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Suspended solid and nitrate removal from aquaculture system wastewater by different approaches

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ABSTRACT

The present work aimed to develop the wastewater treatment process for the recirculating aquaculture system (RAS). Sedimentation, coagulation, and filtration were applied for treating suspended solid (SS) and nitrate in wastewater from a tilapia pond. The combination in series of sedimentation and dual-media filtration of sand–anthracite was found as the appropriate process for SS separation. The size of media and suspended particles can affect the filtration mechanism as well as filtration time and removal efficiency. SS removal efficiency of 92% with an average particle size of 28 μm in the effluent was obtained from the optimal experimental conditions of sedimentation and dual-media filtration. An overflow rate of 4.1 m/h was obtained as the optimal level, followed with an effective size of sand and anthracite of 0.80 and 2.00 mm, respectively. Moreover, up to 90% of nitrate was successfully removed via bio-filtration (with biofilm) after applying a C:N ratio of 2.1:1 and a filtration rate of 0.20 m/h.

Keywords: Bio-filtration; Dual-media rapid filtration; Nitrate removal; Recirculating aquaculture system; Suspended solid separation

1. Introduction

A recirculating aquaculture system (RAS) is an alternative method for aquaculture farms of shrimp and fish cultivation in many countries. Water quality management is strongly required for the operation of RASs, particularly the control of suspended solids (SSs), including fecal matter and uneaten food, and nitrogen compounds such as ammonia, nitrite, and nitrate [1]. The daily accumulation of SS in the RAS leads to a negative impact on aquatic life and reduces water quality, leading to such ill effects as damage to fish gills, the reduction of fish resistance to disease, and increase in biochemical oxygen demand [2–5]. Therefore, the reduction of SS and turbidity in the water is necessary for improving the water quality both for reuse in RAS and discharge to the environment. Furthermore, nitrate removal should be considered as well in order to prevent its adverse effects on dissolved oxygen depletion and ammonia toxicity in the aquatic system [6,7]. Common processes used for SS separation in the RAS are sedimentation, coagulation–flocculation, and filtration process. These conventional processes have different pros and cons in practical applications as well as in design and operation. As previously mentioned, the accumulation of various forms of nitrogen in water, for example, ammonia, nitrite, and nitrate can adversely affect the aquatic ecosystem. Post-treatment for nitrate removal is, therefore, necessary to maintain good water quality for the system. Slow sand filter (SSF) can be used to remove nitrogen in wastewater through biological nitrification and denitrification processes [8,9].

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However, SSF cannot be used as a single-stage treatment for raw water with certain turbidity [10]. Therefore, an appropriate series of treatment systems need to be thoroughly investigated in conjunction with optimal design criteria and operating conditions in order to achieve maximum treatment efficiency for RAS.

The objective of this work is to study and propose the suitable treatment processes for SSs and nitrates of RAS wastewater from the tilapia pond. The investigated processes, including sedimentation, coagulation–flocculation, rapid filtration (single and dual media), and bio-filtration, were examined to optimize the design criteria and operation conditions. The obtained results were compared in terms of treatment efficiency and operation conditions. The suitable treatment process was finally proposed for the RAS of a tilapia pond.

2. Materials and methods

The studied tilapia pond used for feeding 1-year-old Nile tilapias was constructed as a cylindrical high-density polyethylene tank with a diameter of 3 m and a depth of 0.7 m for containing a volume of 7 m^3. Thirty rigid diffusers were installed at the bottom of the pond for both aeration and mixing SSs. The wastewater from the pond was collected daily and analyzed for several parameters by the standard methods as summarized in Table 1 [11]. The change in a daily basis was observed. In addition, the particle size distribution in the wastewater was examined by the Malvern 2000 particle size analyzer (Malvern Inc., Worcestershire, UK). A range of particle size 0.1–995 μm was obtained, with a majority between 60 and 100 μm.

The overall flow concept of the wastewater treatment system is shown in Fig. 1. The influent wastewater was taken from the pond to enter the sedimentation tank, mixing tank for coagulation, and rapid sand filter. Finally, nitrate removal via bio-filtration was tested. Each process was conducted separately as batch experiments for individual laboratory performance and effortless control.

