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Powdered activated carbon for fouling reduction of a membrane in a pilot-scale recirculating aquaculture system

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ABSTRACT

Recirculating aquaculture systems (RAS) are essential for the reduction in fresh water usage as well as the discharge of nutrients along with aquaculture effluents. A RAS consisting of an anoxic reactor, a membrane bioreactor (MBR) and a UV-disinfection unit was used to process 10,000 L/d of aquaculture effluent providing high-quality treated water for recirculation to a Barramundi fish culture. The system maintained low levels of nitrate (<20 mg/L), nitrite (<3 mg/L) and ammonia (<0.6 mg/L) in the fish tank. Permeate from the membrane that was recirculated to the fish tank contained <21 mg/L of nitrate, <2 mg/L of nitrite and 0 mg/L of ammonia. However, the rate of fouling of the membrane in the MBR was around 1.47 kPa/d, and the membrane in the MBR required cleaning due to fouling after 16 days. Cleaning of the membrane was initiated when the TMP reached around 25 to 30 kPa. In order to reduce the rate of fouling, 500 mg of powdered activated carbon (PAC) per litre of MBR volume was introduced, which decreased the rate of fouling to 0.90 kPa/d. Cleaning of membrane was needed only after 31 days of operation while maintaining the treated effluent quality. Thus the frequency of cleaning could be halved due to the introduction of PAC into the MBR.

Keywords: Denitrification; Fouling; Membrane bioreactor (MBR); Powdered activated carbon (PAC); Recirculating aquaculture system (RAS); Transmembrane pressure (TMP)

1. Introduction

As the need to combat the ever-increasing problems of excessive demands on capture fisheries coupled with the diminishing number of species due to over-exploitation, the aquaculture industry is expected to alleviate some pressure in the near future. However, the challenges brought about by human population growth and competition for water, land and natural resources force the aquaculture industry to maximise productivity and minimise water usage. Both these criteria could be met if efficient recirculating aquaculture systems (RAS) were brought into practice. A RAS could theoretically eliminate the daily water exchange required in an aquaculture farm by treating the effluent for recirculation [1–3].

The effluent should be treated to remove the water quality parameters such as total ammonia (NH_3/NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), chemical oxygen demand (COD), biological oxygen demand (BOD), suspended solids (SS), turbidity and micro-organisms such as bacteria

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and viruses. An effective RAS system consisting of an anoxic reactor followed by a membrane bioreactor (MBR) and a UV disinfecting unit could treat the aquaculture effluent and provide significant reductions in the water quality parameters that have been mentioned above. However, one major problem of this system would be the fouling of membrane in the MBR.

Fouling is the coating of the membrane surface or blocking of the pores with a solid or gelatinous material (cake), which creates a barrier through which the treated effluent (permeate) must pass. Thus, the effective pore size distribution of the membrane is reduced. The net effect of blockage is to reduce the permeate flux passing through the membrane. There are four major categories of membrane fouling: inorganic, organic, microbiological and deposition (or plugging) of membrane due to particulates and debris. Most inorganic fouling occurs due to scale-forming dissolved solids such as calcium. The most common inorganic fouling problems can be dealt with by appropriate pre-treatment. Organic foulants have a natural affinity for the membrane surface. Due to this affinity, organic foulants such as oils, wet out the membrane, spreading directly onto the membrane surface. Organic fouling may be cleaned with a detergent or caustic soda. Biological foulants are aerobic and anaerobic living materials such as bacteria, fungus, algae, and the extra-cellular polymeric substances (EPS) and metabolic wastes they generate. Inorganic fouling is not typically encountered in MBRs to such a degree as organic and biological fouling.

Microbes literally grow into massive quantities that effectively block flow through the membrane surface. Cellulose acetate membranes may support microbiological growth while the polyamide type does not. However, both types are subject to fouling by microorganisms. This can be controlled in cellulose acetate membranes by chlorination of the feed water. Polyamide membranes cannot tolerate the oxidative properties of chlorine. Chlorinated feed water must be de-chlorinated before entering the module. If the use of a bactericide is considered instead of chlorination, the bactericide must be approved for the application. Halogens other than chlorine may be used to control microbiological fouling. On the other hand, Ying and Ping [4] found that the EPS in the mixed liquor of MBR deposited gently on the membrane made of polyvinylidene fluoride (PVDF). In the presence of powdered activated carbon (PAC), the rate of deposition of EPS on PVDF membranes was reduced even further. Microorganisms form in suspended particles which agglomerate at the membrane surface and pores, usually in the leading membranes of an array, whereas biological growth occurs in areas where "food" is available. Iron-reducing bacteria, for example, grow in areas containing iron fouling. Fungus tends to grow in areas such as silica-phosphate gel, which provides both protection from flow and food for additional growth. Thus, the causes of fouling are:

- Slow build-up of precipitates over extended periods of time.
- Precipitation of initially dissolved species as a result of: (1) concentration process, (2) changes in the feed stream composition, (3) failure of a pre-treatment system and (4) inadequate flushing of the system after a shutdown.
- Adsorption of organics on the membrane surface.
- Formation of bacterial slime on the membrane surface.

