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Performance of a submerged membrane bioreactor for wastewater mimicking fish meal processing effluent

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Abstract. The objective of this work was to analyze organic matter removal, nitrification, biomass growth and membrane fouling in a submerged flat-sheet membrane bioreactor, fed with synthetic wastewater, of similar composition to the effluents generated in a fish meal industry. After biomass acclimatization with saline conditions of 12 gNaCl/L and COD/N ratio of 15 in the bioreactor, results showed that the organic matter removal was higher than 90%, for all organic loading rates (0.8, 1, 1.33 and 2 gCOD/L·d) and nitrogen loading rates (0.053, 0.067, 0.089 and 0.133 gN/L·d) tested during the study. However, nitrification was only carried out with the lowest OLR (0.8 gCOD/L·d) and NLR (0.053 gN/L·d). An excessive concentration of organic matter in the wastewater appears as a limiting factor to this process' operating conditions, where nitrification values of 65% were reached, including nitrogen assimilation to produce biomass. The analysis of membrane fouling showed that the bio-cake formation at the membrane surface is the most impacting mechanism responsible of this phenomenon and it was demonstrated that organic and nitrogen loading rates variations affected membrane fouling rate.

Keywords: membrane bioreactor; nitrification; aerobic biodegradation; saline wastewater; fouling

1. Introduction

In many countries with access to a coast such as Canada, China, Thailand, India, Mexico or Sweden, an increasing activity of the industries producing fish meal, generate a large amount of polluting effluents that are in most cases still discharged directly to the sea without any treatment. This is the case of the fish meal industries of Guaymas, in the state of Sonora (Mexico), where it is estimated that 1495 m^3/d of sewage is discharged into the sea (DGPOT, 2014). This type of effluent is characterized by a high concentration of nitrogen, organic matter and salt, in addition to various toxic micropollutants (Chowdhury *et al*. 2010, Muthukumaran and Baskaran 2013).

Therefore, the discharge of these wastewater without previous treatment causes an imbalance of the physical, chemical and biological properties of sea water. These properties are affected by changes in salinity, decrease in dissolved oxygen, increase in biological oxygen demand (BOD), chemical oxygen demand (COD) and nutrients, high sulfur and ammonium loading rates and temperature increase, which can lead to eutrophication, avoiding the rapid oxygenation of water and leading to the subsequent death of living organisms (Aloui *et al*. 2009, Sun *et al*. 2009). Consequently, in light of the global fish consumption increase in developing and developed countries (Chowdhury *et al*. 2010), proper and efficient management of the wastewater generated by this industry is necessary.

Although it could be found in the literature experiments and methodologies for the treatment of related effluents, there is limited information about the aerobic biological treatment of wastewater of marine products that focus on the removal of organic and nitrogenous matter in the presence of a high saline concentration (Lefebvre and Moletta 2006, Reid *et al*. 2007, Jiang *et al*. 2016, Chen *et al*. 2017). In this regard, Cristóvão *et al*. (2015), studied the fish canning wastewater treatment by activated sludge; however, they did not study nitrification. Boopathy *et al*. (2007), worked with effluents from the shrimp processing industry and they have operated an SBR reactor (sequential batch reactor) to nitrify and denitrify the nitrogen. Similarly, Fontenot *et al*. (2007), conducted studies in an upflow sludge blanket filtration (USBF) reactor where they were treating effluents from an anaerobic digester in the fish canning industry, like Huiliñir *et al*. (2011), who worked with wastewater from salmon industry in a biofilm reactor, but their studies were focused only on nitrogen removal. Moreover, Ruíz *et al*. (2006), studied effluents from the fish processing industry with traditional anaerobic and aerobic biological methods, showing good results in the removal efficiencies of organic components, but their use is limited by the high nitrogen loading rate and the presence of salt, causing the need of tertiary treatment to the wastewater treatment process.

An alternative treatment is to use submerged membrane

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bioreactors (sMBR), a technology which is currently considered as one of the most important innovation in wastewater treatment, as it minimizes the problems of separation of solid-liquid phases, which are found in activated sludge systems (Fangang *et al*. 2012, Aslam *et al* 2017). They also have the advantage of working with a longer sludge residence time, allowing a lower production of sludge; for that reason, wastewater can be treated in smaller spaces than those used in conventional systems and, in addition, the effluent obtained has a better quality as conventional process effluents and can be reused for different applications (Hao *et al*. 2015, Judd 2016).