2.1. Sedimentation and coagulation process

The sedimentation process was conducted in a cylindrical acrylic column with a diameter of 0.3 m and a height of

Table 1
Characteristics of wastewater from tilapia pond

Parameter	Ranges	Mean	Analytical method
Ammonia nitrogen (NH_3–N), mg/L	0.0055–0.1800	0.07	4500–NH_3 D
Nitrite nitrogen (NO_2–N), mg/L	0.00042–0.14000	0.02	4500–NO^-_2 B
Nitrate nitrogen (NO_3–N), mg/L	7.09–13.4	8.34	4500–NO^-_3
Chemical oxygen demand (COD), mg/L	80.16–104.2	91.52	5220D
Turbidity, NTU	72.86–96.61	83.42	Turbidity meter
pH	7.28–8.69	7.88	pH meter
Suspended solid (SS), mg/L	123–204	156.90	2540D

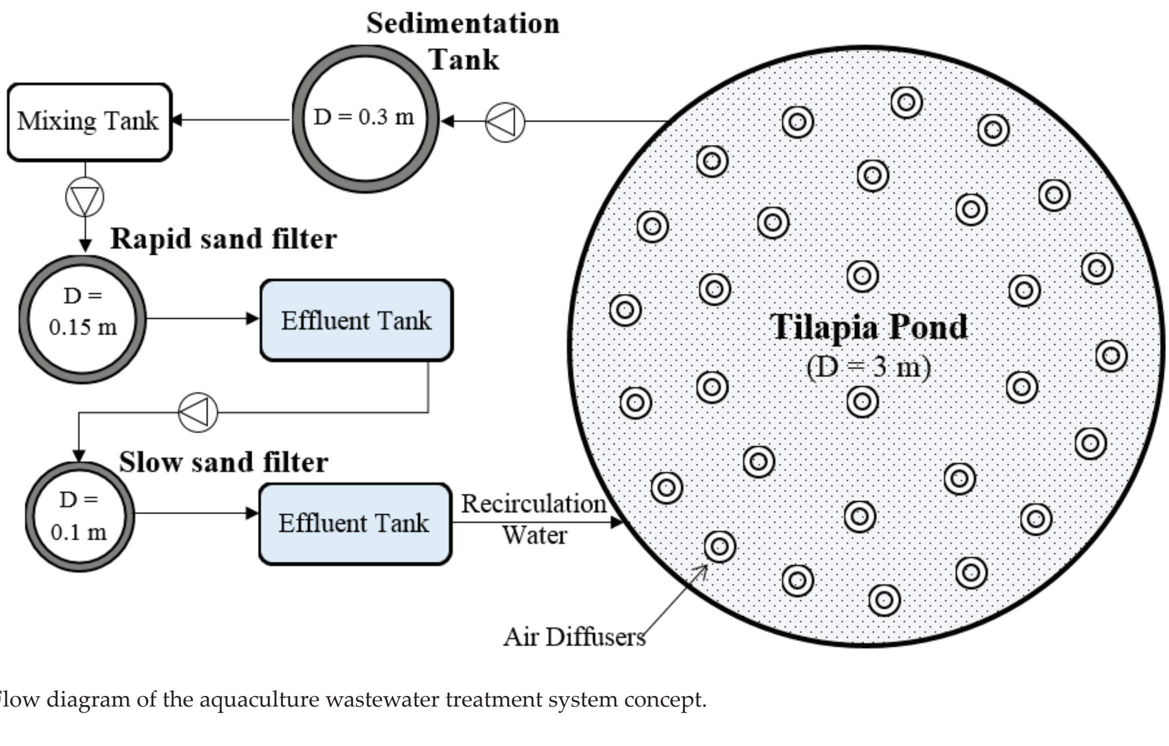

Fig. 1. Flow diagram of the aquaculture wastewater treatment system concept.

