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Nitrification performance of a propeller-washed bead clarifier supporting a fluidized sand biofilter in a recirculating warmwater fish system

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Abstract

A propeller-wash bead filter (PWBF) and a fluidized sand filter (FSF) on a 28 m^3 recirculating system stocked with tilapia maintained favorable water quality at five different feed rates, ranging from 0.9 to 4.5 kg feed per day. TAN removal rates ranged up to about 200 g TAN/m^3 of media per day for each of the units. Peak rates of 244 g TAN/m^3 of media per day were observed when the recirculating flow was boosted by 20%. Roughly 75% of the removal was accomplished by the fluidized sand filter an observation that is consistent with the difference between the fluidized sand filter volume (0.92 m^3) and the bead filter media volume (0.28 m^3). The bead filter's primary function was clarification. At the highest daily feed load, over 570 g dry weight of solids were removed during each daily bead filter backwashing event. A 20% increase in flow, at the same daily feed rate, improved solids removal to over 670 g dry weight per bead filter backwash event. The PWBF and FSF combination provided suitable water quality for fish production; however, further increases in feed loading were limited by carbon dioxide buildup and oxygen limitations.

Keywords: Recirculation; Bead filter; Sand filter

1. Introduction

Properly designed and managed water treatment components of a recirculating aquaculture system provide a healthy environment promoting fish growth and survival. A variety of waste products are generated within a recirculating system that must be removed from the culture water before toxic conditions are reached. The wastes generated include solid material from fecal matter and uneaten feed, bacterial biofloc, total ammonia nitrogen, TAN (ammonia, NH_3 and the ammonium ion, NH_4^+), carbon dioxide and other soluble and non-soluble materials. These waste materials need to be managed so that the stress on the system and fish are minimized.

The basic processes used to recondition the water in a recirculating aquaculture system includes: (1) water recirculation, (2) solids capture to remove fecal waste,

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uneaten feed and biofloc material, (3) biological filtration, to oxidize biodegradable organics, ammonia and nitrite-nitrogen, (4) aeration supplying oxygen for the fish and biofilters, and (5) carbon dioxide removal. Some systems can require additional components for disinfection of culture water or components for removal of fine particulate and dissolved organic matter (Losordo et al., 1998). Both the bead filter and fluidized sand filter have documented success in aquaculture applications (Timmons and Summerfelt, 1998; Malone et al., 1993). A distinguishing characteristic of the bead filter is its ability to maintain ammonia removal rates comparable with other fixed film filters while removing solids (Wimberly, 1990; Chitta, 1993). Normally, solids capture and biofiltration processes are accomplished as sequential unit operations. A floating plastic bead media (approximately 3 mm in diameter) provides a granular matrix for particle filtration by straining, settling and intercepting suspended particles from the wastewater stream. Simultaneously, the floating plastic bead media operates as a fixed film bioreactor allowing nitrifying bacteria within the media biofilm to perform the nitrification process. Backwashing the bead filter either mechanically, pneumatically or hydraulically induces the shedding of excess biofloc and solids accumulated within the interstitial space of the floating beads. Since the low-density polyethylene beads float, a natural separation process occurs between the dislodged heavier solids and floating plastic media during the settling phase of the backwash process. The use and ability of the bead filter for solids capture is straightforward (Drennan et al., 1995). However, for integrated treatment, the nitrification capacity of the floating bead filter is affected by several factors including the

Fig. 1. Photo of a 0.28 m^3 propeller-wash bead filter evaluated in the study with an inset of the floating plastic bead media.

backwash frequency and duration, the intensity of the backwash, feed loading rates, and the media configuration.

The use of the filter to serve concurrently in a solids removal and nitrification capacity has been demonstrated in various recirculating aquaculture systems. Good nitrification in this ‘‘bioclarifier’’ mode is dependent on filter management. These same principles apply when the bead filters is operated as a clarifier in conjunction with a biofilter. Alleviated of the primary nitrification burden, the filters can handle clarification loads as high as 80 kg feed per m^3 of media (Wheaton et al., 1994). This paper focuses on the nitrification performance and solids removal capabilities of a 0.28 m^3 propeller-wash bead filter (PWBF, Fig. 1) operated as a clarifier in series with a fluidized sand filter. Emphasis is placed upon the factors influencing the PWBF's nitrification capacity.