There have been fewer sMBR studies for the treatment of fish processing wastewater such as Sridang *et al*. (2008), who reported that the biomass from membrane bioreactors can be effectively adapted to the wastewater from an actual process of seafood with low salt concentration. Moreover, Artiga *et al*. (2008) and Cheng *et al*. (2010), treated wastewater from fish canning factories with high salt concentrations in hybrid MBR reactors, but with a very low nitrogen loading rate. Also, Hong *et al*. (2013), studied the effect of salt on effluents produced in aquaculture with low concentrations of ammonium in a sMBR reactor and recently, Jemli *et al.* (2015), studied the biological treatment of fish processing wastewater by a continuous stirred tank reactor and membrane bioreactor at different organic loading rates; however, the treatment of wastewater with high salt concentration and high nitrogen loading rates, like those produced by the fish meal industry, has not been thoroughly studied in this kind of reactors.

This work presents the analysis of organic matter removal, nitrification, biomass growth and membrane saturation in a submerged membrane bioreactor using synthetic waters like those discharged by the fish meal industries. The objective was to determine the effectiveness in removal of these pollutants in aerobic conditions and the feasibility of using this type of advanced process for its treatment.

2. Material and methods

2.1 Experimental set-up

Experiments were carried out on a lab-scale submerged membrane bioreactor (Fig. 1) with an operating volume of 30 L, where a flat-sheet microfiltration membrane module (A3 Company, U.S.A.) was immersed directly into the bioreactor. The membrane module was made of polyvinylidene difluoride (PVDF) with a pore size of 0.14 µm and a surface area of 0.258 m^2. Filtration through the membrane was carried out by a permeate pump, creating a depression between the module and the pump. The transmembrane pressure (TMP) was monitored by a negative manometer located at the permeated site to indicate the evolution of membrane fouling. In addition, aeration was provided at the bottom of the reactor where the dissolved oxygen was always maintained above 4 mg O_2/L in order to avoid oxygen limitation for biomass growth. Temperatures in the reactor were maintained within the 15-25°C range, with pH varying between 7 and 7.8. The sMBR

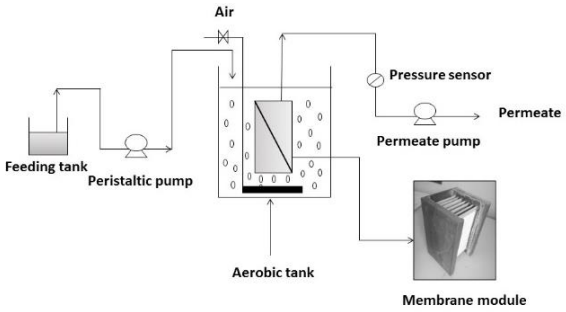

Fig. 1 Schematic diagram of the lab-scale submerged membrane bioreactor

Table 1 Fish processing wastewater composition

Parameter	Concentration (g/L)
COD	92.2 ± 10.5
BOD_5	28.7 ± 2.1
Conductivity (mS/cm)	13.38 ± 3.98
TDS (%)	0.122 ± 0.052
Fats and Oils	23.72 ± 13.99
pH	6.06 ± 0.06
$N\text{-}NH_3$	0.552 ± 0.194
N-Org	6.633 ± 1.540
FSS	13.5 ± 3.5
VSS	53.0 ± 10.0
TSS	67.0 ± 14.0
COD/N	15.0 ± 4.3

was operated with 5 days of hydraulic retention time (HRT) and 40 days of sludge retention time (SRT). Wasting sludge was removed daily from the aerobic tank to maintain the predetermined SRT and to control the solid concentration increase inside the reactor.

2.2 Wastewater composition

A synthetic wastewater of similar composition as that typically discharged by the fish meal industry was used. To know its composition and physic-chemical properties, the wastewaters were collected from a factory in Guaymas (Mexico) three times per year and they were analyzed by standard methods (APHA, 2012). Table 1 shows the effluent average characteristics from the fish meal industry. The substrate for synthetic wastewater was proposed by Rene *et al*. (2008), where $Na_2MoO_4 \cdot 2H_2O$ was discarded. Glucose and ammonium chloride were used as organic matter and ammonia source respectively and NaCl was added to mimic the salinity of a fish meal industry effluent. The synthetic wastewater composition was (g/L): KH_2PO_4 (0.220), $MgCl_2 \cdot 6H_2O$ (0.050), $CaCl_2 \cdot 2H_2O$ (0.065), $NaHCO_3$ (2.5), NaCl (1-12), $C_6H_{12}O_6$ (3.752-7.504) and NH_4Cl (0.475-2.036).