0.7 m, as shown in Fig. 2(a). The effect of the overflow rate (OFR) on SS removal was considered as the selection parameter. It was varied from 4.1 to 7.3 m/h to obtain the optimal level in terms of removal efficiency. Samples were collected and measured for changes in turbidity over time. Afterwards, the coagulation was examined by the jar test experiment to obtain the optimal coagulant dosage and pH as well as to observe sludge production. Alum was selected due to its benefits, including low price, high solubility, and availability in the market. The variation of alum concentrations from 5 to 80 mg/L was applied in rapid mixing of 100 rpm for 3 min, followed by 30 min of 40 rpm as slow mixing before allowing the aggregate to settle down for 45 min. However, some small particles might be expected to remain forming a cake layer that has the advantage of serving as a cake filtration mechanism [12].

2.2. Rapid and bio-filtration

Rapid filtration was examined at 0.15 m inner diameter and 1.8 m height clear acrylic column, as shown in Fig. 2(b). A conventional depth filtration using single media, sand with 0.55 mm of effective size, was used with bed porosity in the range of 0.42 to 0.45. Moreover, dual-media filtration was employed by using sand and anthracite. The thicknesses of the sand (D_{10} of 0.5 and 1.0 mm) and anthracite (D_{10} of 2.0 and 2.8 mm) layers were 0.15 m and 0.55 m, respectively. The same porosity of sand was used together with the conventional porosity of anthracite bed, 0.50. Three effective sizes of sand (0.55, 0.80, and 2.00 mm) and five effective sizes of anthracite (0.85, 1.60, 2.00, 2.36, and 2.80) were combined in the experiments by simple experimental design in order to obtain the optimum conditions. Gas diffusers were installed at the top, middle, and bottom of the filter depths for backwashing and enhancing the filtration performance by aeration. The filtration was continuously operated until clogging, which was indicated based on the pressure loss measured by the piezometer. The optimal results for the selected criteria were evaluated in terms of filtration rate, treatment efficiency, and operating time. The direct SSF which worked as bio-filtration was performed in an acrylic column with a diameter of 0.1 m and a height of 1.35 m as shown in Fig. 2(c). Ethanol was fed through the filter as the carbon source for bacteria, which are responsible for denitrification. The process was carried out at a constant flow rate until the media was clogged. The top 2 cm biofilm of the sand during the bio-filtration process was scraped off for analysis. The optimum ratio of carbon-to-nitrogen (C:N) was first investigated to optimize the carbon source for treating the nitrate present in the wastewater since it was reported as an important factor for biological denitrification.

3. Results and discussion

3.1. Suspended solid removal by sedimentation and coagulation

The experimental results showed that the SS removal efficiency decreased by 70.2%, 53.4%, 51.4%, 36.8%, 18.8%, and 16.0% after increasing respective OFR of 4.1, 4.9, 5.1, 5.8, 6.8, and 7.3 m/h. From these results, the highest efficiency of 70% was achieved at an OFR of 4.1 m/h. The efficiency decreased after increasing OFR further, since particles do not have enough time to settle down in the tank. It can be concluded that an OFR of less than 5 m/h should be selected in order to obtain a separation efficiency higher than 50%. However, the low flow rate or large surface of sedimentation tank to acquire this OFR range was the major drawback. The chemical coagulation, another pretreatment technique for SS removal from aquaculture wastewater [13], was ,therefore, tested to overcome this disadvantage.

In chemical coagulation, there was no pH adjustment since the wastewater contained sufficient alkalinity to counter the change of pH. As shown in Fig. 3, SS removal efficiencies higher than 97% were observed from alum dosages of 5–30 mg/L. At greater dosages, the efficiency was reduced. This can be explained by the destabilization mechanism that related to the change of pH. The dissociation of aluminum

