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Biofilm Processes for Volume Decrease in Recirculating Water Treatment Systems for Aquaculture

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The engineering aspect of water treatment processes in the recirculating aquaculture system was studied. To recycle the water in the aquaculture system, a wastewater treatment process was required to maintain high water quality for the growth and health of the cultured fish. In this study, three different biofilm processes were used to reduce the concentration of organic matters and ammonia from the recirculating water - two phase fluidized bed, three phase fluidized bed, and trickling filter. The objectives of this research were to evaluate the optimum treatment conditions of the biofilm processes for the recirculating aquaculture system, and thereby reduce the volume of biofilm processes, which are commonly used for the recycle water treatment processes for aquaculture.

The result of this study showed that the removal efficiency of organic matters by trickling filter was found to be lower than that of the fluidized bed. In the trickling filter system, anthracite showed better organic removal efficiency than crushed stone as a media.

In the two phase fluidized bed, the maximum removal efficiency of either organics or ammonia was obtained when both the packing rate of media was maintained to 40% of total reactor depth excepting sediment zone and the bed expansion rate was maintained to 100%.

When 100 tilapia (Oreochromis niloticus) of each average 200 g was reared, the pollutant production rate was 0.07 g NH_4^+-N/kg fish/day and 0.06 g PO_4^{-3}-P/kg fish/day, and sludge production rate was 0.39 g SS/kg fish/day.

In the two phase and three phase fluidized bed, the volume of water treatment tank could be calculated from an empirical equation by using the relationship between the influent COD to NH_4^+-N ratio (C/N, -), media concentration (Cm, g/L), influent ammonia nitrogen concentration (Ni, mg/L), effluent ammonia nitrogen concentration (Ne, mg/L), bed expansion rate (E, %), and influent flowrate (Q, m^3/hr). The empirical equation from this study is

$$V_2 = 10^{3.1279}\, C/N^{3.5461}\, C_m^{-3.7473}\, N_i^{4.6477}\, E^{0.0326}\, N_e^{-0.8849}\, Q \quad \text{(Two Phase FB)}$$
$$V_3 = 10^{11.7507}\, C/N^{-1.2330}\, C_m^{-6.5715}\, N_i^{1.5091}\, N_e^{-1.8489}\, Q \quad \text{(Three Phase FB)}$$

Key words: recirculating water treatment, aquaculture, fluidized bed, ammonia removal

Introduction

High density recirculating culture system has benefits of increasing productivity and maintaining water temperature with lower expense. Because the circulating water can be reused, this system is being used in the water shortage place (Muir, 1981) However, ammonia produced from fish waste and feed disturbs fish growth and even kills fish in the recirculating culture system. EPA (Environmental Protection Agency) in USA advices to maintain unionized ammonia (NH_3) below than 0.02 mg/L in culture tank (Roger and Klemetson, 1985) Dissolved organic matters in the culture tank consume dissolved oxygen and repress nitrification when they are decomposed by heterotrophic micro-organisms. Suspended solid reduces resistance to fish disease, and then kills fish living in bad water quality. It is, therefore, required proper water treatment in recirculating water system (Muncy et al., 1979).

Generally, RBC (Rotating Biological Contactors) (Antonie et al., 1974), TFC (Trickling Filter) (Roger and Klemetson, 1985), SFC (Submerged Filter) (Nijhof and Bonverdeur, 1990), AWP (Aquatic

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Weeds Process) (Lewis et al., 1978) and FBP (Fluidized Bed Process) (Jewell and Cummings, 19 90) are used to maintain good water quality in high density culture system. Although there are many studies for good water quality for recirculating water system, most of them still have problems such as low efficiency of water treatment, high cost for maintenance and difficulty in operation (Kim, 1993). For instance, at the same volume of water treatment area as culture area, the culturing area becomes restricted in the most of traditional recirculating culture system, and FBP is regarded as a higher water treatment efficiency but more difficult in operation than TF. Therefore, this study was compared water treatment efficiency of FBP with TF, and also calculated the unit production of pollutants to design recirculating culture system for Nile tilapia (*Oreochromis niloticus*). Finally, the object of this study is to reduce the volume of water treatment area, and then to increase fish productivity in recirculating culture system.

