

Application of submerged membrane bioreactor for aquaculture effluent reuse

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Abstract

Discharging the nutrient rich aquaculture effluents into inland water bodies and oceans is becoming a serious concern due to the adverse effect that brings in the form of eutrophication and subsequent damages to those waters. A laboratory scale biological reactor consisting of a denitrifying compartment followed by a submerged membrane bioreactor (SMBR) compartment was used to treat 40 L d⁻¹ of aquaculture effluent with an average concentration of 74 mg L⁻¹ nitrate (NO₃⁻). Sugar was added to the aquaculture effluent in order that to enter into the denitrifying compartment at a carbon: nitrogen ratio (C:N) of 2:1 and 4:1. A hollow fibre membrane with a pore size of 0.4 μm and a filtration area of 0.20 m² was used in the SMBR and was operated at an average flux of 0.20 m³ m⁻² d⁻¹. An intermittent suction period of 12 min followed by a relaxation period of 3 min was maintained in the SMBR throughout the experiment. Different aeration rates of 1, 3, 5 and 10 Lpm were applied to the SMBR to determine the rate of membrane fouling and 5 Lpm aeration rate was found to be optimum with respect to the rate of fouling of membrane at a C:N ratio of 4:1. The average rate of fouling at 1, 3, 5 and 10 Lpm were 1.17, 0.70, 0.48 and 0.52 kPa d⁻¹, respectively. The increase in the rate of fouling when the aeration was increased from 5 to 10 Lpm may be due to the breakage of suspended particles into finer particles which could have increased the fouling of membrane. It was also found that increasing the C:N ratio from 2:1 to 4:1 resulted in more cake being formed on the membrane surface as well as an increase in the reduction of NO₃⁻ from 64% to 78%. Preliminary calculations show that 2.4 to 3.2 g of suspended solids could be accumulated per square meter of membrane surface before physical cleaning of membrane is required (at a transmembrane pressure of 20 kPa).

Keywords: Aquaculture; Denitrification; Effluent reuse; Rate of fouling; Submerged membrane bioreactor

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1. Introduction

Some of the major problems with the rapid expansion of the aquaculture industry due to high seafood demand include water quantity and quality, cost of land, restrictions on water discharge, environmental impacts (i.e. algal blooms and eutrophication) and diseases. These factors have driven the industry to undertake intensive practices as well as adopting environmentally friendly technologies due to increased regulatory pressure from environmental agencies to protect the environment [1]. In order for the industry to be sustainable, this continued expansion will depend entirely on the high level of production per unit area (or volume) and the type of technology used that is considered to be environmentally sustainable [2]. Currently, some of the main areas of research are focussed on genetics and stock improvement, improved feed formulations, disease control and farming of new species while intensive recirculated aquaculture systems (RAS) with linkages to hydroponics are considered as sound technologies that have minimal environmental impacts [3].

RAS is defined as “aquaculture systems that incorporates the treatment and reuse of water with less than 10% of total water volume replaced per day” [4]. RAS are also known as “closed systems” (i.e. denitrification included) due to minimal connection with ambient environment and water sources. They consist of mechanical and biological filtration components, pumps and holding tanks and may include a number of additional water treatment elements that improve water quality and provide disease control within the system [5].

RAS is considered to offer a number of potential advantages for aquacultural practices which includes the following:

- Full control of all parameters that influence growth so that the fish farmer can better manage economic and production performance,
- Production in locations where limited water is available,
- An ability to manage waste production to provide greater environmental sustainability than traditional aquaculture systems,
- Bio-security,
- Ability to locate the operation close to markets to reduce product transport time and costs,
- Reduction in land area required when compared to pond-based systems, and
- Ability to integrate with agricultural activities (e.g. use of water effluent for hydroponics, horticulture or pre-use of irrigation water).

However, despite these advantages, there are also impediments involved such as high capital and running costs (e.g. mechanical filtration, pumping and maintenance), rigorous monitoring of water quality thus requires high level of management and pathogen outbreak [3,4].

