22.4	15.3		22.3	14.3	35.9			
	PO_4^-	19.8	13.2	33.3				18.9	13.2		19.9					
Control Parameters	MLSS (mg/l)	12020			12330			11170			11120					
	MLVSS (mg/L)	10970			11590			10320			10490					
	T air (°C)	20														
	T inside MBR (°C)	21.1														
	DO aerated	2.84						1.8			3.4					
	DO anoxic	0.03						0.0			0.04					
	Recirc. Ratio	4			4			4			4			4		
	Blower on (min)	Whole day			Whole day			Whole day			Whole day			Whole day		
	Blower off (min)	---------			---------			---------			---------			---------		
	Aeration valve opening	Full			Full			Full			Full			Full		
Comments		Sludge wasted 50L/day			Sludge wasted 50L/day			Sludge wasted 50L/day			Sludge wasted 50L/day			Sludge wasted 50L/day		
		Rec. Ratio = 4			Rec. Ratio = 4			Rec. Ratio = 4			Rec. Ratio = 4			Rec. Ratio = 4		
		Aeration "ON" the whole day, with valves full opened			Aeration "ON" the whole day, with valves full opened			Aeration "ON" the whole day, with valves full opened			Aeration "ON" the whole day, with valves full opened			Aeration "ON" the whole day, with valves full opened		
					DO meter broken			DO meter broken			DO meter broken			DO meter broken		
		GROUP 5														

Table 29: MBR influent and effluent characterization during Group 6 operational conditions

		Fri. 11/03			Sat. 12/03			Sun. 13/03			Mon. 14/03		
		Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)	Influent	Effluent	Effic.(%)
Treatment efficiency	COD										960	68	92.9
	NH_4										65	6.2	90.5
	NO_2^-											0.4	
	NO_3^-										1.4	6	
	TN										108	23.8	78.0
	BOD (mg/L)										380	<30	>92.1
	TSS (mg/L)										632	0	100
	pH										7.6	8.23	
	Total Coliforms (CFU/100mL)												
	Fecal Coliforms (CFU/100mL)												
	TKN										106.6	17.4	
	TP										23.1	15.2	34.2
	PO_4^-										20.3	13.5	
Control Parameters	MLSS (mg/l)										11870		
	MLVSS (mg/L)										10930		
	T air (^oC)										25		
	T inside MBR (^oC)										23.5		
	DO aerated										0.64		
	DO anoxic										0.00		
	Recirc. Ratio	4			4			4			4		
	Blower on (min)	5			5			5			5		
	Blower off (min)	15			15			15			15		
	Aeration valve opening	Full			Full			Full			Full		
Comments		Sludge wasted 50L/day			Sludge wasted 50L/day			Sludge wasted 50L/day			Sludge wasted 50L/day		
		Rec. Ratio = 4			Rec. Ratio = 4			Rec. Ratio = 4			Rec. Ratio = 4		
		Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min, with valves full opened			Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min, with valves full opened			Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min, with valves full opened			Cycles of aeration "ON" during 5 minutes and "OFF" during 15 min, with valves full opened		
		DO meter broken			DO meter broken			DO meter broken			DO measured at laboratory		
		GROUP 6											