Materials and Methods

2.1 Experimental reactor design

2.1.1 Two Phase Fluidized Bed Process

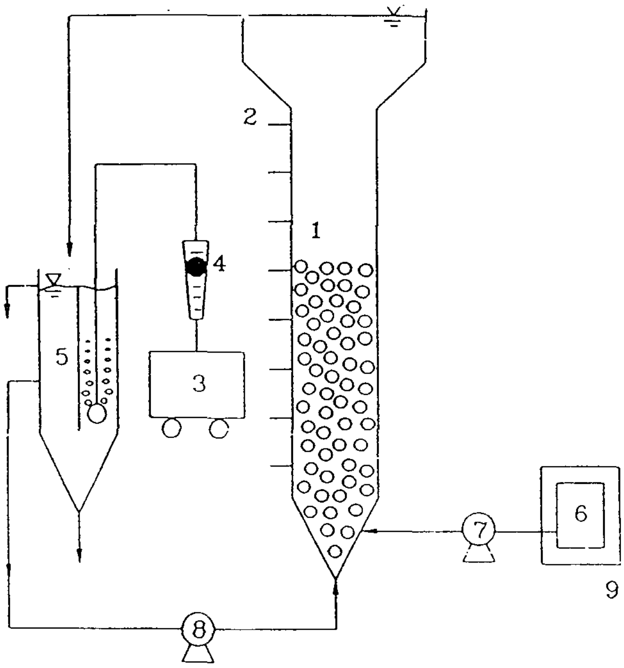
The diagram of the biological two phase fluidized bed process for recirculating culture system is shown in Fig. 1. The reactor was made with 6.4 cm diameter of acrylic cylinder, the total volume was 1.91 L, and height/diameter was 12.8. A peristaltic pump (Cole-Parmer Instrument Company) was used for input of substrate. Activated carbon with diameter 0.71~0.84 mm was filled up inside of the reactor. Table 1 represents the physical specification of activated carbon used.

2.1.2 Three Phase Fluidized Bed Process

Three phase fluidized bed process for recirculating water treatment system is shown in Fig. 2. The reactor was made with 6.4 cm diameter of acrylic cylinder and the total volume was 1.76 L. Air was supplied using 3.6 mm diameter draft tube which was located inside of the reactor. The ratio of the diameter of reactor to draft tube was 1.88 : 1 and the ratio of upflowing area to downflowing area was 1 : 2.16, height/diameter was 12.8. Activated carbon with diameter 0.71~0.84 mm was filled up inside of the reactor. Table 1 represents physical specification of activated carbon used.

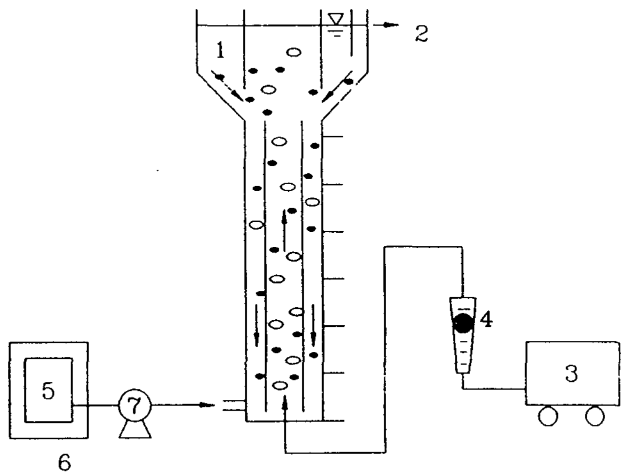
2.1.3 Trickling Filter Process

Trickling filter process used in this study is shown in Fig. 3. The trickling filter reactor was made with acrylic cylinder with 4.5 cm in diameter and 170 cm in length. Liguid and media sampling ports were made every 35 cm. Distributor was set up 4 cm below the top of the reactor and backwashing hole was made 5 cm upward on the bottom of the reactor. The substrate was supplied by a peristaltic



1. Reactor 4. Rotameter 7. Feed inlet pump
2. Sampling port 5. Aeration tank 8. Recycle pump
3. Air pump 6. Feed tank 9. Refrigerator

Fig. 1. Schematic diagram of two phase fluidized bed.