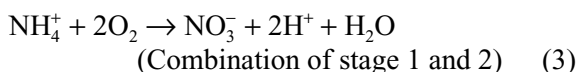
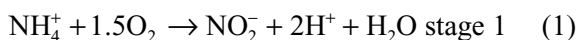
Ammonia stripping is classified as a chemical process while nitrifying and denitrifying biological filtrations (biofilters) are considered as biological processes used in RAS to remove nitrogenous wastes from the system [6]. Nitrifying biofilters are commonly used in recirculating systems for ammonia removal where nitrate is the end product which is relatively harmless to fish at low to moderate concentrations. The denitrifying biofilters are used particularly for nitrate removal and they are still under development [7]. Therefore accumulation of nitrate within RAS is usually controlled by water exchange (<10% per day) [8].

Physical processes such as mechanical filtrations are critical in high stocking densities in RAS to remove large amount of waste production (uneaten feed and faeces) due to high inputs of feed [4]. Efficient mechanical filtrations will greatly reduce oxygen demand since the breakdown of these organic solids consumes large amount of oxygen in the culture system. Coarse settleable solids (>100 μm) are generally removed from RAS using some form of settlement device such as swirl separators, settlement chambers, inclined plate separator while suspended solids

(<100 μm) can be removed through depth filtration (e.g. pressure sand filters, cartridge filters, filter matting) or screen filtration (e.g. inclined screens, rotating drum filters, conveyor filters) [4].

1.1. Nitrification

Nitrification is a two-stage process where stage one is mediated by the bacterium *Nitrosomonas*, which oxidizes ammonium to nitrite and stage two is mediated by *Nitrobacter*, which oxidizes nitrite to nitrate [9]. These two different stages are shown below:

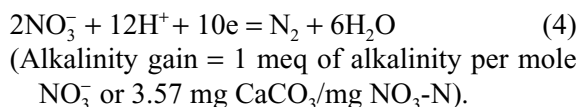


During nitrification, alkalinity decreases by approximately 7 mg CaCO_3 for each mg of ammonia-N oxidized to nitrate as shown in a combined reaction (Alkalinity loss = 2 meq of alkalinity per mole NH_4^+ or 7.14 mg CaCO_3/mg $\text{NH}_4^+\text{-N}$) [10]. Usually in a RAS, autotrophic nitrifying bacteria remove ammonia at a sufficient rate to maintain water quality at a level adequate to prevent ammonia toxicity to the fish [11]. Heterotrophic bacteria constitute an important factor in terms of oxygen consumption, metabolic by-products they release after cellular lysis, the diseases they may cause in fish and, finally, for the competition they may have with autotrophic bacteria for oxygen and space [12,13].

1.2. Denitrification

In RAS and conventional wastewater treatment plants, heterotrophic denitrification is often applied using external electron and carbon donors to enhance denitrification given that the wastewater has undergone carbonaceous BOD level and

nitrification reactions [14]. These carbon donors could be carbohydrates and organic alcohols or endogenous organic donors originating from the waste. During denitrification reaction, alkalinity is increased thus replenishes some of the inorganic carbon lost through nitrification. It is reported that each mg of nitrate-N reduced to N_2 causes an alkalinity increase of 3.57 mg CaCO_3 according to the following stoichiometry [10]:



Organic carbon discharge from recirculating systems is reduced when endogenous carbon sources originating from the fish waste are used to enhance denitrification. Although, it seems that there are numerous studies undertaken in the field, information and data on nitrate removal in recirculating systems is limited to studies with small-scale experimental systems which makes it difficult to design a unified denitrifying biofilters in recirculating systems [7].

This study evaluates the performance of a treatment system that is composed of an anoxic compartment (for denitrification) as well as an aerated submerged membrane bioreactor (SMBR) compartment to obtain effluent that could be recirculated back to an aquaculture system. The denitrification efficiency and rate of membrane fouling were used in the performance evaluation.