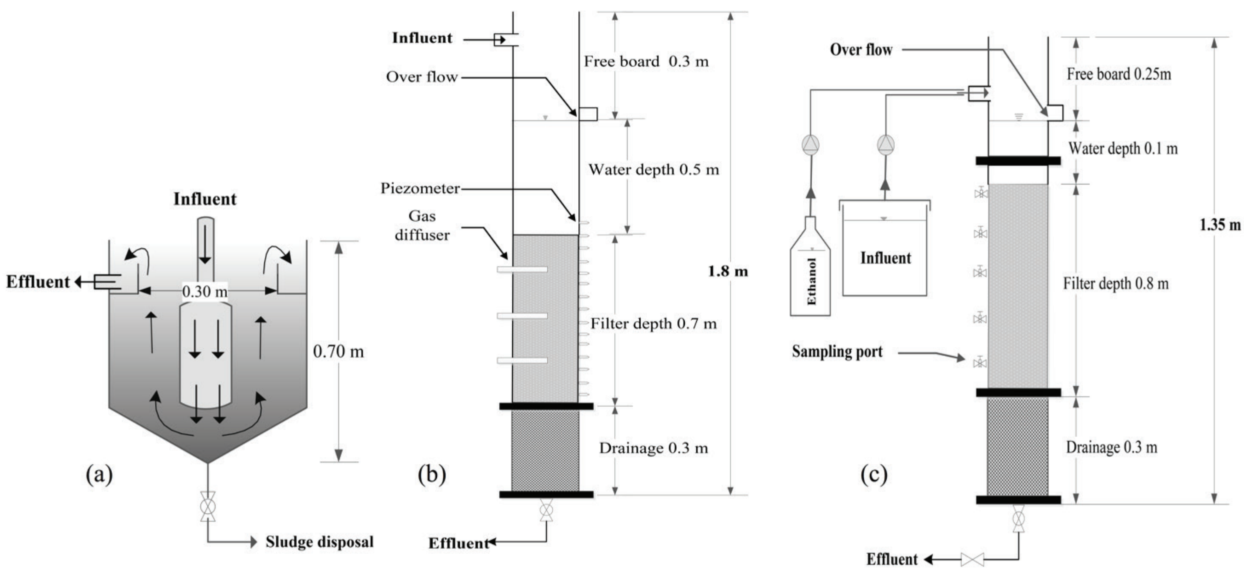

Fig. 2. Detail schematic diagrams of (a) sedimentation tank, (b) rapid sand column, and (c) slow sand column for bio-filtration.

sulfate resulted in a reduction of pH [14]. A pH of 5–7 was obtained in the effective alum dosages corresponding to the range of the sweep flocculation mechanism [15]. This can be proven by the flocs formed in the system. However, large volumes of generated sludge, approximately 153.3 mg/L, was the main problem of the coagulation as the appropriate disposal process is required. Moreover, this process contains a large footprint consisting of mixing tank, flocculation tank, and sedimentation tank, which is hard to apply in a practical scenario. As a result, another SS removal method was considered. Solid separation by rapid filtration was applied. The single media of sand tested as well as the dual media of sand–anthracite is shown in the next section.

3.2. Suspended solid removal by rapid filtration

First, a depth filtration using sand as a single media with porosity of 0.42–0.45, which corresponded to typical sand filters for wastewater treatment (0.40–0.45) [16], was performed. However, it encountered a clogging problem resulting in a short operation time (5–7 min) with a low accumulated effluent volume of approximately 7 L. This single media filtration was, therefore, unsuitable for SS removal from the tilapia pond wastewater. For improving overall filtration performance, dual-media filtration was employed with sand and anthracite. The same porosity of sand media was used altogether with the anthracite bed (porosity of 0.50) [17]. Three effective sizes of sand (0.55, 0.80, and 2.00 mm) and five effective sizes of anthracite (0.85, 1.60, 2.00, 2.36, and 2.80) were combined in separation tests by simple experimental design. The results can be summarized in Table 2. As can be seen, the operating time and accumulated effluent volume were enhanced by using the dual-media filtration compared with the single media application. These values depend on the effective size of both media. By using a dual media of 2.80 mm anthracite and 2.00 mm sand, the operating time and the effluent volume were enlarged to 96 min and 350 L, respectively. However, the best scenario of the rapid filtration, considering the efficiency with operating time, was 0.80 mm of sand and 2.00 mm of anthracite, which provided efficiency up to 89% and an operation time of 80 min. It was indicated that the dual media with the large sand size, 2.00 mm, was inappropriate for the separation of SS due to its lower efficiency. On the other hand, a size variation of anthracite slightly affected the efficiency. These two cases were selected in further experiments for improving the treatment performance in combination with sedimentation.