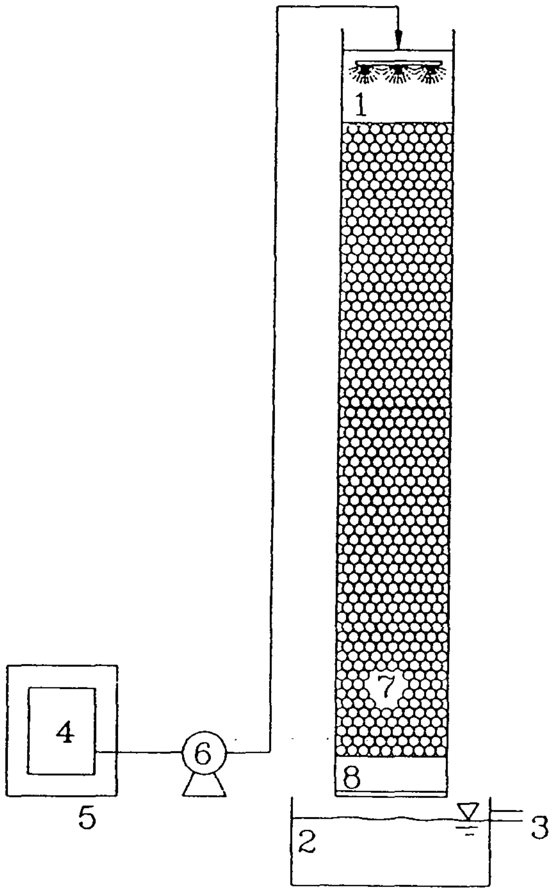


1. Reactor 4. Rotameter 7. Feed inlet pump
2. Sampling port 5. Feed tank
3. Air pump 6. Refrigerator

Fig. 2. Schematic diagram of three phase fluidized bed.

Table 1. Specification of coconut shell activated carbons

Contents	Values
Moisture, %	1.7
Volatile matter, %	1.4
Ash, %	1.7
Bulk density, g/cc	0.44
Hardness	97.4
Iodine value, mg/g	1140
MB adsorption, mℓ/g	250
Surface area, m^2/g	1180



1. Reactor 2. Settling tank 3. Effluent 4. Feed tank 5. Refrigerator 6. Feed inlet pump 7. Media (anthracite) 8. Screen

Fig. 3. Schematic diagram of trickling filter.

pump (Cole Parmer Instrument Company) and a hose. Anthracite was used as a media.

2.2 Synthetic feedstock solution

Table 2 shows the synthetic feed solution used in this study. Glucose and NH_4Cl were used as organic matter and ammonia source, respectivery. Predetermined amount of $NaHCO_3$ was added for filling up alkalinity which decreases during nitrification. Tap water was used to make the solution for supplying trace elements.

2.3 Methods

2.3.1 Two Phase Fluidized Bed Process

For early formation of biofilm, activated sludge was obtained from a wastewater treatment plant. After removing impurities using 60 mesh (dia. : 0.24 mm), the sludge was acclimated in the synthetic feedstock solution for a week. The acclimated activated sludge was filled into about ⅔ of the reactor, then the rest of the part was filled with tap water. Low concentration synthetic feedstock solution was input to the batch reactor for creating biofilm.

After 10 days of operation, microorganism film was formed. After 20 days, the microorganism concentration represented as MLSS reached 4,500 mg/L. Microorganism concentration was evaluated from MLSS of activated sludge for each sample.

The experiment was carried out 16 stages with the different concentration of organic matters ranged 0. 085~3.165 kg COD/m^3/day and 0.044~1.816 kg NH_4^+-N/m^3/day. The effect of media bed volume was also examined at 15 cm and 30 cm of the bed height of activated carbon. The experiment was carried out with 20% and 40% of the media volume in the total length of the reactor. To calculate the optimum bed expansion, bed expansion was changed from 10 to 100%. Excess microorganisms were removed from reactor to maintain constant bed expansion. Sludge production was estimated from the removed microorganisms.

2.3.2 Three phase fluidized bed process

To acclimate microorganism, activated sludge obtained for a wastewater treatment plant was used after removing impurities using 60 mesh. To maintain pH 7, $NaHCO_3$ was added to the reactor during the operation. The initial organic matter concentration was about 20 mg COD/L and then the organic matter loading was increased to change HRT, 10 minute - 6 hours. Ammonia removal

Table 2. Synthetic feedstock solution

Composition	mg/L
Glucose	20
$NaHPO_4$	40
$NaHCO_3$	125
$MnSO_4$	2
NH_4Cl	As needed

effect was monitored as changing ammonia nitrogen concentration from 4.21 to 18.35 mg NH_4^+-N/L and ammonia nitrogen loading rate from 0.040 to 1.575 kg NH_4^+-N/m^3/day.

To estimate the effect of media concentration on the ammonia removal, 88 g and 150 g of activated carbon were used as media. The operation temperature was 25 ± 1℃. Airflow rate was 0.85 ± 0.05 L/min. per unit volume (L) of reactor. The air flow rate was reduced up to 0.57 L/min at the HRT 2 hr to compare organic matter and ammonia removal rates.