2. Materials and methods

The experimental set up used in this study is depicted in Fig. 1. The treatment system has three compartments: (i) the feeding tank, (ii) the anoxic tank and (iii) the aerobic tank, with working volumes of 50, 23 and 14 L respectively. A hollow fibre membrane with a pore size of 0.4 μm and a filtration area of 0.2 m^2 (supplied by Mitsubishi Ryan) was submerged in the aerobic

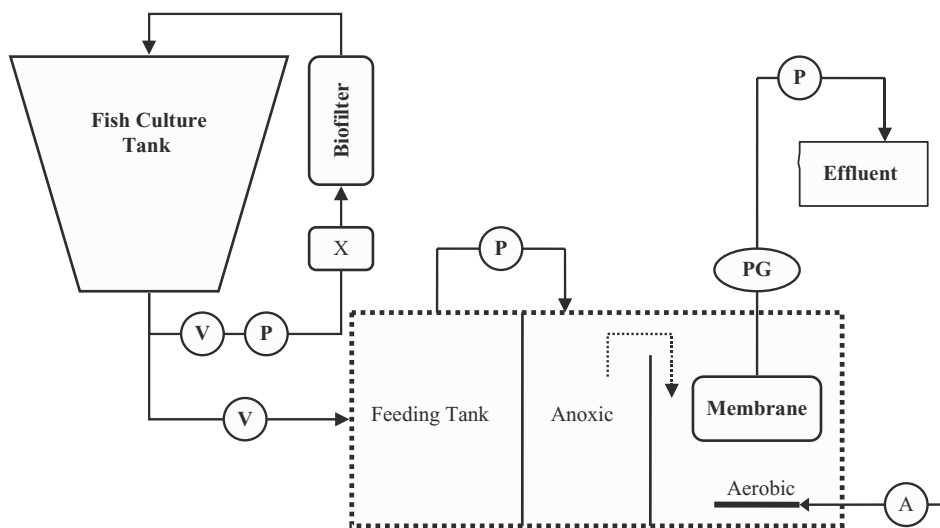


Fig. 1. Schematic of the experimental setup (A = airflow meter, P = pump, PG = pressure gauge, V = valve, X = sand and foam biofilters).

tank where the microfiltration process took place. The treatment system was supplied with 50 L of aquaculture wastewater everyday from the barramundi culture tank which had a maximum culture density of 6 kg m^{-3} and a volume of 2.5 m^3 .

There were two pumps (Aquarius Controller & Dosing System) with constant flow rates of 1.65 L per hour, which allowed the wastewater to pass into (influent) the anoxic tank and out (effluent) of the aerobic tank. A horizontal centrifugal pump is used to recirculate water back into the fish culture tank via biofilters as shown in Fig. 1. The anoxic tank contained a mixture of approximately 10 L of sludge and mixed liquor for denitrification process while the aerobic tank consisted of a hollow fibre membrane module as well a perforated pipe under the membrane module to supply air which supported bacterial growth and reduced the rate of fouling of membrane. The air supplied into the aerobic tank was controlled manually.

A transmembrane pressure of 14 kPa was set as a maximum working pressure for different aeration rates of 1, 3, 5 and 10 Lpm investigated in the study. To optimize the denitrification in

the treatment system, sugar was used as a carbon source at a carbon to nitrogen ratio (C:N) of 4:1 given its higher nitrate removal of 75% [15]. Another two sets of experiments at an aeration rate of 5 Lpm was used at 2:1 carbon to nitrogen ratio (C:N) for the purpose of comparison (Table 1). An average constant flux of $0.2 \text{ m}^3 \text{ m}^{-2} \text{ d}^{-1}$ was maintained and an intermittent suction period of 12 min followed by a relaxation period of 3 min was maintained in the SMBR throughout the experiment. Using this intermittent suction period, 19 h filtration and 5 h rest per day was maintained throughout the experimental period.

Table 1
Experimental schedule

Aeration (L/min)	Days	C:N ratio
5	1–37	2.1
5	38–83	2.1
5	84–131	4.1
1	133–147	4.1
10	148–180	4.1
3	188–207	4.1

Membrane cleaning was undertaken outside the treatment system once the transmembrane pressure (TMP) had reached 14 kPa in each experiment. The membrane module (fibers) was washed with 12 L of water using a brush and then submerged in sodium hypochlorite solution while suction was on for 30 min. Then the membrane module was washed again with water and submerged in water for another 30 min while suction took place to remove any traces of chlorine remained in the membrane. Three samples of 1 L each were taken from the cleaning water to determine the cake mass that had been accumulated on the membrane surface area through suspended solids analysis.

