



A FRAMEWORK FOR MODELLING WATER QUALITY AND FISH GROWTH PARAMETERS IN RECIRCULATING AQUACULTURE SYSTEM

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ABSTRACT

Recirculating Aquaculture System (RAS) is a technology used to culture aquatic animals in a controlled environmental condition. The concept of RAS is very much relevant in commercial aquaculture sector where water exchange is a necessity for proper maintenance of water quality variables. The present study is aimed to develop a modelling framework for an RAS assuming that make up water for maintenance of nitrate-nitrogen concentration in the culture tank is added only when its concentration reaches its permissible limit. This approach of adopting water exchange at a time predicted by the model instead of daily exchange can be advantageous due to reduced operating cost and provision to set up RAS even in areas of intermittent water supply. Model expressions were formulated to predict the major water quality variables viz. total ammonia nitrogen, nitrate-nitrogen, dissolved oxygen, suspended solids in the culture environment based on simple mass balance approach.

KEY WORDS: Recirculating aquaculture system; modeling framework; water quality; mass balance.

INTRODUCTION

As per the sustainability of aquaculture system is concerned, two techniques are gaining popularity worldwide- i) water reuse and ii) biofloc. Water reuse systems have become popular in small capacity systems due to high initial capital investments required by recirculating aquaculture system (RAS) (Schneider *et al.*, 2006). High stocking densities and productions are required to cover investment costs; which may also lead to accumulation of minerals, drug residues, hazardous feed compounds and metabolites affecting the health, quality and safety of the cultured species (Martins *et al.*, 2009a; Martins *et al.*, 2009b). The technique of recirculating aquaculture system (RAS) offers a scope for large scale ecologically sustainable fish production. This technique is very much relevant and required in commercial aquaculture sector where proper maintenance of water quality variables necessitates water exchange. The typical RAS consist of: i) rearing unit, ii) solid removal unit: a) mechanical filter and b) foam fractionator and iii) nitrification unit: a) trickling filter. In RAS, water quality management plays a major role in fish production. RAS is a dynamic system in which the response of fish growth varies with changes in the water quality parameters, thereby making the monitoring and management of the culture difficult for the entrepreneur or farmer. In this context, development of a mathematical model for providing real time information about various parameters related to biomass growth and water quality will be of immense help. The present study is aimed to develop a modelling framework for an RAS assuming that make up water for maintenance of nitrate-nitrogen concentration in

the culture tank is added only when its concentration reaches its permissible limit.

MATERIALS & METHODS

Recirculating aquaculture experimental set-up

The recirculating aquaculture experimental set-up consisted of: i) rearing unit, ii) solid removal unit: a) screen filter and b) foam fractionator and iii) nitrification unit: a) trickling filter. A typical schematic diagram showing all the components as mentioned above is presented in Fig. 1.

Determination of recirculation flow rate

The accurate estimation of water recirculation flow rate and appropriate sizing of nitrifying biofilters are of critical importance to the successful design of any recirculation system. An approach for sizing of biofilter based on nitrification rate is outlined by Losordo and Hobbs (2000). In the present study, partial water exchange was allowed to maintain the level of nitrate-nitrogen concentration in the rearing tank within the permissible limit. As goldfish is quiet sensitive to water quality parameters, it was decided to fix the permissible limit for NO₃-N concentration at 20 mg/L. Based on this criterion, a mass balance approach was adopted to determine the water flow rate requirement for the RAS under consideration Model expressions were formulated based on simple mass balance approach for determination of various important water quality variables namely total ammonia nitrogen, nitrate-nitrogen, dissolved oxygen, suspended solids in the culture environment as a function of time in a typical RAS without a denitrifying unit. Following the Losordo and Hobbs (2000) procedure, Q_r was calculated by setting the time derivative to zero for each of the mass balances and assuming the appropriate

permissible values of the above water quality variables. The model would forecast the important water quality parameters in a typical RAS, thus enabling the user to go

for timely adoption of management programs which are otherwise difficult to decide.