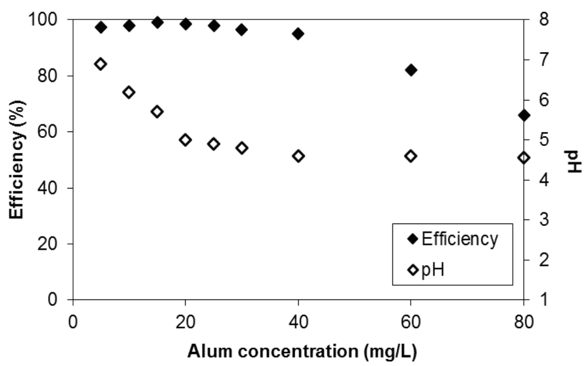

Fig. 3. Variation of treatment efficiency and pH with alum concentration.

3.3. Pre-treatment by combination of sedimentation and dual-media filtration

The selected conditions of the rapid filtration were applied with an optimal OFR of sedimentation of 4.1 m/h in this part. The results without and with sedimentation are summarized in Table 3. The removal efficiencies of the studied conditions of dual-media filtration without and with sedimentation showed only slight differences. However, the operating time was greatly increased. The highest efficiency was obtained from set B (sand 0.80 mm and anthracite 2.00 mm with sedimentation) with a longer operating time compared with only filtration under the same conditions as set A.

The advantage of this combined process was an increase of filtration rate, operating time, and total effluent volume, since the removal of SSs via sedimentation can reduce the solid loading of the filter as well as the particle deposition on the media surface. It can be clearly seen from Table 4 that large particle sizes were eliminated after the sedimentation since the particle size interval was greatly changed as well

Table 2
Results of rapid filtration with different sizes of media

Effective size of sand/anthracite (mm)	Filtration rate (m/h)	Efficiency (%)	Turbidity (NTU)	Operating time (min)	Effluent volume (L)
0.55/0.85	8.18 ± 2.3	89.47 ± 5.4	8.64 ± 4.4	30	65
0.80/1.60	7.41 ± 3.6	89.94 ± 3.3	8.17 ± 2.7	74	130
0.80/2.00	8.42 ± 3.5	89.65 ± 2.6	8.68 ± 2.3	80	180
0.80/2.36	6.14 ± 2.1	93.2 ± 1.6	4.96 ± 1.1	57	100
0.80/2.80	6.44 ± 1.8	90.65 ± 2.9	7.44 ± 2.3	54	100
2.00/1.60	19.63 ± 4.5	78.15 ± 7.4	20.08 ± 6.8	27	150
2.00/2.00	13.44 ± 4.1	75.5 ± 9.0	18.89 ± 7.0	54	210
2.00/2.36	14.65 ± 4.5	73.76 ± 8.7	23.73 ± 7.9	80	300
2.00/2.80	13.97 ± 4.6	71.23 ± 10.3	27.79 ± 10	96	350

Table 3
Results of the combined process between rapid filtration and sedimentation

Parameter	Sand 0.8 mm / anthracite 2.00 mm		Sand 2.0 mm / anthracite 2.80 mm	
	Without sedimentation (A)	With sedimentation (B)	Without sedimentation (C)	With sedimentation (D)
Filtration rate (m/h)	8.42 ± 3.5	13.22 ± 4.6	13.97 ± 4.60	16.70 ± 3.5
Efficiency (%)	89.65 ± 2.6	92.22 ± 1.0	71.23 ± 10.3	61.28 ± 14.2
Turbidity (NTU)	8.68 ± 2.3	4.25 ± 0.6	27.79 ± 10.0	23.92 ± 6.4
Operating time (min)	80	130	96.2	375
Effluent volume (L)	180	445	350	1,710

Table 4
Size of suspended solid

Sample	Interval (μm)	Mean (μm)
Influent	0.1–995	412
Effluent from sedimentation	0.1–120	95
Effluent from set B	0.1–110	28
Effluent from set D	0.1–110	55

as the average diameter. Furthermore, the average size of particles was reduced when combining with the dual-media filtration, as the results of sets B and D clearly show. For the smaller sand size of 0.80 mm, the benefit of SS separation can be seen on the prolonged operating time since the clogging probability was reduced. The remaining small particles can still form a cake layer, resulting in similar efficiency achieved when comparing sets A and B.