2.3.3 Trickling filter process

To operate trickling filter process the microorganisms were applied to batch system prior to operation and the chemicals were inserted continuously during operation. Experiments were divided into four stages under the conditions of 0.082~0.500 kg COD/m^3/day, 0.044~0.27 kg NH_4^+-N/m^3/day, and 6.712~40.341 m^3/m^2/day. The sample was analyzed after 1 week acclimation. Wastewater was equally distributed on the surface of the media. Anthracite was used as a media and filled up whole reactor. The operation temperature of reactor was 25 ± 1℃.

Results and discussion

3.1 Effluent water quality

3.1.1 Effluent COD concentration

The effluent COD concentration versus organic loading rate in each process is shown in Fig. 4. For fish culture, less than 5 mg/L of COD has been recommended in Japan. In this study, effluent COD concentration showed less than 4 mg/L at organic loading 0.235~3.165 kg COD/m^3/day in two phase fluidized bed process, three phase fluidized bed process maintained less than 8.5 mg//L at 0.139~2.739 kg COD/m^3/day, and trickling filter process maintained below 7.2 mg COD/L relatively with low organic loading at 0.082~0.500 kg COD/m^3/day. According to the results from this study, two phase fluidized bed process was most effective for removing the organic matters.

3.1.2 Effluent ammonia concentration

Standard water quality for fish culture is different from fish to fish. Jewell and Cummings (1990) suggested that freshwater fish could be cultured at about 3 mg/L of NH_3 and salmonid fish needed under 0.5 mg/L. EPA (1976) restricted NH_3-N concentration to 0.02~2.0 mg/L and Alabaster (1982) suggested that proper water quality for fish culture was from 0.12 mg/L (pH 8.5, 30℃) to 19.6 mg NH_3-N (pH 7.0, 5℃).

Fig. 5 shows the variation of unionized NH_3-N at each pH. And Fig. 6 shows the variation of unionized NH_3-N at each pH and temperature. In this study, unionized ammonia concentration was 0.005 mg/L at pH 7 and total ammonia 1 mg/L in the culture tank. It was less than 0.02 mg/L which is water quality recommended for fish culture by US EPA. Usually 1 % of total ammonia exists as NH_3-N in the water. In order to maintain less than 0.02 mg/L of standard value the ammonia nitrogen concentration should be less than 2 mg/L in the effluent water.

Results from this study suggest that NH_3-N

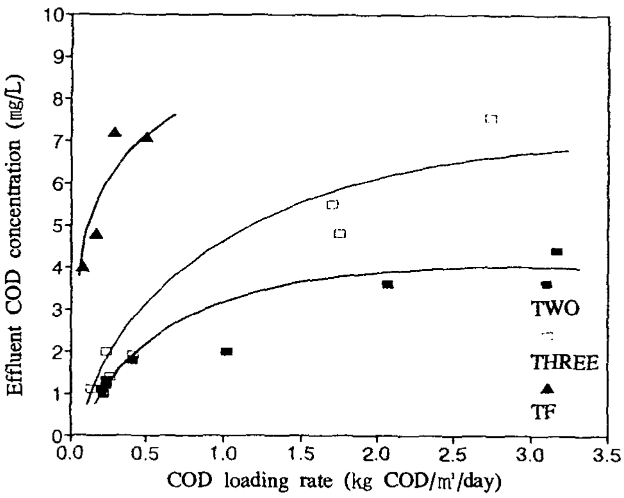


Fig. 4. Effluent COD concentration versus organic loading rate in each treatment process.

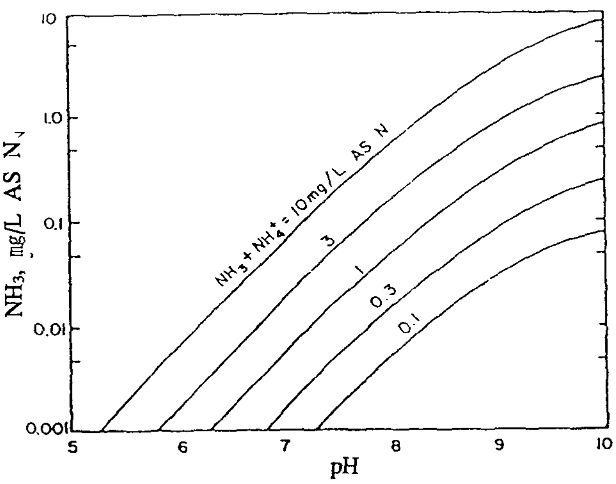


Fig. 5. Variation of unionized NH_3-N at each pH (WPCF, 1983).