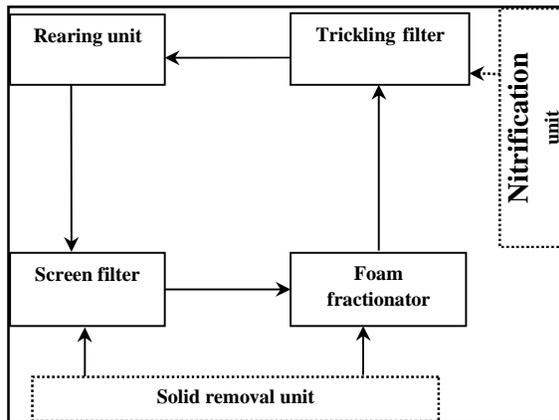


FIGURE 1: Recirculating aquaculture system showing individual components



FIGURE 2. Batch culture operation in trickling filters

Trickling filter sizing

The nitrification rate (NR) of trickling filter varies in between 0.2 – 0.4 g TAN / m²/day (Parker *et al.*, 1995). In the present study, a conservative value of 0.2 g TAN / m²/day was assigned for the nitrification rate of trickling filter. The active nitrification surface area required and volume of filter media required in the trickling filter were found out using the following equations:

$$\begin{aligned}
 \text{Active surface area required for nitrification} \\
 (A_s) &= PR_{\text{TAN}}/NR \quad \dots (1) \\
 &= 6.68 / 0.2 \\
 &= 33.4 \text{ m}^2 \text{ say } 34 \text{ m}^2.
 \end{aligned}$$

$$\begin{aligned}
 \text{Total volume of filter media required } (V_t) &= A_s/A_{ss} \quad \dots (2) \\
 &= 34 / 1213 \\
 &= 0.028 \text{ m}^3 \\
 &\text{say } 0.03 \text{ m}^3
 \end{aligned}$$

Where, A_{ss} is specific surface area of filter media (m²/m³). Further assuming 3 numbers of trickling filters and effective depth of the trickling filter i.e., depth of filter media (d_m) as 1.6 m,

$$\begin{aligned}
 \text{cross-sectional area of trickling filter } (A_{tf}) &= V_t / d_m \quad \dots (3) \\
 &= 0.03 \text{ m}^3 / 1.6 \text{ m} \\
 &= 0.018 \text{ m}^2.
 \end{aligned}$$

$$\begin{aligned}
 \text{Diameter of trickling filters} \\
 (D) &= [4 \times A_{tf} / (\text{No. of trickling filters} \times \pi)]^{1/2} \quad \dots (4) \\
 &= 0.09 \text{ m}.
 \end{aligned}$$

Based on the above calculations, the design dimensions of the trickling filters were selected as follows:

Design dimensions

Material: Acrylic column; Media: Nylon pot scrubber; Diameter: 90 mm Height = 1600 + 200 mm (freeboard) = 1800 mm and number of trickling filters: 3

Fabrication of trickling filter

Three cylindrical acrylic columns of diameter 90 mm and height 1800 mm were fabricated (Vayenas *et al.*, 1997).

An air pump was provided at the bottom of all the columns with diffuser air stones. The specifications of air pump are (Make: Resun ACO-003, Power: 0.037 kW). A water spraying mechanism was also provided for uniform distribution of effluent over the top surface of the columns.

Batch culture operation

The three cylindrical columns were filled up with nylon pot scrubber media and inoculated with a synthetic substrate containing ammonium chloride, sodium bicarbonate and other necessary nutrients for optimum growth of nitrifiers as well as removal of the entire ammonia and nitrite from the solution (Zhu and Chen, 2001). This is essential to ensure the presence of nitrifying bacteria—both *Nitrosomonas* and *Nitrobacter* in the biofilter media. Further, these columns were covered with a black paper (Fig. 2) along its outer periphery to avoid the growth of heterotrophic bacteria. To reduce the acclimatization time of nitrifiers, probiotics (Biogreen) were also added to the trickling filters. The batch culture operation took almost 35 days, after which the ammonia and nitrite contents were found to be almost negligible and thereby the filters were ready for continuous operation

RESULTS & CONCLUSION

The developed model expressions were discretized using the central finite difference technique. The time step was chosen to be same as that of the detention time of the biofilter. Thus, within each time step, the recirculated water enters and leaves the biofiltration chamber. Therefore, the variation in concentration of the nitrogenous compounds along the length of biofiltration chamber did not matter in the modeling process and thus was not considered in the model. The discretized forms of the model expressions for various water quality parameters are presented as follows:

REARING TANK**Total ammonia nitrogen (TAN)**

$$C_{cTAN-out}(t+ t) = [Q_r \{C_{fTAN-out}(t) - C_{fTAN-in}(t)\} + (1-k_b) PR_{TAN}] 2 t/V + C_{cTAN-out}(t- t) \quad \dots(5)$$

Nitrite nitrogen (NO₂-N)

$$C_{cNO2-out}(t+ t) = \{Q_r \{C_{fNO2-out}(t) - C_{fNO2-in}(t)\} + k_b PR_{TAN}\} 2 t/V + C_{cNO2-out}(t- t) \quad \dots (6)$$