2. Materials and methods

2.1. Recirculating system

The recirculating aquaculture production system is located in the aquaculture research park of Harbor Branch Oceanographic Institution, Fort Pierce, FL. The system consists of two 3.65 m diameter panel fiberglass circular tanks with a sloping bottom. Culture volume for each tank is approximately 12,500 L with a Cornell dual drain design. A center bottom drain (5 cm diameter) of each tank provides low-volume, high solids effluent flow (approximately 10% of system flow) into a 0.6 m diameter (265 L) swirl separator (W. Lim Corportion, San Diego, CA). Flow from the swirl separator joins the high volume flow from the elevated sidewall drain (10.2 cm diameter) of each tank into a wastewater sump of approximately 700 L. Flow from the sump is pumped to a propeller-wash bead filter with 0.28 m^3 of floating plastic bead media (Aquatic Systems Technologies LLC, New Orleans, LA) at a flow rate of approximately 305 Lpm. Backwashing of the PWBF was an automated process activated daily. The prop-wash duration was set for 1 min, the settling time after the prop-wash is factory set for 10 min, and the time to purge the backwash for solids removal after the settling period was 1 min. Additional biofiltration was provided by a fluidized sand filter, (Aquaneering Inc., San Diego, CA) that is 1.5 m in diameter with a volume of 2180 L. The filter was filled with 1510 kg of silica sand (0.92 m^3) that had a D_{50} equal to 0.37 mm and a uniformity coefficient of 3.1. From the sand filter, water gravity flowed back to the culture tanks

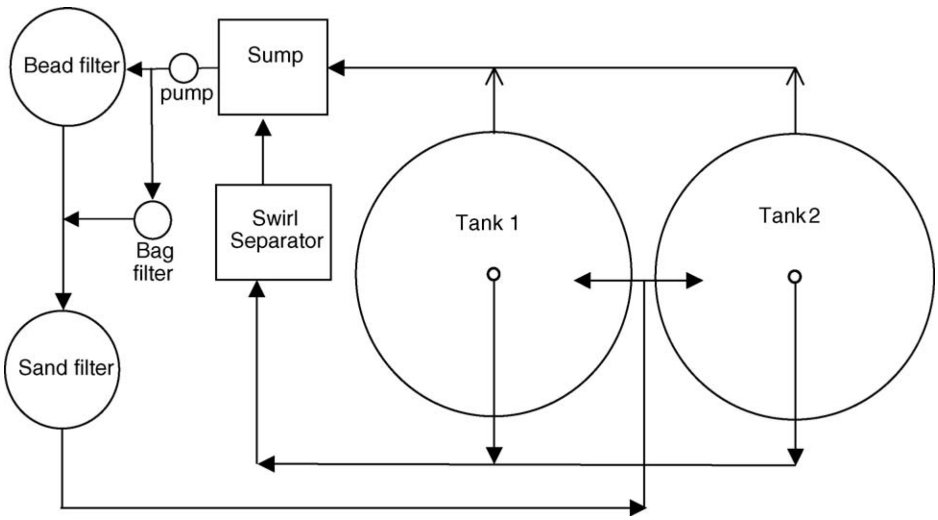

Fig. 2. Schematic of recirculating aquaculture system with the two 12.5 culture tanks, propeller-wash bead filter, fluidized sand filter, 25 micron bag filter on the bead filter bypass, the 700 L sump, 650 L swirl separator, and two pump (2 hp) array. Approximate system volume of 28.1 m^3 a with a tank turnover time of roughly 80 min.

through a 10.2 cm diameter PVC pipe. Water entered each culture tank via a slotted 5.1 cm diameter PVC pipe. Water flow into the tank was controlled by a manual ball valve. All PVC piping and fittings were Schedule 40. Tank aeration was provided by four 1.5 m bioweave diffuser hoses (Aquatic Eco-Systems, Apopka, FL) placed around the tank perimeter and supplied with air by a 5 kW regenerative air blower. The schematic of the system is provided in Fig. 2.