2.3 Biomass acclimatization

In order to adapt biomass to fish processing wastewater

Table 2 Acclimatization operating conditions

Time (d)	NaCl (g/L)	OLR (gCOD/L·d)	OL (gCOD/gVSS·d)	% COD Removal	NLR (gN/L·d)	% Nitrification	VSS (g/L)	COD/N
1-25	1-2	2	0.25	96	0.080	91	8	25
26-33	3-5	2	0.20	98	0.129	92	10	15
34-53	6-10	4	0.26	99	0.266	82	15	15
54-79	11-12	1.33	0.15	99	0.086	97	9	15

Table 3 Operating condition of the membrane bioreactor

Phase	Time (d)	OLR (gCOD/Ld)	NLR (gN/Ld)	NaCl (g/L)	COD/N
I	80-96	1.33	0.089	12	15
II	97-124	2	0.133	12	15
III	125-180	1.33	0.089	12	15
IV	181-240	0.8	0.053	12	15
V	241-280	1	0.067	12	15

characteristics (COD/N of 15 and 12 g/L of salt concentration), a start-up procedure of 79 days was performed before conducting membrane experiments. The biomass acclimatization was carried out in an activated sludge reactor. An operating volume of 30 L and hydraulic retention time of 3 days. The reactor was inoculated with 10 L of aerobic biomass with 3.8 gTSS/L and 3.01 gVSS/L from a Municipal Wastewater Treatment Plant. The temperatures in the reactor were maintained within the 15-18°C range, with neutral pH and 4 mgO_2/L aeration. The reactor was fed with synthetic wastewater described in 2.2. During the first 53 days of acclimatization, organic loading rate (OLR), nitrogen loading rate (NLR) and salt concentration, were progressively increased, to adapt the consortia to the introduced effluent. Except in the last step (day 54 to 79), where OLR and NLR had to be reduced, due to nitrification problems. After nitrification efficiency was stabilized, influent salt concentration was increased to obtain the required concentration (12 g NaCl/L). Acclimatization operating conditions are summarized in Table 2.

2.4 Operating conditions

Experimentation with a submerged membrane bioreactor started from day 80 to day 280, once the stationary conditions were obtained during the acclimatization period. Operating conditions of each stage are shown in Table 3.

2.5 Analytical methods

The system performance was followed by evaluating substrate degradation, biomass production and biomass characteristics in terms of microbial community by respirometric measurements. Effluent samples were taken from the MBR tank to measure COD, NH_4^+-N, NO_2^--N and NO_3^--N concentrations with spectrophotometric analysis on a Hach 2500 (Hach, Loveland, CO, U.S.A.).

Approximately once a week, sludge samples were taken to analyze the total suspended solids (TSS) and volatile suspended solids (VSS) based on standard methods (APHA, 2012).

2.6 Sludge activity in sMBR

To measure the respirometric activity of cells, the sludge was transferred into sealed bottles (250 mL) where the dissolved oxygen was monitored using an OD sensor (WTW 340i) which allowed to calculate the oxygen uptake rate (OUR). The operating procedure first determined the endogenous OUR (OURendo) by monitoring the dissolved oxygen after 24 hours of aeration without any external substrate input. After the dissolved oxygen concentration decreased, $NaClO_3$ (Nitrobacter inhibitors) was added to the sludge sample and OUR determination was performed. After the dissolved oxygen decreased again, allylthiourea (ATU) (Nitrosomonas inhibitors) was added to the mixed liquor sample and sodium acetate solution trihydrate was injected as the organic carbon source, the remaining OUR (OUR_{COD}) was measured, which represents the oxygen consumption due to the oxidation of the carbonaceous substrate oxidation. Oxygen uptake rate due to nitrification, called OUR_{NH4} was determined by addition of ammonium chloride as the source of NH_4 for Nitrosomonas bacteria and the solution of $NaClO_3$ as an inhibitor of Nitrobacter bacteria (Wang *et al*. 2005, Lahdhiri *et al*. 2015).