In the cases of the sets C and D with large effective size of sand and anthracite, the combination of sedimentation and filtration provided a negative effect due to the large particles having already been separated by sedimentation. Less deposition on the media surface can be expected. As a result, the cake filtration mechanism was less effective for entrapping small particles. Therefore, a lower efficiency was obtained. The prolonged operating time and increased effluent volume of respective 375 min and 1,710 L can affirm the lower levels of the formation of cake layer on the filtration media.

To analyze the variation in pressure and the media clogging in the filtration, water height from the piezometer was analyzed and its result was shown in Fig. 4. Heights of 50–70 cm and 0–50 cm (as shown in Fig. 2(b)) were measured for pressure loss (ΔP) of anthracite and sand layers, respectively. The effects of sedimentation on pressure distribution of the filter can be noticed, which resulted in the improvement of the overall operating time and the accumulated effluent volume. Complete clogging did not occur in the anthracite layer, but did in the sand layer (ΔP = 0 cm). In the case of the dual media with sedimentation (sets B and D), the clogged position in the sand layer was lower than that of the dual media without sedimentation (sets A and C). This corresponded to the fact that larger particles were already removed by the sedimentation. It can be suggested that the evaluation of pressure distribution is necessary for analyzing the clogging mechanism in the filter media.

In conclusion, for SS separation, the combined process of sedimentation and dual-media filtration is suitable for tilapia pond wastewater with optimal conditions including 4.1 m/h for sedimentation OFR, and 0.80 mm of sand with 2.00 mm of anthracite for dual-media filtration. However, this process is unable to solve another problem of this wastewater in the form of nitrate (NO_3^-). The SSF that functioned as bio-filtration was, therefore, selected to deal with this problem.

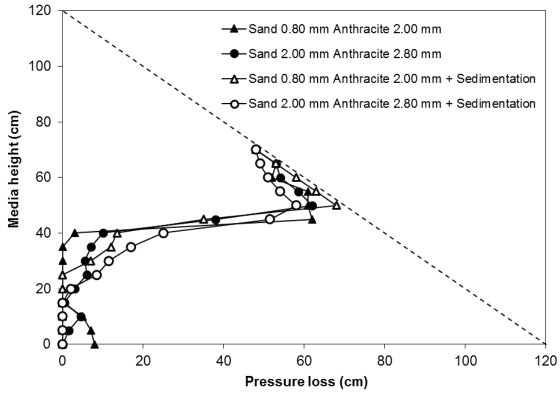

Fig. 4. Pressure distribution of filter depth variation in dual media until and after clogging.

3.4. Nitrate removal by bio-filtration

Direct SSF without sedimentation and dual-media filtration were studied as the control system with a very short operating time (less than 15 min) due to clogging from the excessive amounts of SS in wastewater corresponding to that suggested by Kawamura [18]. Using only SSF was inappropriate for removing nitrate due to the filtration time and insufficient detention time for the biological process. Subsequently, the combined process from SS separation was used as pre-treatment before SSF at a filtration rate of 0.4 m/h. This can increase the filtration time of the SSF, but no nitrate removal was observed. The biological process can assist this via the denitrification mechanism [19]. An idea of bio-filtration was selected since it was reported as a simple method for water reuse in the RAS [20].

Therefore, microbial growth on the filter media was stimulated using ethanol as a carbon source for the denitrification process as presented in Fig. 2(c) [21]. As mentioned, the optimal C:N ratio was investigated due to it being an important factor for biological denitrification [22] that its amount was added based on the initial wastewater characteristic as shown in Table 1. Nitrate concentrations of 45–53 mg-N/L were maintained during the experiments. At the initial start-up, a low velocity of about 0.02–0.03 m/h was used to enhance the microbial growth along the filter bed, and the nitrogen compounds (NH_3, NO_2^-, and NO_3^-) were measured. Subsequently, when effluents were obtained with a low nitrate concentration, the filtration rate was gradually raised to 0.05 m/h regardless of the C:N ratio. Fig. 5 presents the variation in nitrate concentrations with operating time for different C:N ratios at a filtration rate of 0.05 m/h.