Measurement of TMP, turbidity, temperature, pH, were recorded daily while dissolved oxygen in the aerobic and anoxic tank and nutrient analysis for the influent and the effluent were conducted at every third day during the entire experiment. Standard methods for the examination of water and wastewater were used for all the analyses [16]. The total membrane resistance was calculated using a resistance-in-series model.

3. Results and discussion

Long term experiments were conducted at two different C:N ratio in order to reduce the nitrate present in the influent. The average temperature at which the experiments were conducted was 25°C (Fig. 2(a)). The pH level in the influent ranged between 6 and 9 with an average value of 7.3 while the effluent pH averaged 7.8 (Fig. 2(b)). In fact the pH of the effluent was always higher than the pH of the influent due to the denitrification process that took place in the treatment system [7]. The membrane was operated at a constant flux of $0.2 \text{ m}^3 \text{ m}^{-2} \text{ d}^{-1}$ while the TMP increased gradually to 14 kPa as a working suction pressure in order to determine the rate of fouling for each aeration rate. Fig. 2(c) illustrates the membrane flux throughout the experimental period and corresponding TMP. Throughout the experiments

the effluent from the SMBR had turbidity less than 0.5 NTU (Fig. 2(d)) which is important if the effluent is to be recirculated back to an aquaculture system.

3.1. Rate of increase of TMP at different rates of aeration

The average rate of increase of TMP was calculated using the number of days needed for the TMP to reach 14 kPa from the initial TMP at the start-up of an experiment. Table 2 shows the average rate of increase of TMP at different rates of aeration for two different C:N ratio. When the experiments were conducted at 5 Lpm of aeration, the rate of increase of TMP was higher for higher C:N ratio (4:1) than the lower C:N ratio (2:1). This is expected as higher the C:N ratio, higher the biomass production and faster the rate of fouling. Subsequently when the experiments were conducted at 1, 3, 5 and 10 Lpm of aeration (for a C:N ratio of 4:1), the rates of fouling were 1.17, 0.70, 0.48 and 0.52 kPa/d, respectively. The rate of increase of TMP decreased when the rate of aeration was increased from 1 to 5 Lpm. Thus, in order to operate the membrane at a lower rate of fouling, a minimum of 5 Lpm of aeration is required. Further increase in the rate of aeration to 10 Lpm did not decrease the rate of fouling. In fact, it increased the rate of increase of TMP slightly which is probably due to the breakage of suspended particles into finer particles that could have increased the rate of fouling of membranes.

3.2. Cake formation on the membrane and the membrane resistance

Table 3 shows the amount of suspended solids accumulated on the membrane surface during each experimental run. Around 2.4 to 3.2 g of suspended solids could be accumulated per square meter of membrane surface before physical cleaning of membrane is required (at a transmembrane