loading has to be kept below 1.2 kg NH_4^+-N/m^3/day at media bed height 30 cm and total expansion 100 % for two phase fluidized process to maintain less than standard NH_3-N concentration. In the three phase fluidized process which was operated with 85 g/L of media concentration, 0.85 L/min in airflow rate and the ratio 1.88:1 of the diameter of reactor to draft tube are needed to maintain NH_3-N concentration less than 0.15 kg NH_4^+-N/m^3/day. NH_3-N concentration in the effluent was over 2 mg/L in the tricking filter process due to the high NH_3-N concentration in influent water. The concentration of NH_3-N in this study showed less concentration than EPA suggestion levels. Fig. 7 shows the relationship between effluent NH_4^+-N concentration and organic loading rate in each process. When ammonia loading rate was 0.086~0.716 kg NH_4^+-N/m^3/day and 1.816 kg NH_4^+-N/m^3/day, ammonia nitrogen concentration of effluent was less than 0.72 mg/L and 2.57 mg/L, respectively, in the two phase fluidized process. In the three phase fluidized process, ammonia nitrogen concentration of effluent water was less than 3.73 mg/L under 0.128~0.692 kg NH_4^+-N/m^3/day of the ammonia loading rate, and the ammonia nitrogen concentration of effluent water was 5.50 mg/L under 1.575 kg NH_4^+-N/m^3/day of ammonia loading rate. In the tricking filter process, when ammonia loading rate was 0.044~0.143 kg NH_4^+-N/m^3/day, the ammonia nitrogen concentration was less than 6.38 mg/L. Therefore, it can be concluded that the two phase fluidized process was more effective in removing ammonia nitrogen than other two systems.

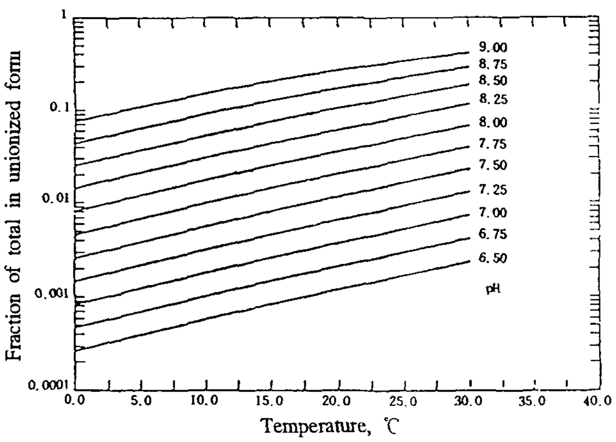


Fig. 6. Variation of unionized NH_3-N at each pH and Temperature (EPA, 1993).

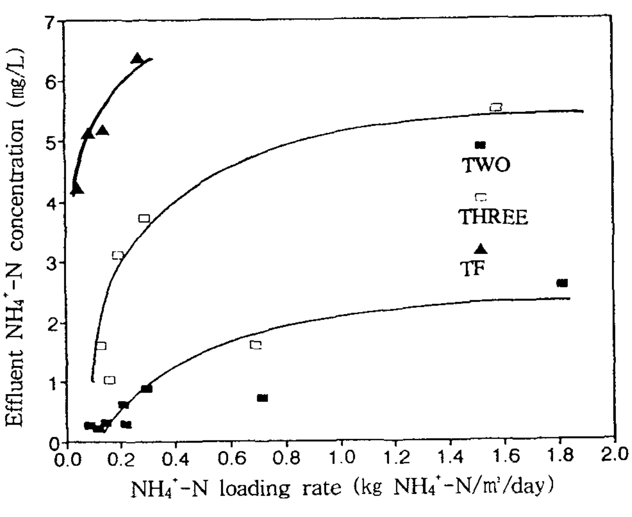


Fig. 7. Effluent NH_4^+-N concentration versus organic loading rate in each process.