Nitrate removal by bio-filtration occurred after 2 d, possibly because the ethanol promoted the accumulation of native microorganisms in the tilapia pond. The nitrate profile along the filter depth showed that high treatment efficiency was obtained, especially at the top of the filter media. About 88% of the nitrate removal efficiency was achieved at the first 10 cm of the bed, which was in accordance with the results of Aslan [23]. Efficiency higher than 90% can be acquired at all C:N ratios in this study as the remaining nitrate concentration in the effluent was 1.9–3.37 mg-N/L. A comparison of the various C:N ratios from 10:1 to 2.1:1 showed that there is no significant difference in nitrate removal. However, increased nitrate concentration in the effluent from 3.37 to 45.78 mg-N/L was detected at the C:N ratio of 1.8:1, which could be the result of insufficient carbon source for the bacterial growth. The remaining carbon should be evaluated in terms of chemical oxygen demand (COD) as presented in Fig. 6. The COD at the C:N ratios of 10:1 and 8.5:1 remained at a high concentration in the effluent (<1,000 mg/L). Under these conditions, some ethanol might be consumed by the anaerobic bacteria for growth, and hydrogen sulfide (H_2S) was produced [24]. Moreover, with C:N ratios of 5:1 and 3.5:1, a lower C concentration (100 < COD < 500 mg/L) can be found, although the carbon source was still incompletely consumed in the SSF. For a C:N ratio of 2.1:1, the C concentration (as COD) was roughly constant and close to 100 mg/L. Finally, the lowest remaining C concentration (62.07 mg/L) was found with a C:N ratio of 1.8:1, at which level the nitrate concentration unexpectedly increased. This affirmed the discussion on the insufficient carbon source for the denitrification. Therefore, it can be concluded that the C:N ratio of 2.1:1 was the optimal value for nitrate treatment of wastewater from the tilapia pond. This ratio value was similar to that used for nitrogen removal in a batch experiment [25] but much lower than those in several works for denitrification [22,25,26].

Furthermore, the effects of the filtration rate on nitrate removal by bio-filtration were determined. Fig. 7 exhibits the variation of nitrate concentration with operating time for different filtration rates. A C:N ratio of 2.1:1 was used in this experiment. The high consumption of ethanol as a carbon source occurred when the filtration rate was low (0.5 m/h). For higher rates of 0.2 m/h, surplus nitrate from 2.16 to 3.2 mg/L was found. Nevertheless, these values were acceptable since the standard for nitrate was 10 mg-N/L. Augmenting the filtration velocity provides an advantage to the bio-filtration construction and operational cost. Therefore, the optimal conditions of filtration in this study should be 0.2 m/h of filtration rate and a C:N ratio of 2.1:1. This information should be useful and applicable for scaling up the system in real application processes.

In order to confirm denitrification in bio-filtration, the additional experiment on nitrate consumption in the batch unit was conducted with a C:N ratio of 2.1:1 and a filtration rate of 0.2 m/h. A biomass concentration of 1,437 mg-volatile solid/L was obtained. Then, the biofilm was used in a batch filtration experiment for nitrate removal. From the result, nitrate concentrations decreased from the initial concentration of 50 to 9 mg/L, which is compatible with the discharged

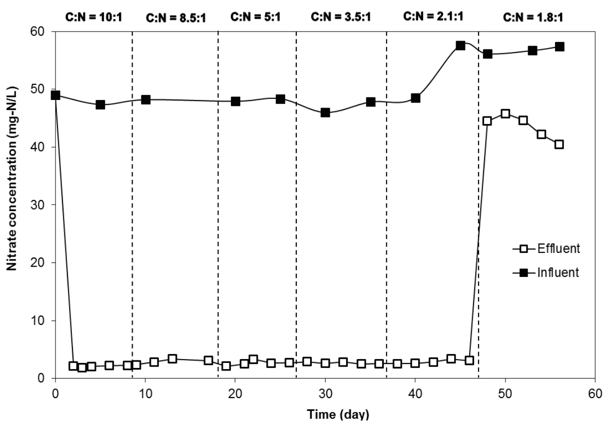

Fig. 5. Nitrate concentrations of influents and effluents for the various C:N ratios.