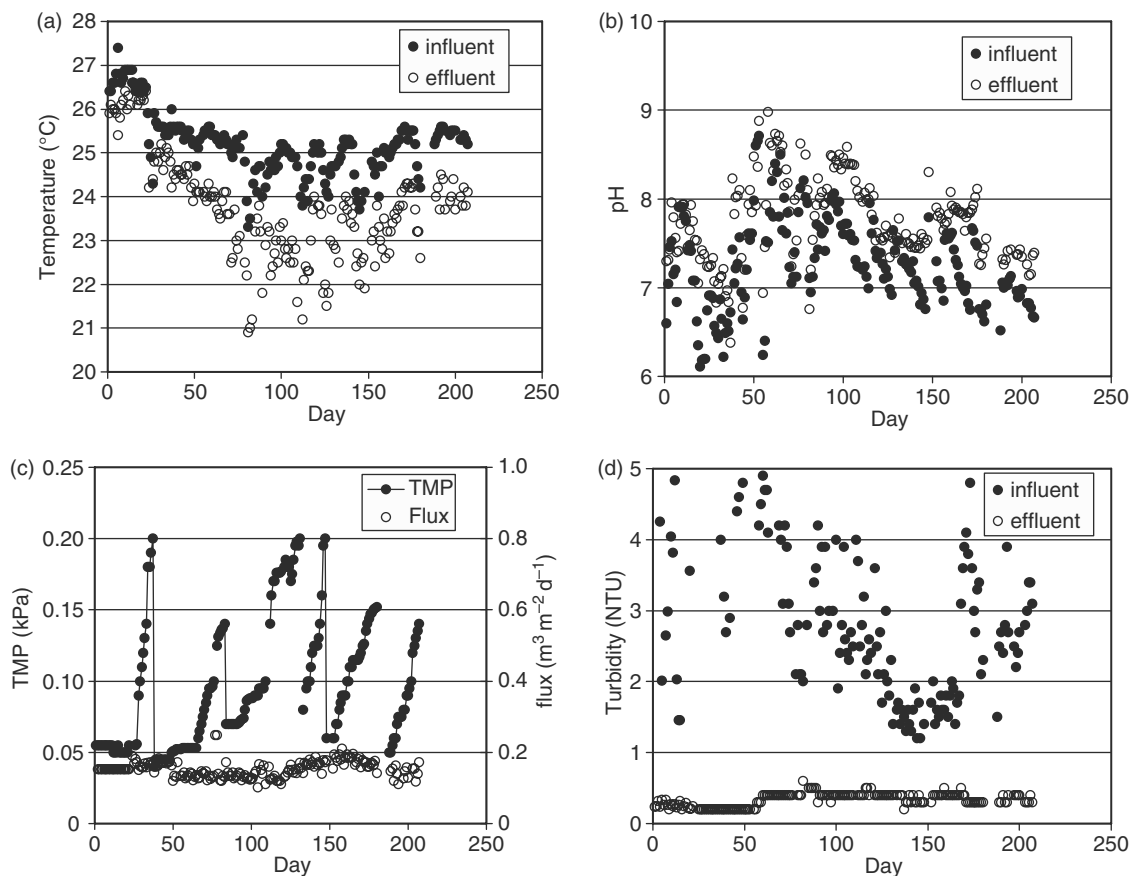


Fig. 2. (a) Temperature of the influent (to the feed tank) and effluent (SMBR permeate) (b) pH of the influent and the effluent (c) TMP and flux of the membrane (d) Turbidity of influent and the effluent.

pressure of 20 kPa and C:N ratio of 4:1). Table 3 also shows the membrane resistance at the end of each experimental run and corresponding resistance due to cake as well as irreversible internal fouling. The intrinsic resistance (R_m)

of the membrane module used was $4.04 \times 10^{11} \text{ m}^{-1}$. It can be seen from the table that the total membrane resistance at a TMP of 20 kPa was between $9.52 \times 10^{12} \text{ m}^{-1}$ to $10.2 \times 10^{12} \text{ m}^{-1}$ and the corresponding resistance due to cake and

Table 2
Average transmembrane pressure gradient for each aeration rate at 14 kPa

Experiment no.	1	2	3	4	5	6
C:N ratio	2:1	2:1	4:1	4:1	4:1	4:1
Rate of aeration (Lpm)	5	5	5	1	10	3
Time taken for TMP to reach 14 kPa (d)	33	46	29	12	27	20
Average $\frac{d(\text{TMP})}{dt}$ (kPa d ⁻¹)	0.42	0.30	0.48	1.17	0.52	0.7

Table 3
Cake density and membrane resistance at the end of each experiment

Experiment no.	1	2	3	4	5	6
C:N ratio	2:1	2:1	4:1	4:1	4:1	4:1
Rate of aeration (Lpm)	5	5	5	1	10	3
TMP at cleaning (kPa)	20	14	20	20	15.2	14
Cake density (g m^{-2})	4.0	2.8	2.4	3.2	1.2	0.8
Total membrane resistance, R_t ($\times 10^{12} \text{ m}^{-1}$)	9.52	8.45	10.2	9.52	7.14	6.74
Cake resistance, R_c ($\times 10^{12} \text{ m}^{-1}$)	8.44	6.73	7.51	7.27	4.55	4.49
Resistance due to irreversible fouling, R_f ($\times 10^{12} \text{ m}^{-1}$)	0.67	1.32	2.32	1.84	2.19	1.84
Contribution of cake to the total resistance (%)	88.7	79.6	73.4	76.4	63.7	66.7