The aim of this study is to elucidate the effectiveness of PAC as a means to mitigate the fouling of **a** membrane in a RAS. PAC could adsorb dissolved organic substances and the EPS which are the major components that cause fouling the membrane in a MBR [5–12]. Also the cake that forms on the membrane surface would have large porosity in the presence of PAC.

2. Materials and methods

The RAS system is comprised of a fish tank (2,500 L) that was used to raise Barramundi fish and a treatment system including an anoxic reactor (1,000 L), MBR (1,000 L) and a UV-disinfection unit to treat the aquaculture effluent in order to recirculate the treated effluent back to the fish tank (Fig. 1). The effluent from the fish tank was flowing to a sump through the drain pipe. A pump was dividing the flow into two streams, one returned back to the fish tank through water sprayers and the other stream was passed to the bottom of the anoxic reactor. A brown sugar solution was allowed to drip into the anoxic reactor to adjust the carbon to nitrogen ratio in the anoxic reactor to 4:1 by weight. The overflow from anoxic reactor was allowed into the MBR. The MBR was

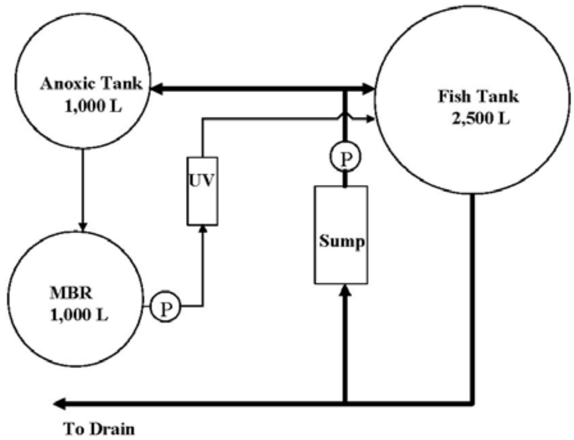

Fig. 1. Schematic of the RAS.

aerated by perforated air pipe that is placed inside the MBR (at the bottom). A suction pump was used to obtain permeate from the MBR which was passed through a UV disinfectant unit to kill the micro-organisms that pass through the membrane pores. The microfiltration membrane in the MBR supplied by Kolon Industry (South Korea) was capable of treating 10,000 L/d. It is a composite hollow-fiber membrane having a thin layer (comprised of polysulfone, polyethersulfone and PVDF) coated on the surface of reinforcing material of a tubular braid (Fig. 2). Specifications of the membrane are given in Table 1.

Two sets of experiments were conducted using the system to study the rate of fouling with and without the addition of PAC into the MBR. The experiment that was conducted with PAC used 500 mg of PAC for every litre of MBR volume based on previous experiments [4,13]. The transmembrane pressure (TMP) was measured at the suction side (or permeate) of the membrane everyday to calculate the rate of fouling of membrane. Water quality parameters such as NH_4^+, NO_3^-, NO_2^-, turbidity and pH were measured in the fish tank, MBR and the treated effluent to evaluate the performance of the RAS.

Table 1
Specifications of micro-filtration membrane

Parameters	Description
Module type	Cleanfil-S20
Type of membrane	Braid-reinforced hollow fiber
Material of coating layer	Polysulfone, polyether-sulfone, PVDF
Coating thickness, mm	0.05–0.1
Outer diameter, mm	2
Inner diameter, mm	0.8
Pore size, μm	0.3
Dimensions of the module, (L×W×D), mm	1184×105×628
Area of membrane, m^2	20
Flux, $Lm^{-2}h^{-1}$	20–25
Manufacturer	Kolon Industry, South Korea

Fig. 2. Microfiltration membrane used in the MBR of the RAS.

3. Results and discussion

The non-PAC run began with very low start up TMP of 2 kPa and increased up to 24 kPa over a period of 15 days (Fig. 3). However, the run with PAC started with 1 kPa of TMP and increased up to 28 kPa over period of 30 days. Thus the rate of increase of TMP was 1.47 and 0.90 kPa/d for non-PAC and PAC runs respectively. The membrane was operated for an intermittent suction period of 3 h followed by a relaxation period of 5 min. A small-scale RAS processing 40 L/d of aquaculture effluent coming from a similar Barramundi culture tank showed a rate of increase of TMP of around 0.48 kPa/d at a C:N ratio of 4:1 [14]. The operation of the membrane in that system was an intermittent suction period of 12 min followed by a relaxation period of 3 min. Thus, it could be seen clearly that a shorter time interval between consecutive relaxation periods could reduce the rate of fouling significantly. However, in large-scale operations, this time interval should be chosen carefully in order to extend the life period of pumps.