2.7 Membrane cleaning

A specific procedure which consisted of gradually removing the different layers of fouling (rinsing, wiping, chemical cleaning) and measuring their respective hydraulic resistances was used when TMP reached 35 kPa. Then, the fouling intensity could be linked to reversible deposit (R_{cake}), biofilm ($R_{biofilm}$) and non-reversible internal fouling ($R_{adsorption}$) (Lahdhiri *et al*. 2017).

Total membrane resistance was calculated according to Darcy's law, which expresses the flux in terms of pressure change, viscosity and resistance (Eq. 1).

$$\frac{TMP}{J_P} = \mu \times R_t \quad (1)$$

Where, J_P is the permeation flux ($m^3/m^2 \cdot s^1$), TMP is the transmembrane pressure (Pa), μ is the permeate viscosity at the filtration temperature (Pa·s) and R_t is the total resistance to filtration (m^{-1}).

The fouled membrane resistance R_t (Eq. 2) was considered as the sum of the pure membrane resistance R_m, resistance due to cake deposits R_{cake}, resistance due to biofilm formation $R_{biofilm}$ and resistance due to adsorption of molecules onto the membrane surface and internal pore wall $R_{adsorption}$ (Lee *et al*. 2016).

$$R_t = R_m + R_{cake} + R_{biofilm} + R_{adsorption} \quad (2)$$

The membrane cleaning procedure was carried out in order to know the membrane fouling origins and consisted of three steps. First, the fouled membrane module was scrubbing with a soft sponge to remove compounds attached on the membrane surface. Distilled water was then filtered with the scrubbed membrane to calculate its resistance after scrubbing ($R_{scrubbing}$). After, rinsing was then carried out for 2 hours with distilled water to remove any compounds mechanically blocking the pores. Distilled water was then filtered with the rinsed membrane to calculate its resistance after rinsing ($R_{rinsing}$). Finally, chemical cleaning was used in the third step. Membranes were then soaked successively in a 4 g/L sodium hydroxide solution, 22 g/L of citric acid solution and 0.2 g/L of sodium hypochlorite solution (2 h for each solution). $R_{chemical}$ was then obtained after filtering distilled water. If the chemical cleaning was sufficient, the final membrane resistance $R_{chemical}$ would have to be equal to the intrinsic membrane resistance R_m (Thongmak *et al*. 2015).

The specific hydraulic resistances due to each fouling origin can be expressed and calculated, respectively, as follows.

$$R_{cake} = R_{total} - R_{scrubbing} \quad (3)$$

$$R_{biofilm} = R_{scrubbing} - R_{rinsing} \quad (4)$$

$$R_{adsorption} = R_{rinsing} - R_m \quad (5)$$

3. Results and discussions

3.1 Biological performances of the system

3.1.1 Biomass growth

Fig. 2 shows the evolution of VSS, FSS and TSS concentration at different OLRs during the whole experiment, keeping constant the main characteristics of the fish meal industry wastewater, such as COD/N ratio of 15 and 12 g/L of salt concentration.

The results obtained shows a progressive increase in TSS and VSS concentrations, reaching levels close to 12.4 g/L and 11 g/L respectively, when the OLR had an increase from 1.33 gCOD/L to 2 gCOD/L·d. This increase in biomass is linked to the carbon source conversion for the growth and reproduction of heterotrophic microorganisms, based on Eq. (6). In addition, when the organic loading rate was reduced in phase III, solids concentration remained constant and the same occurred when the OLR was reduced again to 0.8 gCOD/L·d due to the growth of heterotrophic microorganisms and nitrogen assimilation to produce autotrophic biomass, based on Eq. (7). Afterwards, a slight decrease of solids occurred, when the organic loading rate was increased to 1 gCOD/L·d (Phase V), obtaining concentrations of 11 gTSS/L and 10 gVSS/L at day 280.

$$C_6H_{12}O_6 + 2.5O_2 + 0.7NH_3 \rightarrow 0.7C_5H_7O_2N + 2.5CO_2 + 4.6H_2O \quad (6)$$

$$NH_4^+ + 1.863O_2 + 0.098CO_2 \rightarrow 0.0196C_5H_7O_2N + 0.98NO_3^- + 1.98H^+ + 42H_2O \quad (7)$$