irreversible fouling were between $7.27 \times 10^{12} \text{ m}^{-1}$ to $8.44 \times 10^{12} \text{ m}^{-1}$ and $0.67 \times 10^{12} \text{ m}^{-1}$ to $2.32 \times 10^{12} \text{ m}^{-1}$, respectively. Irreversible fouling found to increase at the end each experiment and the increase was significant for the first three experiments. Also, it could be seen that the resistance due to cake on the membrane at the time of cleaning found to decrease with each experiment as the resistance due to irreversible fouling was increasing. A power correlation could be obtained between the cake density and the cake resistance as follows:

$$[\text{Cake resistance (m}^{-1}\text{)}] = 4.6595 \times 10^{12} [\text{Cake density (g m}^{-2}\text{)}]^{0.413} \quad (r^2 = 0.91) \quad (5)$$

These information are useful when designing a full scale SMBR for the purpose of RAS.

3.3. Nitrogen species removal by the SMBR

Nitrate: Using sugar at a carbon to nitrogen (C:N) ratio of 4:1, the average concentration of nitrate measured in the influent (to the feed tank) and in the effluent (SMBR filtrate) were 74 and 16 mg L^{-1} respectively (Fig. 3(a) and (b)). Therefore an average of 58 mg L^{-1} or 78% of nitrate in the influent was being reduced daily.

Nitrite: The concentration of nitrite produced during nitrification reactions in the culture tank was between 2 and 12 mg L^{-1} in which the average

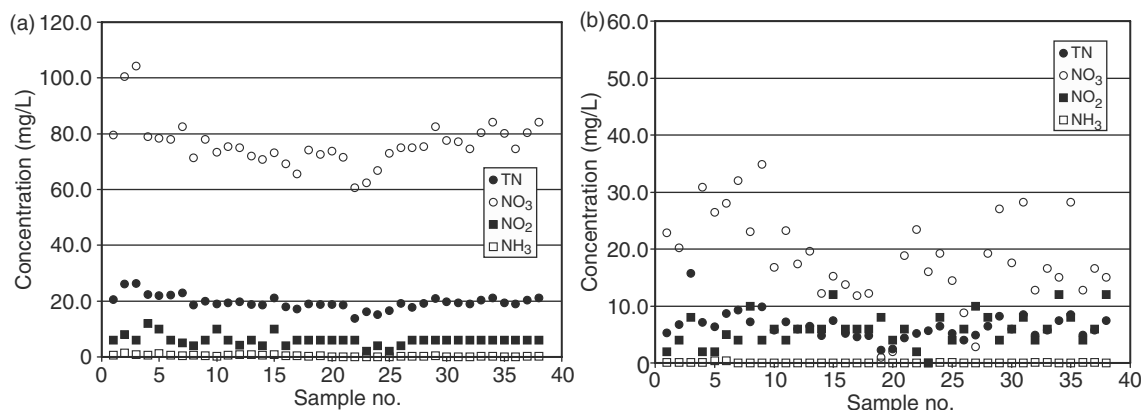


Fig. 3. TN, NO_3 , NO_2 and NH_3 concentrations, (a) influent (b) effluent (Experiment 2: sample no. 1–8; Experiment 3: sample no. 9–24; Experiment 4: sample no. 25–30; Experiment 5: sample no. 31–34; Experiment 6: sample no. 35–38).

being 5.6 mg L^{-1} as shown in Fig. 3(a). In some effluent samples, the nitrite concentration reached a maximum of 12 mg L^{-1} ; in fact it was higher at most times compared to nitrite level in the influent. This was due to incomplete nitrification in the SMBR compartment.

Ammonia: The concentration of ammonia present in the influent and effluent is shown in Fig. 3(a) and (b), respectively. In the influent, the concentration was between 0.02 and 0.40 mg L^{-1} while in the effluent it was less than 0.1 mg L^{-1} at all times. This low concentration was possible due to nitrification reactions occurred in the aerobic tank where ammonia was being reduced to nitrite and nitrate. At the beginning of the experiment, the levels of ammonia was quite high but then reduced to a stable level due to the acclimatisation of nitrifying bacteria.