Membrane resistance to permeate flow was measured on the clean membrane after each run to see the effectiveness of PAC in reducing the irreversible resistance. Generally, the resistance to permeate flow is contributed by three different components: (1) intrinsic membrane resistance, R_m; (2) cake resistance, R_c and (3) irreversible resistance due to pore blocking, R_f. Thus, the total resistance, R_t, can be given by:

$$R_t = R_m + R_c + R_f \tag{1}$$

Once the membrane is cleaned after each run, the

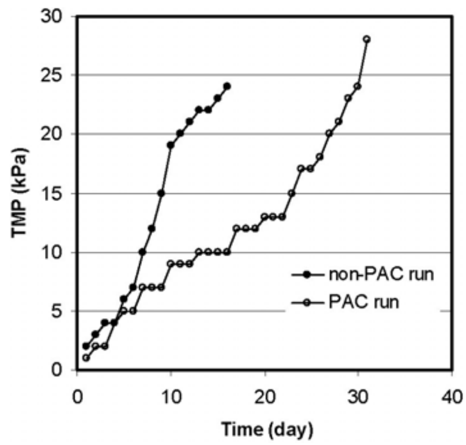

Fig. 3. Increase in TMP with time in both non-PAC and PAC runs.

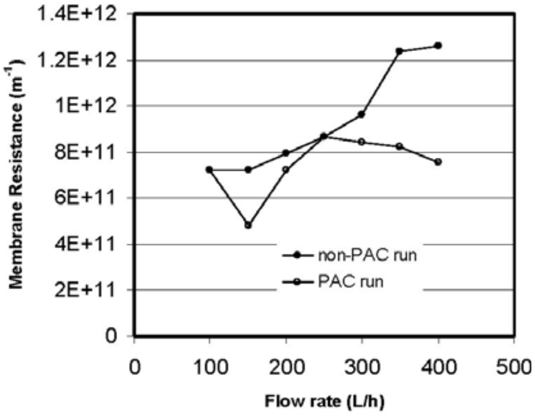

Fig. 4. Combined resistance due to membrane and irreversible fouling ($R_m + R_f$) in both non-PAC and PAC runs.

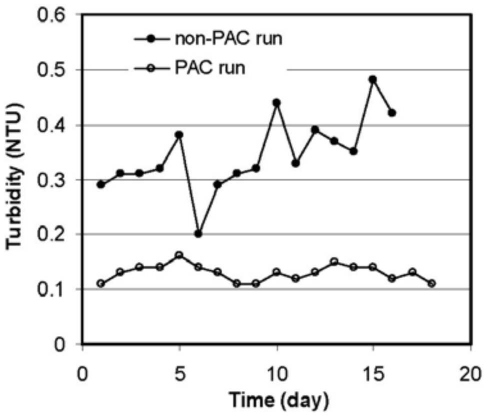

Fig. 5. Turbidity of the permeate from the MBR in both non-PAC and PAC runs.

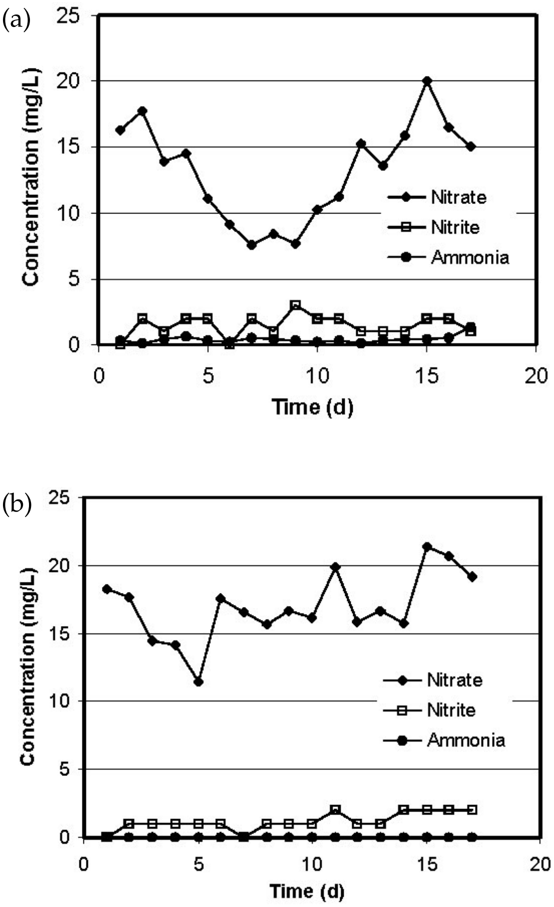

Fig. 6. Concentration of nitrogen species during the non-PAC run. (a) Fish tank. (b) Permeate from the MBR.