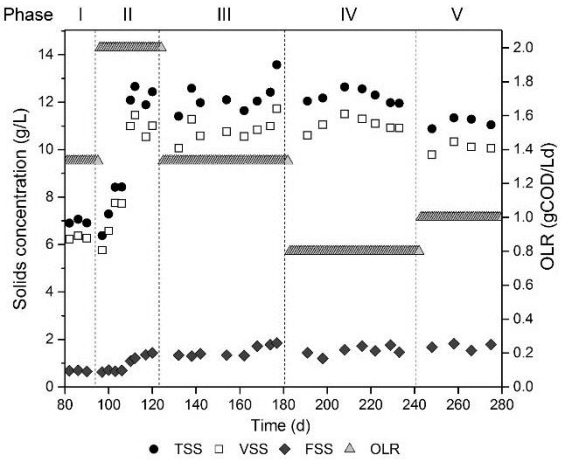

Fig. 2 Biomass concentration and OLR during the experimental period

Garzón-Zúñiga *et al*. (2005), studied nitrogen transformation mechanism in an organic media aerated biofilter and they concluded that 0.036 and 0.02 grams of nitrogen are assimilated to produce heterotrophic and nitrifying biomass, respectively. In the aerobic processes, both organic and nitrogenous matters are assimilated to produce biomass.

3.1.2 Organic matter removal

The evolution of the COD concentration in permeate at different organic loading rates is presented in Fig. 3. During the first phase with the membrane bioreactor (16 days of operation), COD concentration in the permeate were kept constant at 0.03 gCOD/L with an OLR of 1.33 gCOD/L·d. Based on the influent COD concentration, the corresponding COD removal efficiency was around 99%. From day 97 to 124, the OLR increased to 2 gCOD/L·d, therefore, COD concentration of the effluent increased progressively until reaching levels close to 0.83 gCOD/L (COD removal efficiency of 90%), for this reason, it was decided to reduce the organic loading rate again to 1.33 gCOD/L·d, to recover better organic matter removal. After this period, the OLR was reduced due to the high ammonium concentration in permeate (shown below) and a COD/N ratio fixed at 15, resulting an insignificant increase of COD concentrations in the effluent. Finally, during the last 40 days of the experiment (Phase V), the organic loading rate was increased to 1 gCOD/L·d, obtaining a concentration of 0.23 gCOD/L in the permeate and a 95% COD removal efficiency.

Removal of carbonaceous matter is analogous to removal efficiencies observed by Sridang *et al*. (2008), treating effluents from the fish processing industry in a MBR reactor, which was approximately 90%, and by Sun *et al*. (2010), using a membrane bioreactor system under different operating conditions for the treatment of municipal effluents, which was higher than 95%. Similarly, these values are like those obtained by Ahn *et al*. (2006), Najafpour *et al*. (2006) and Khannous *et al*. (2003) for the fish processing wastewater in a combined system (anaerobic upflow bed filter and aerobic membrane bioreactor), an aerobic rotating biological contactor reactor

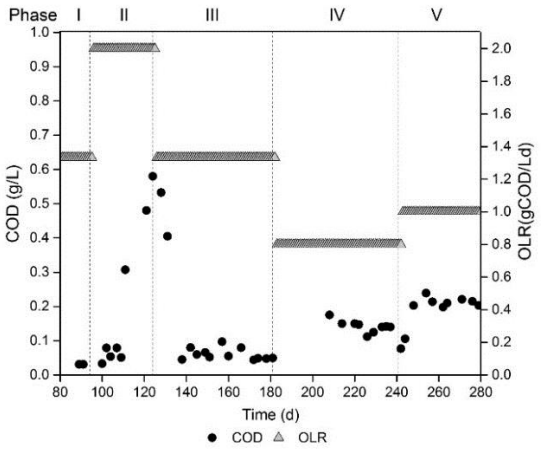

Fig. 3 COD concentration in permeate at different OLRs during the experiment

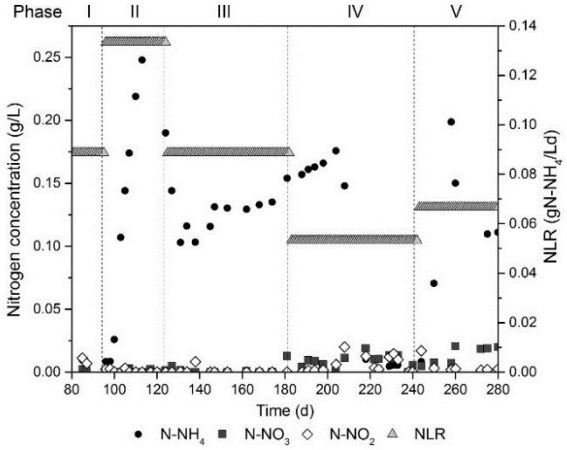

Fig. 4 Nitrogen compounds in permeate at different NLRs during the experiment

and an activated sludge reactor, respectively.