Total nitrogen (TN): The TN concentration in the influent averaged at 19 mg L^{-1} (at C:N = 4:1) and in the effluent it averaged at 5.75 mg L^{-1} . Thus a 70% TN removal was achieved by the treatment system.

4. Conclusions

Recirculated aquaculture systems require efficient treatment to remove suspended solids, ammonia, nitrate and nitrite from the aquaculture effluent in order to reuse the treated effluent. Aquaculture effluent with average TN and NO_3 concentrations of 74 and 19 mg L^{-1} was treated by a submerged membrane bioreactor attached to the back of an anoxic reactor; the average flow rate was 40 L d^{-1} . The treatment system was able to remove 70% of the total nitrogen and 78% nitrate when sugar is used as carbon source for denitrification at a C:N ratio of 4:1. The SMBR produced an effluent with turbidity less than 0.5 NTU consistently for more than 200 days. An air flow rate of 5 Lpm is required to operate the membrane and at this air flow rate the TMP reached 14 kPa after a month of operation. A power-law equation correlated the cake resistance

at the end of a treatment cycle with the cake density on the membrane surface.

References

- [1] M.T. Gutierrez-Wing and R.F. Malone, Biological filters in aquaculture: trends and research directions for freshwater and marine applications, *Aquacult. Eng.*, 34 (3) (2006) 163–171.
- [2] Y. Avnimelech, Bio-filters: the need for a new comprehensive approach, *Aquacult. Eng.*, 34 (3) (2006) 172–178.
- [3] J. Lucas and P.C. Southgate (eds), *Aquaculture: Farming Aquatic Animals and Plants*, Blackwell Publishing Ltd., 2003.
- [4] W. Hutchinson, M. Jeffrey, D. O'Sullivan, D. Casement and S. Clarke, *Recirculating Aquaculture Systems: Minimum Standards for Design, Construction and Management*, South Australia, Inland Aquaculture Institution, 2004.
- [5] S. Chen, J. Ling and J.P. Blancheton, Nitrification kinetics of biofilm as affected by water quality factors, *Aquacult. Eng.*, 34 (3) (2006) 179–197.
- [6] W.J. Golz, Biological Treatment in Recirculating Aquaculture Systems, in: *Recirculating Aquaculture*.
- [7] J. van Rijn, Y. Tal and H.J. Schreier, Denitrification in recirculating systems: theory and applications, *Aquacult. Eng.*, 34 (3) (2006) 364–376.
- [8] J. Colt, Water quality requirements for reuse systems, *Aquacult. Eng.*, 34 (3) (2006) 143–156.
- [9] T.B. Lawson, *Fundamentals of Aquaculture Engineering*, Chapman and Hall, 1995
- [10] T.B. Losordo and H. Westers, System carrying capacity and flow estimation, *Aquaculture water reuse systems: Engineering Design and Management* (1994).
- [11] S. Zhu and S. Chen, An experimental study on nitrification/biofilm performances using a series reactor system, *Aquacult., Eng.*, 20 (4) (1999) 245–259.
- [12] N. Léonard, J.P. Guiraud, E. Gasset, J.P. Caillères and J.P. Blancheton, Bacteria and nutrients — nitrogen and carbon — in a recirculating system for sea bass production, *Aquacult. Eng.*, 26 (2) (2001) 111–127.
- [13] R. Nogueira, L.F. Melo, U. Purkhold, S. Wuertz and M. Wagner, Nitrifying and heterotrophic

- population dynamics in biofilm reactor: effects of hydraulic retention time and presence of organic carbon, *Water Res.*, 36 (2002) 469–481.
- [14] M.L. Davis and D.A. Cornwell, *Introduction to Environmental Engineering*, McGraw-Hill, 1998.
- [15] J. Monk and V. Jegatheesan, *Sugar and Molasses Optimization During Denitrification of Aquaculture Wastewater In A Membrane Bioreactor*, 2006 World Water Congress, Beijing, Sep. 10–14, 2006.
- [16] APHA, AWWA, WPCF, *Standard Methods for the Examination of Water and Wastewater*, 20th edn., Washington DC, USA, 1998, ISBN 0-87553-235-7.