Nitrate nitrogen (NO₃-N)

$$C_{cNO3-out}(t+ t) = \{Q_r \{C_{fNO3-out}(t) - C_{fNO3-in}(t)\} + k_b k_c PR_{TAN}\} 2 t/V + C_{cNO3-out}(t- t) \quad \dots (7)$$

Dissolved oxygen (DO)

$$C_{cDO-out}(t+ t) = [Q_r \{C_{fDO-out}(t) - C_{cDO-out}(t)\} + PR_{DO}(t) - (k_{oxy} + k_{BOD}) W(t) N(t) V \%BW - 4.57 k_b PR_{TAN}] 2 t/V + C_{cDO-out}(t- t) \dots(8)$$

Suspended solids (SS)

$$C_{CTSS-out}(t+ t) = [Q_r \{C_{CTSS-in}(t) - C_{CTSS-out}(t)\} + PR_{SS}] 2 t/V + C_{CTSS-out}(t- t) \dots(3.30)$$

SCREEN FILTER**Suspended solids (SS)**

$$C_{mfSS-out}(t+ t) = [Q_r \{C_{mfSS-in}(t) - C_{mfSS-out}(t)\} - E_{mf} PR_{SS}] 2 t/V + C_{mfSS-out}(t- t) \quad \dots(9)$$

FOAM FRACTIONATOR**Suspended solids (SS)**

$$C_{cfSS-out}(t+ t) = Q_r \{C_{mfSS-out}(t) (1 - E_{cf}) - C_{cfSS-out}(t)\} 2 t/V_{cf} + C_{cfSS-out}(t- t) \quad \dots(10)$$

TRICKLING FILTER**Total ammonia nitrogen (TAN)**

$$C_{fTAN-out} = (C_{fTAN-in}(t) - C_{fTAN-out}(t)) - (k_1 V_f C_{fTAN-in}(t) / Q_r) \quad \dots (11)$$

Nitrite nitrogen (NO₂-N)

$$C_{fNO2-out} = (Q_r C_{fNO2-in}(t) + k_1 C_{fTAN-in}(t) - k_2 V_f C_{fNO2-in}) / Q_r \quad \dots (12)$$

Nitrate nitrogen (NO₃-N)

$$C_{fNO3-out} = (Q_r C_{fNO3-in} + k_2 C_{fNO2-in} \times V_f) / Q_r \quad \dots (13)$$

Dissolved oxygen (DO)

$$C_{fDO-out}(t+ t) = [Q_r \{C_{fDO-in}(t) - C_{fDO-out}(t)\} + PR_{fDO} (t) - 4.57 (1-k_b) PR_{TAN} - 2.3 K_{BOD} W(t) N(t) V (1-E_{mf})(1-E_{cf})] 2 t/V_f + C_{fDO-out}(t- t) \dots (14)$$

Suspended Solids (SS)

$$C_{cfSS-out}(t+ t) = Q_r \{C_{mfSS-out}(t) (1 - E_{cf}) - C_{cfSS-out}(t)\} 2 t/V_{cf} + C_{cfSS-out}(t- t) \quad \dots (15)$$

The model parameters are T_{GC} , M , a , b , k_1 , k_2 , k_{TAN} , k_{oxy} , k_{BOD} , k_b , k_c and .

*where, k_b = fraction of nitrification occurring in rearing tank, $C_{cTAN-out}$ = concentration of total ammonia nitrogen in rearing tank (mg/L), $C_{fTAN-out}$ and $C_{fTAN-in}$ = concentration of total ammonia nitrogen at the outlet and inlet of trickling filter respectively (mg/L) and PR_{TAN} = production rate of TAN (mg/L), V_f = volume of trickling filter (L) and k_1 = reaction rate constant (day^{-1}) for conversion of TAN to nitrite-N, $C_{cNO2-out}$ = concentration of nitrite-nitrogen in rearing tank (mg/L) and $C_{fNO2-out}$ and $C_{fNO2-in}$ = concentration of nitrite-nitrogen at the outlet and inlet of trickling filter respectively (mg/L), k_2 represents reaction rate constant (day^{-1}) for conversion of nitrite-N to nitrate-N, k_{oxy} and k_{BOD} = g of oxygen required for fish respiration per kg of feed applied and g of oxygen required for consumption of carbonaceous waste per kg of feed per unit time, k_c = fraction of NO₂-N converted to NO₃-N, $C_{cNO3-out}$ = concentration of nitrate-nitrogen in rearing tank (mg/L) and $C_{fNO3-out}$ and $C_{fNO3-in}$ = concentration of nitrate-nitrogen at the outlet and inlet of trickling filter respectively (mg/L), PR_{DO} = production of DO inside the rearing tank (mg/L), $C_{fDO-out}$ = concentration of DO at the outlet of trickling filter and $C_{cDO-out}$ = concentration of DO inside the rearing tank as well as at