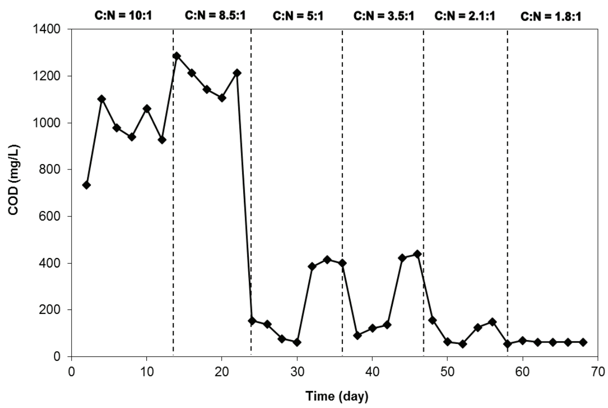

Fig. 6. COD of the effluent at different C:N ratios.

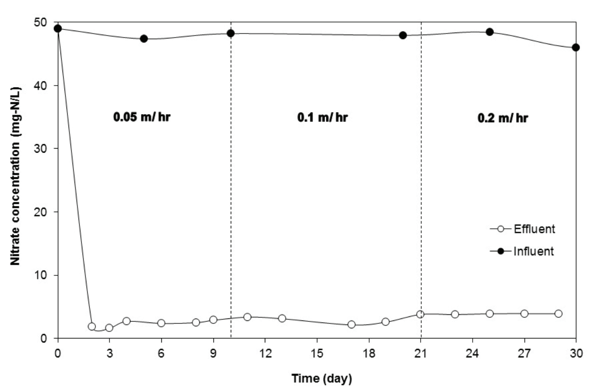

Fig. 7. Nitrate concentrations at different filtration rates (0.05–0.2 m/h).

water quality in Thailand [27], at 330 min. The filtration rate of less than 0.2 m/h of this batch experiment can provide acceptable NO_3–N (<10 mg N/L) levels in effluent from tilapia wastewater. Moreover, the COD of the wastewater was analyzed to evaluate the ethanol consumption in this process. The concentration of COD in the effluent was reduced compared with the initial concentration from 2,700 to 517 mg/L at 360 min, and then remained roughly constant. Therefore, 143.75 mg/L of ethanol was used in the batch unit in order to remove a nitrate concentration of 50 mg-N/L. Note that this value was higher than the ethanol consumption calculated from a stoichiometric equation that includes the cell synthesis of heterotrophic denitrification with ethanol as a carbon source [28].

4. Conclusions

In this work, the multi-treatment process, including sedimentation, dual-media filtration, and bio-filtration, was able to treat wastewater from a 7 m^3 tilapia pond. First, the sedimentation tank at an OFR of 4.1 m/h was used as pre-treatment to remove the SS. Consequently, it was combined with the dual-media rapid filtration of sand and anthracite to achieve effective separation of SSs. The effective media sizes of 0.80 and 2.00 mm of sand and anthracite, respectively, were found as the optimal values. Finally, the slow sand filtration with microbial growth as a biofilm can effectively remove nitrate from the wastewater with a C:N ratio of 2.1:1 and a filtration rate of 0.2 m/h. The suitable design criteria and operating conditions for tilapia wastewater treatment as determined by this study are described below:

- For pre-treatment by sedimentation with an OFR of 4.1 m/h is required for SS removal of different treatment purposes such as wastewater recirculation, wastewater discharge, and SS and nitrate removal for RAS.
- For the SS removal, the combination of pre-treatment (sedimentation) and separation unit by dual-media filtration is required. In wastewater discharge purpose, dual-media filtration with 0.80 mm sand and 2.00 mm anthracite are preferred, while 2.00 mm sand and 2.80 mm anthracite are required for wastewater recirculation purpose.
- For SS and nitrate removal for RAS, sedimentation as pre-treatment followed by separation and biological units are required. Dual-media filter with 0.80 mm sand and 2.00 mm anthracite was optimized for SS removal. SSF with 0.45 mm sand, filtration rate of 0.2 m/h, and a C:N ratio of 2.1:1 was finalized for bio-filtration.

Acknowledgments

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