Reducing the ammonia nitrogen concentration in culture tank to less than 2 mg/L is related with the volume of water treatment tank. Therefore, if the two phase fluidized process and the three phase fluidized process were used for treatment of recycling water, the model could be calculated as below;

$$V_2 = 10^{3.1279}\, C/N^{3.5461}\, C_m^{-3.7473}\, N_i^{4.6447}\, E^{0.0326}\, N_e^{-0.8849}\, Q \quad \text{(Two Phase FB)} \qquad (1)$$

$$V_3 = 10^{11.7507}\, C/N^{-1.2330}\, C_m^{-6.5715}\, N_i^{1.5091}\, Q \quad \text{(Three Phase FB)} \qquad (2)$$

where V = volume of water treatment tank (m^3)
C/N = influent COD to NH_4^+-N ratio
C_m = media concentration (g/L)
N_i = influent ammonia concentration (mg/L)
N_e = effluent ammonia concentration (mg/L)
E = expansion (%)
Q = influent flowrate (m^3/hr)

3.2 Ammonia removal rate

Table 3 summarized the ammonia removal rate in each process. Rogers and Klemetson (1985) reported that the average ammonia removal rate of unit reactor was 11.43 mg NH_4^+-N_{rem}/L/day with 0.80~92.63 g NH_4^+-N/m^3/day using trickling filter, 10.72 mg NH_4^+-N_{rem}/L/day with 0.10~11.63 g NH_4^+-N/m^3/day using biodrum filter and 40.14 mg NH_4^+-N_{rem}/L/day with 0.26~30.41 g NH_4^+-N/m^3/day using RBC. Jewell and Cummings (1990) gained 40 mg NH_4^+-

Table 3. Ammonia removal rate in each process

Process	mg NH_4^+-N_{rem}/L/day
Trickling filter (Roger and Klemetson, 1985)	11.43
Biodrum filter (Roger and Klemetson, 1985)	10.72
Rotating biological contactor (Roger and Klemetson, 1985)	40.14
Two phase fluidized bed (Jewell and Cummings, 1990)	40
Three phase fluidized bed(Tijhuis at el, 1992)	6 kg N/L/day
This study (Two phase fluidized bed)	114.7~1569.6
This study (Three phase fluidized bed)	117.2~1086.2
This study (Trickling filter)	27.2~119.5

N_{rem}/L/day using two phase fluidized bed process. All of the ammonia removal rate reported above are relatively quite low, because the authors operated the processes under the condition of low ammonia loading, 0.010 g NH_4^+-N/m³/day. Tijhuis et al. (1992) reported that maximum nitrification rate using three phase fluidized bed process was 6 kg N/L/day. It was very high level of nitrification rate due to the high concentration of media (175 g/L), high ammonia loading rate (10 kg/L/day) and different microorganism concentration if comparing with this study.

According to the this study, the ammonia removal rate was 114.7~1,569.6 mg NH_4^+-N_{rem}/L/day when the bed height was 30 cm, the expansion rate was 100%, and the ammonia loading rate was 0.117~1.816 mg NH_4^+-N/m³/day when using the two fluidized bed process. In the three fluidized bed process, the nitrogen removal rate was 117.2~1,086.2 mg NH_4^+-N/m³/day when the media concentration was 85 g/L and ammonia loading was 0.128~1.575 kg NH_4^+-N/m³/day. When the ammonia loading rate was 0.044~0.271 kg NH_4^+-N/m³/day, the ammonia removal rate was 27.2~119.5 mg NH_4^+-N_{rem}/L/day using anthracite as a media in trickling filter process. It had more efficient removal rate than that of trickling filter process operated by Rogers and Klemeston (1985). It seemed that different results from this study were due to different kind of media and expansion rate compared to other results. The ammonia removal rate of two fluidized bed process in this study was 25.9~39.2 times higher than RBC process per unit volume.

Fig. 8 compares the ammonia removal rate under various hydraulic loading rate (m³/m³/day) at each process. Hanaki suggested that HRT was the first factor affecting the ammonia removal rate. Fig. 8 also illustrated that two and three fluidized bed processes and tricking filter process had relatively higher ammonia removal rate even with longer HRT. Therefore, if fluidized bed processes were operated for recirculating culture system, the production of fish would be increased and than the water treatment tank volume could be reduced.

3.3 Design of recycling water treatment system

3.3.1 Evaluation of pollutant production rate in culture system

100 tilapia of each average 200 g were kept in 360 L culture tank for calculation of pollutant production rate in recirculating water system. Fishes were fed 1 % of body weight per day and water exchange rate was 10%. The water was not replaced when pollution production rate was calculated. The feed conversion ratio was 1.52 during experimental period.