the outlet of the rearing tank, PR_{fDO} = production of oxygen in the trickling filter (mg/L), $C_{CTSS-out}$ and $C_{CTSS-in}$ = concentration of suspended solids in water in foam fractionator outlet and inlet (mg/L) respectively, V_s = effective volume of mechanical filter (L), $C_{mfSS-out}$ and $C_{mfSS-in}$ = concentration of suspended solids in mechanical filter outlet and inlet respectively (mg/L), E_{mf} = efficiency of screen filter and PR_{SS} = production of suspended solids (mg/day), $C_{cfSS-out}$ = concentration of suspended solids in water in foam fractionator outlet (mg/L), V_{cf} = effective volume of foam fractionator column (L) and E_{cf} = efficiency of foam fractionators, $W(t)$ and $N(t)$ = weight and no of fish at time t, % BW = percentage body weight.

A program in MATLAB environment will be written to solve the above mentioned model expressions simultaneously. Given the values of input and the model parameters, the program generated output for each of the water quality and biomass variables.

The model expressions, once calibrated and validated for a particular fish species, can be used in the prediction of major water quality variables at any instant of the culture period, thus enabling the user to go for timely adoption of

management programmes which are otherwise difficult to decide.

PROCEDURE FOR CALIBRATION AND VALIDATION

Calibration of the model

For calibration of the model for any RAS with a particular species of fish, the RAS has to be operated at the recirculation flow rate Q_r obtained from the mass balance approach and subsequently the concentrations of various water quality variables, viz., TAN, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, SS and DO should be measured at the rearing tank, outlet of the screen filter, foam fractionator and trickling filter on a daily basis. The temperature and pH of the culture water are to be noted daily as they have a direct influence on determining the proportion of unionized ammonia concentration. Apart from these, number of fish and their average weight are also required to be noted on a daily basis. During the experimental run, the nitrate-nitrogen concentration will slowly build up and after a certain time interval (say t_p days) it will approach its permissible value. To maintain the nitrate-nitrogen concentration, partial water exchange is to be conducted to reduce it to at least half of the permissible value. Thus, based on the observed

data, the time interval, t_p , can be found out. The permissible value of nitrate-nitrogen concentration can be made as a model input so that the operator can fix the proportion of water to be exchanged after t_p days. After water exchange, recalculation of the concentrations of various water quality variables can be done and the procedure should be repeated as stated above till the harvesting size is achieved. The model expressions are presented in Equations 5- 15. In each case, the values of the model parameters, i.e. M , TGC , k_1 , k_2 , k_{TAN} , k_{oxy} , k_{BOD} , k_b and can be adjusted in such a way that the sum of square of differences between the observed and predicted values of water quality variables under consideration becomes negligible. Once the model parameters are fixed for a system, the model can be validated during the subsequent operation of the RAS.

Validation of the model

The calibrated model with its model parameters fixed for the particular fish species and experimental setup can then be validated. The validation is done to determine the effectiveness of model in serving the purposes for which it has been formulated.

The model can be evaluated using the following three criteria:

(a) Root Mean Square Error (RMSE)

$$RMSE = \left[\left(\sum_{i=1}^N (O(i)-S(i))^2 / N \right)^{0.5} \right] \dots (16)$$

Where, $O(i)$ = i^{th} observed value, $S(i)$ = i^{th} simulated value and N = total number of measurements.

(b) Coefficient of Determination (R^2) which is given by

$$R^2 = \left[\frac{\sum_{i=1}^N (O(i) - O_{avg})(S(i) - S_{avg})}{\left\{ \left(\sum_{i=1}^N (O(i) - O_{avg})^2 \right)^{0.5} \left(\sum_{i=1}^N (S(i) - S_{avg})^2 \right)^{0.5} \right\}} \right]^2 \dots (17)$$

Where, O_{avg} = mean of the observed values and S_{avg} = mean of the model simulated values and

(c) Modelling efficiency or Simulation efficiency (E_{NS}) as proposed by Nash-Sutcliffe (1970) is as follows:

$$E_{NS} = 1 - \left\{ \frac{\sum_{i=1}^N (S(i)-O(i))^2}{\sum_{i=1}^N (O(i)-O_{avg})^2} \right\} \dots (18)$$

LIMITATIONS OF THE MODEL

The influences of mineral ions, which may be present in water, were not accounted for on the functioning of nitrifying biofilters. Another major limitation of the model lies in excluding the impact of continuous pH variation on culture species as well as on the nitrifying bacteria. Further, it does not take into account of the variation of temperature which may occur in the system.

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