3.1.3 Nitrification

Fig. 4 shows nitrogen compounds at different nitrogen loading rates (NLRs), maintaining a COD/N ratio of 15. During the first 16 days of submerged membrane bioreactor operation with a NLR of 0.089 gNH_4-N/L·d, nitrification was 99%; however, in phase II with a NLR of 0.133 gNH_4-N/L·d, nitrification was reduced to 38%, which lead to ammonium concentrations in the permeate of 0.249 gN/L. Thus, in phase III, nitrogen loading rate was decreased to 0.089 gNH_4-N/L·d, in order to get better nitrification efficiency; however, as ammonium concentration in the permeate continued to increase, NLR was reduced to 0.053 gNH_4-N/L·d. During this period (Phase IV), a low ammonium concentration and an increase of nitrate and nitrite concentration were measured in the effluent, demonstrating that the nitrification process was carried out based on reaction (4) and showing the best reactor stability throughout the experiment. In the last 40 days of the reactor, the nitrogen loading rate was increased to 0.067 gNH_4-N/ L·d and concentrations of 0.11 gNH_4-N/L and 0.020 gNO_3-N/L were obtained in the permeate, with a nitrification efficiency of 65%, without nitrite accumulation. With these results, the sensitivity of nitrifying bacteria to high nitrogen loading rate and to high organic matter concentrations in the effluent can be verified.

The results obtained show the importance of microorganisms' acclimatization to allow the wastewater treatment of an effluent with a suitable COD/N ratio for nitrification. As reported by Carrera *et al*. (2004) and Del Pozo *et al*. (2010), there are several factors, which affect the nitrification process, one of the most important is the substrates concentration (expressed in COD/N ratio), since it determines the relation between the heterotrophic/autotrophic population present in biological systems of wastewater treatment plants. When the organic matter concentration is elevated (high COD/N ratio), heterotrophic bacteria dominate the process, therefore, it could lead to an inhibition of nitrifying bacteria activity and cause a reduction in nitrification efficiency. The same happened, with Cao *et al*. (2016), who concluded that at low COD/N ratios, the oxygen competition between heterotrophic and nitrifying bacteria is minimal, favouring the nitrification process. In addition, Komorowska-Kaufman *et al*. (2006) have established that with COD/N ratios less than 4, nitrification is enhanced with an effectiveness greater than 95%.

Regarding to salt concentration within the biological process of the experiment, it is known that elevated salt concentrations have a negative effect on the organic matter, nitrogen and phosphorus biotransformation due to high salinity can raise osmotic pressure, separate microbial cell plasma, at the same time it can reduce the metabolic enzyme activity, destroy the structure of microbial enzymes and inhibit the growth of microorganisms (Hong *et al*. 2013, Zhang *et al*. 2017). It is also known that nitrification processes are the most sensitive to high saline concentrations, however, He *et al*. (2017) and Wang *et al*. (2017), reported that after a gradual acclimatization of biomass to saline conditions, high nitrification efficiencies can be obtained. In addition, Dincer and Kargi (1999) and Vendramel *et al*. (2011) have investigated the effect of salt concentration on nitrification in different types of bioreactors and they found that nitrification is not affected when the sodium chloride concentration of the effluent is less than 12 g/L. On the other hand, Panswad and Anan (1999) found that nitrification is inhibited at about 55% with 30 g/L of salt. Therefore, as the salt concentration handled in this study is lower than those previously reported, it can be assumed that it has no significant effect on the substrate biodegradation.