Table 5 represents the pollution occurring per unit reacter volume per fish weight. The cancentration of NH_4^+-N, PO_4^{-3}-P, NO_3^--N were 0.07 g/kg fish/day, 0.01 g/kg fish/day, and 0.33 g/kg fish/day, respectively. And the pollution production rate per supplied feed were estimated as 7.75 g/kg food/day, 6.65 g/kg food/day, and 34.40 g/kg

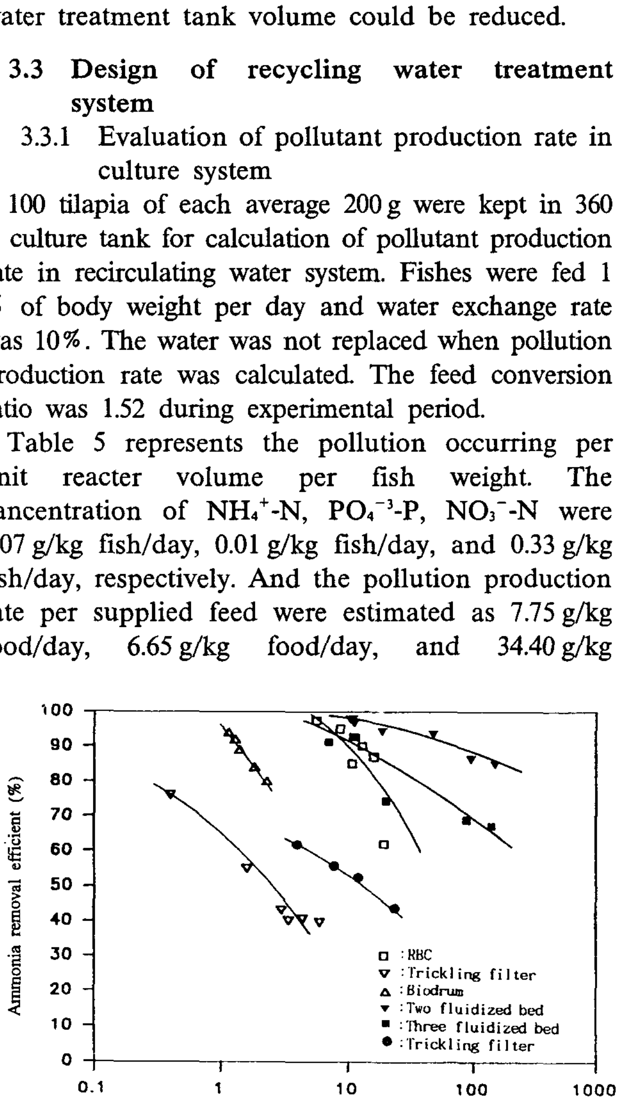


Fig. 8. NH_4^+-N removal efficiencies versus hydraulic loading rate.

Table 4. The biomass, average fish weight and fish numbers that can be maintained in the rearing tanks

Parameter		Result
Species		*Oreochromis niloticus*
Temperature	(℃)	25.5
Initial biomass	(g)	19,720
Final biomass	(g)	21,565
Total number	(number)	97
Food rate	(g/day)	200
Feed conversion ratio	(−)	1.68
Rearing tank volume	(L)	353.2
Flow rate	(mg/sec)	2,714

food/day for NH_4^+-N, PO_4^{-3}-P, NO_3^--N, respectively. Clark et al. (1985) reported that NH_4^+-N, PO_4^{-3}-P, and NO_3^--N were measured 0.02 g/kg fish/day, and 0.01 g/kg fish/day, 0.21 g/kg fish/day, respectively. And the pollution production rate per supplied feed were estimated as 0.92 g/kg food/day, 0.70 g/kg food /day, 8 g/kg food/day for NH_4^+-N, PO_4^{-3}-P, NO_3^--N for raising 80~180 g rainbow trout. Comparing the results obatained by clark et. al. (1985) to the this study, the pollution rate was higher with these experimental results due to different feed, fish species, size, and culture method.

3.3.2 Calculation of treatment tank volume

Treatment tank volume can be calculated from the results based on this study when maintaining 0.1 mg/L of effluent ammonia nitrogen concentration for 5,000 tilapia weighed 200 g in 10 m^3 with 10 % exchange rate. Fig. 9. shows the diagram of recirculating culture system. Table 6 represents the treatment volume for each process using formula (1), (2) and Table 5. The traditional recirculating culture system needed the same unit as culture tank volume for water treatment. For instance, operating 10 m^3 of culture system water treatment volume was needed 10 m^3.