Table 2
Average water quality in fish tank, anoxic tank and MBR effluent

	Temperature (ºC)	pH	DO (mg/L)	Turbidity (NTU)	Nitrate (mg/L)	Nitrite (mg/L)	Ammonia (mg/L)
Without PAC addition:							
Fish tank	20.9–26	6.37–7.27	5.65–8.05	0.7–2.88	7.6–17.7	0–3	0.1–1.4
Anoxic tank	20.1–25.3	6.05–7.02	1.76–3.7	82.2–1000	7.9–20.6	0–11	0.26–2.4
MBR effluent	21.1–25.5	6.3–7.36	5.73–6.94	0.2–0.48	11.4–21.4	0–2	0–0.01
With PAC addition:							
Fish tank	23–26	5.81–7.17	5.57–7.08	0.59–1.22	18.3–26.7	1–2 (limited data)	0.2–1.1
Anoxic tank	23.1–27.3	6.37–7.53	2.54–4.68	508–1000	17.8–30	0–3 (limited data)	2.1–5.9
MBR effluent	23.6–27.4	5.3–6.79	5.67–6.72	0.11–0.27	19–30.8	1 (limited data)	0–0.06

resistance should be due to R_m and R_f as the cake layer would have been removed from the surface of the membrane. Thus, if clean water is passed through the membrane at different flow rates and corresponding TMP is measured, the resistance due to R_m and R_f (=R_t) could be computed by using the following equation:

$$J = \text{TMP}/(\mu R_t) \quad (2)$$

where J is the flux through the membrane and μ is the viscosity of the feed water to the membrane. It can be seen from Fig. 4 that the addition of PAC has reduced the fouling due to pore blocking to a very good extent. This can be attributed to the absorption of organic substances and EPS by PAC which are the major components of pore blocking. Further studies on adsorption isotherms of organic substances, present in MBR liquor, by PAC will help to quantify the level of adsorption that aids in reducing the irreversible fouling of the membrane. However, it should be noted that the cleaning of non-PAC and PAC runs were carried out after 16 and 11 days respectively and the PAC run that was used evaluate the irreversible resistance was different to the PAC run that is used to discuss all other results.

The typical water quality of fish tank water (which is feed water to the anoxic tank), anoxic tank (which is feed water to the MBR) and the effluent from the MBR (finished water) are given in Table 2. The average turbidity in the MBR during the non-PAC run was around 839 NTU and which was reduced to 0.34 NTU in the permeate providing a turbidity removal of 99.96% (Fig. 5). Similarly, during the PAC run, the turbidity in the MBR and the permeate were 1000 NTU and 0.13 NTU, respectively, providing a turbidity removal of 99.99%. Thus, both non-PAC and PAC runs yielded very high quality permeate in terms of turbidity. The non-PAC run maintained the nitrate, nitrite ammonia levels in the fish tank between 8 and 20 mg/L, 0 and 3 mg/L and 0.1 to 0.6 mg/L, respectively (Fig. 6). During this time, the permeate from the MBR contained 11 to 21 mg/L of nitrate, 0 to 2 mg/L of nitrite and 0 mg/L of ammonia. This shows that the RAS was functioning as required for the Barramundi culture to grow at desirable rate.

4. Conclusions

An efficient recirculating aquaculture system comprised of an anoxic reactor, membrane bioreactor and a UV-disinfectant unit was used to culture Barramundi fish by treating 10,000 L of aquaculture effluent continuously. The system maintained low levels of nitrate (<20 mg/L), nitrite (<3 mg/L) and ammonia (<0.6 mg/L) in the fish tank. The permeate from the membrane that was recirculated to the fish tank contained <21 mg/L of nitrate, <2 mg/L of nitrite and 0 mg/L of ammonia. The membrane in the MBR required cleaning due to fouling after 16 days. Cleaning of membrane initiated when the TMP reached around 25 to 30 kPa. However, when PAC was introduced into the MBR at 500 mg/L of MBR volume, cleaning of the membrane was needed only after 31 days of opeation. Calculations on membrane resistance due to intrinsic and irreversible fouling showed that PAC reduced irreversible resistance which could be attributed to the adsorption of dissolved organic substances and EPS by PAC. However, further isotherm studies are required to quantify the amount of adsorption of organic substances by PAC.

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