3.1.4 Biological activity

Biomass oxygen requirements to carry out the endogenous respiration and exogenous respiration in the membrane bioreactor, are shown in Fig. 5. Although the significant differences of the OUR values obtained during the experiment are evident, it can be observed that the endogenous needs were maintained around 0.5 kgO_2/ m^3·d through the 200 days of experimentation, showing an apparent stability of the biomass activity. Regarding to the exogenous requirements, oxygen consumption rates of heterotrophic microorganisms (OUR_{COD}) ranged from 0.73

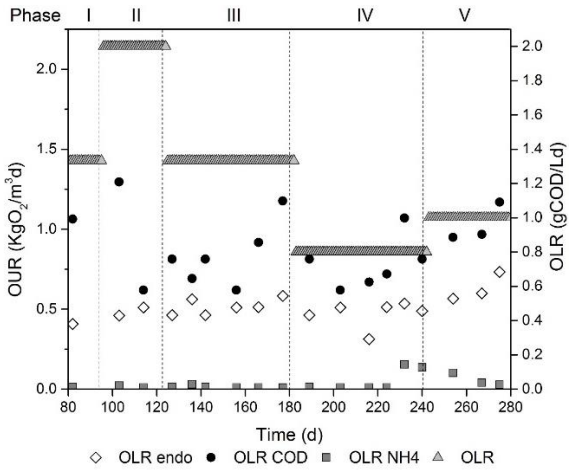

Fig. 5 OUR endogenous and exogenous in the MBR reactor

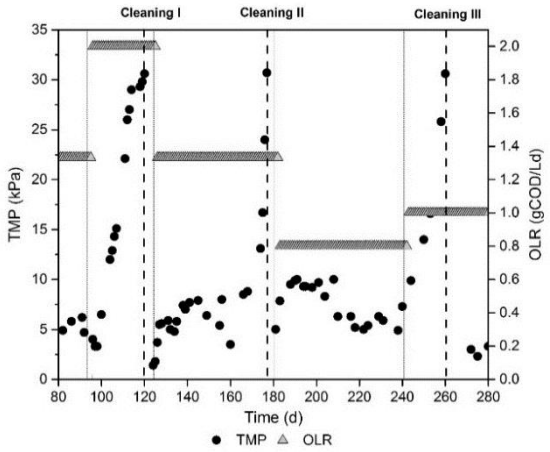

Fig. 6 Transmembrane pressure (TMP) evolution

Table 4 Biomass activity in sMBR

Phase	OUR_{endo} (KgO_2/m^3d)	OUR_{COD} (KgO_2/m^3d)	OUR_{NH4} (KgO_2/m^3d)
I	0.40	1.06	0
II	0.47	0.90	0
III	0.51	0.78	0
IV	0.46	0.73	0.15
V	0.62	1.02	0.14

to 1.06 kgO_2/m^3·d, depending on the substrate loading rate supplied and the nitrifying microorganisms' activity during the experiment (OUR_{NH4}) was near to zero, but in the stage of lower organic and nitrogen loading rate, the oxygen consumption increased, demonstrating the presence of autotrophic bacteria. The average values of the biomass activities in different stages of the membrane bioreactor are summarized in Table 4.

Pellegrin *et al*. (2002), demonstrate that oxygen requirements depend on the quantity of substrates contained in wastewater, as well as on the acclimatization of these microorganisms to the added substrate. In addition, OUR values showed that the substrate oxidation in this experiment was carried out mainly by heterotrophic microorganisms.

3.2 Analysis of membrane fouling in MBR

3.2.1 TMP evolutions

Membrane fouling can be followed by recording transmembrane pressure (TMP) variation within time of operation (Fig. 6). Once a TMP of 35 kPa was reached, the membrane module was removed from the reactor to be cleaned.

Dotted lines indicate the times when membranes were regenerated by the cleaning process. The first cleaning process occurred after 38 days of operation (Day 117) with a low permeate flux of 1 L/h·m^2. It was observed that TMP increased rapidly with an OLR of 2 gCOD/L·d. This can be explained by the high COD concentration values in the supernatant and the increasing biomass concentration within the aerated reactor. A similar behaviour was observed by Yang *et al*. (2014).

The second cleaning process was carried out 60 days after the first cleaning (Day 177). The same permeate flow was recorded. This longer period between two cleaning stages was attributed to the stabilization of the biological activity reactor and the decrease of the organic loading rate (from 2 to 1.33 gCOD/L·d). A third cleaning process occurred after 103 days of operation (Day 280) with the same permeate flow and an OLR of 0.9 ± 0.1 gCOD/L·d. This last observation allows to validate that an increase of organic load, lead to an increase of membrane fouling by suspended matter and thus a transmembrane pressure increase. Nagaoka *et al*. (2000), Johir *et al*. (2012) and Boonyungyuen *et al*. (2014) have studied the organic loading rate effect on membrane fouling and indicate that high organic loads increase the transmembrane pressure and consequently, the membrane saturation velocity; congruent to the situation occurred in this study.