However, based on the results of this study, 0.928 and 1.208 m^3 of treatment tank volume were needed for the two and three phase fluidized processes, respectively. This result corresponds to the reduction of 8 to 10 times of treatment tank volume if compared to the traditional culture system. Although the trickling filter process could not reduce the ammonia nitrogen concentration up to less than 1 mg/L, this method will be useful in case of maintaining effluent ammonia nitrogen concentration by 0.4 mg/L. It also can reduce 3.5 times of treatment tank volume compared to that used in traditional culture system.

Table 5. Production rates of the major metaboliters production

Parameters	Result
Sludge (g SS/kg fish/day)	0.39
Ammonia (g/kg fish/day)	0.07
Ammonia (g/kg food/day)	7.75
Phosphate (g/kg fish/day)	0.06
Phosphate (g/kg food/day)	6.65
Nitrate (g/kg fish/day)	0.33
Nitrate (g/kg food/day)	35.40

Table 6. Treantment tank volume in each process

Processes	Volume (m^3)	safty factor=2
Two phase fludized bed	0.464	0.928
Three phase fludized bed	0.604	1.208
Trickling filter	1.400	2.800

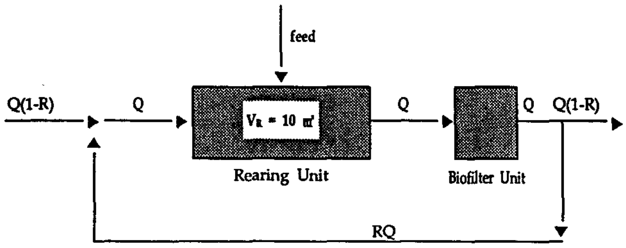


Fig. 9. Recirculated system with biofilter.

V_R = 10 m^3
Species = *Oreochromis niloticus*
Initial biomass = 1000 kg
Number = 5000

Ammonia volume in the culture tank
= 200 g/fish × 5000 fish × 0.07 g NH_4^+-N/kg fish/day (Table 5)
= 70 g NH_4^+-N/day

The circulation volume for maintaining ammonia rate less than 1 mg/L in the culture tank
= 70 g NH_4^+-N/day ÷ 1 mg mg/L
= 70 m^3/day

$$V_2 = 10^{3.1279}\, C/N^{3.5461}\, C_m^{-3.7473}\, N_i^{4.6447}\, E^{0.0326}\, N_e^{-0.8849}\, Q$$
(Two Phase FB)
$$= 10^{3.1279}\ 20^{3.5461}\ 341^{-3.7473}\ 1^{4.6447}\ 100^{0.0326}\ 0.1^{-0.8849}\ (70/24)$$
$$= 0.464\ m^3$$

$$V_3 = 10^{11.7505}\, C/N^{-1.2330}\, C_m^{-6.5715}\, N_i^{1.5091}\, N_e^{-1.8489}\, Q$$
(Three Phase FB)
$$= 10^{11.7507}\ 20^{-1.2330}\ 85^{-6.5715}\ 1^{1.5091}\ 0.1^{-1.8489}\ (70/24)$$
$$= 0.604\ m^3$$

Conclusion

1. Two and three phase fluidized bed processes had more effective than traditional methods for reducing ammonia in the culture system, which can result in the reduction of the water treatment tank volume and the increases in fish production.
2. The maximum ammonia removal rate was gained when the media was filled 40% and the expansion rate was 100 % in the two phase fluidized bed process.
3. Trickling filter process using anthracite as

a media had lower ammonia removal efficiency than fluidized bed processes. However, it had more ammonia removal efficiency than trickling filter process using gravel media.

4. The unit production of pollutants was 0.07 g NH_4^+-N/kg fish/day and 0.06 g PO_4^{-3}-P/kg fish/day, and the sludge production was 0.39 g SS/kg fish/day when raising 200 g tilapia (*Oreochromis niloticus*).

5. The volume of water treatment tank (V, m^3) was determined using follow parameters :

$$V_2 = 10^{3.1279}\, C/N^{3.5461}\, C_m^{-3.7473}\, N_i^{4.6447}\, E^{0.0326}\, N_e^{-0.8849}\, Q$$
(Two Phase FB)

$$V_3 = 10^{11.7507}\, C/N^{-1.2330}\, C_m^{-6.5715}\, N_i^{1.5091}\, N_e^{-1.8489}\, Q$$
(Three Phase FB)

where V = volume of water treatment tank (m^3)
C/N = influent COD to NH_4^+-N ratio
C_m = concentration of media (g/L)
N_i = influent ammonia concentration (mg/L)
N_e = effluent ammonia concentration (mg/L)
E = expansion (%)
Q = influent flowrate (m^3/hr)

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