3.2.2 Hydraulic resistances

During the 200 days of sMBR operation, the membrane module was removed 3 times from the bioreactor and cleaned conforming to the specific procedure described above. The different hydraulic resistances were calculated at each cleaning stage and the results are shown in Fig. 7.

The days between each cleaning were increased, due to the organic loading rates' variation in the reactor; however, there were no significant differences in hydraulic resistance between each cleaning operation. The resistance due to biological cake formation on the membrane surface appeared as the main source of fouling (mean resistance of $8.76x10^{12}$ m^{-1}), representing more than 90% of the total resistance; whereas that pore blocking by biofilm and adsorption were insignificant (5% and 4% of the total resistance, respectively).

Similar results were observed previously in sMBR studies (Sridang *et al*. 2008, Di Bella *et al*. 2013), probably due to the high concentration of colloidal and soluble organic substances developed in this kind of reactors, since it induces a fast particles accumulation on the membrane, despite all the shear forces and movements caused by the air bubbling on its surface. The membrane fouling due to inorganic substances such as the salt concentration present in this type of effluents can be neglected, because the

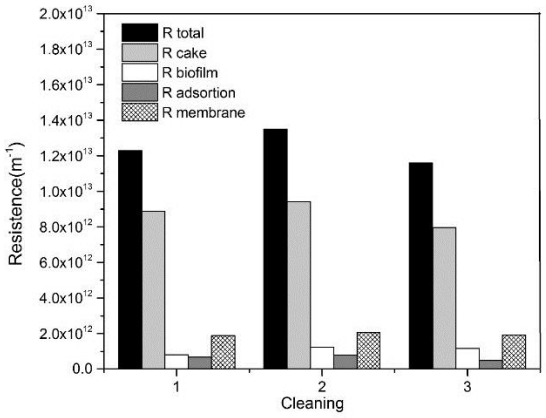

Fig. 7 Resistance of membrane fouling origins

membrane pore size is larger than the ions formed, whereby dissolved salt crosses the membrane to form part of the permeate. As reported by Meng *et al*., (2005), Drews (2010) and Liu *et al*. (2012), soluble microbial products in the biological suspension are considered as one of the main factors affecting membrane fouling in a bioreactor. Such compounds of microbial origin can be derived in solution during substrate metabolism, growth and biomass decomposition. They can be adsorbed onto the membrane surface, block the pores and form a gel structure, called cake, which provides a possible nutrients sources for biofilm formation (Rosenberger *et al*. 2005).

4. Conclusions

In an sMBR, organic removal, nitrification, biomass growth and membrane saturations were studied in the treatment of synthetic wastewater, similar in composition to the effluents generated in the fish meal industry.

• Results showed that the organic matter removal was higher than 90%, for all the organic loads tested during the study (0.8, 1, 1.33 and 2 gCOD/L·d).

• The percentage of ammonium oxidation was higher than 90% for organic loads of 0.8 and 1.33 gCOD/L·d, including nitrogen assimilation to produce biomass. Demonstrating the importance of an adequate microorganisms' acclimatization to the wastewater characteristics.

• Nitrification was only carried out in the lowest OLR and NLR (0.8 gCOD/L·d and 0.053 gN/L·d), since the high concentration of organic matter in the effluent appears as limiting for this process, reaching ammonium oxidation of around 65% for the other loading rates tested.

• In addition, the membrane system favored the reactor retention solids, maintaining the biomass activity at different tested loads.

• Regarding to membrane fouling analysis, this occurred mainly due to the cake accumulation on membrane surface and it was demonstrated that the organic and nitrogen loading rates variation had an effect in membrane saturation.

Therefore, the results obtained through the study demonstrate the feasibility of using aerobic membrane bioreactors to treat wastewater containing organic matter, nitrogen and a high concentration of salt; consequently, a large amount of effluent as those generated during the fish meal production can be treated in smaller spaces than in those used by conventional treatment systems such as activated sludge.

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