2.2. Fish stocking, feeding and harvest

Each tank was stocked with tilapia fingerlings for a two-phase growout production strategy. Tanks 1 and 2 were stocked initially with 360 and 940 fish with a total weight of 121.4 and 20.7 kg, respectively. All feed provided was a floating feed, and a 3.1 mm pellet fed to the larger size fish was 32% crude protein (CP) and a 2 mm, 45% CP pellet was used for feeding the smaller sized fish. There were eight sampling events during the filter evaluation period. Table 1 provides the sampling day, daily feed load into each tank, feeding and PWBF backwashing frequency and the estimated total ammonia production (P_{TAN}) from the feed into the system. P_{TAN} is based upon the fish feeding rate using the following equation (Timmons et al., 2001):

$$P_{TAN}(\text{g/day}) = F \times \text{PC} \times 0.092\,\text{day}^{-1} \quad (1)$$

where F is the daily feed ration in grams, PC the percent crude protein of the feed and 0.092 is a constant in the equation derived from a series of estimates formulated from the percent nitrogen in protein and the protein assimilation.

Sampling of the system was conducted when the system was at steady state which was defined as consistent daily water quality levels (dissolved oxygen, pH, ammonia and nitrite concentrations) and feeding rates. Feed ration was increased after each 3–4 day sampling event except when the backwash intervals or system flow rates were altered. There was one harvest event during the evaluation period. After 143 days, Tank 1 was harvested and restocked with 3415 tilapia fingerlings with a total weight of 87.7 kg. Tank 2 was stocked with an additional 63 fish from the harvest of Tank 1. When the system feed rate was 2.4 kg per day, the feeding frequency was increased from twice a day to three times a day which occurred at 09:00, 12:00 and 18:00 to insure complete consumption of the feed. There were no large mortality events during the 307 day filter evaluation period.

2.3. System sampling

Water quality in the system was sampled daily by measuring pH (in the sump) and dissolved oxygen and temperature in the tanks with hand-held meters (YSI Model Y85 and Y63, Yellow Springs, OH). Alkalinity of the system culture water was measured two to three times weekly with a HACH test kit (Ames, IA) and maintained within the range of 100–150 mg/L $CaCO_3$ through the addition of sodium bicarbonate.

To obtain the apparent nitrification performance of the PWBF and the FSF, the sampling regime for the biofilters was a multi-day, multi-event routine. Sampling was conducted 4 consecutive days and

Table 1
Sampling event log and associated system operating activity for the two tank recirculating aquaculture system for tilapia production

Sampling event	Day	Feed ration (g/feeding)		System feed rate (kg/day)	Backwash frequency (h)	P_{TAN} (g TAN/day)
		Tank 1	Tank 2			
1	76	300	150[a]	0.90	24	30.1
2	112	500	300[a]	1.60	24	54.3
3	132	450	350[a]	2.40	24	83.2
4	188	800[a]	350	3.45	24	130.3
5	202	800[a]	350	3.45	36	130.3
6	230	1050	450	4.50	36	132.5
7	258	1050	450	4.50	24	132.5
8[b]	307	1050	450	4.50	24	132.5

[a] Feed was a 2-mm floating pellet with a 45% crude protein content.
[b] System flow rate during this sampling event increased to approximately 350 Lpm from 305 Lpm due to replacement of pumps.

the biofilters were sampled every 6 h (06:00, 12:00, 18:00 and 24:00) with the backwash frequency set at once every 24 h. Discrete inlet and outlet water samples from the biofilters were collected for TAN analysis. Water samples for TAN were analyzed immediately after collection using the HACH DR/2400 portable spectrophotometer. All analyses were done in duplicate with the mean value being used for data analysis. Flow rates were measured with an Ultrasonic Flow meter (PortaFlow SE model, Greyline Instruments, Messena, NY).

The purged water volumes from the swirl separator and PWBF during the sampling periods were collected in plastic containers. Dimensions of the containers including the height of the purge volume in the container were used to calculate the purged wastewater volume. After volume measurement, one liter of a well-mixed sample was collected from the containers and analyzed in triplicate according to Standard Methods (APHA, 1995) for total suspended solids for each solids removal device.

2.4. Filter performance analysis

For each feed loading, backwash frequency or system flow rate, the volumetric total ammonia nitrogen conversion rate (VTR) was used as the principal indicator for evaluation of the filter performance. The VTR, was obtained by using Eq. (2):

$$\mathrm{VTR} = \frac{K_c(\mathrm{TAN_I} - \mathrm{TAN_E})Q_r}{V_b} \quad (2)$$

where VTR is the g TAN converted per m^3 of filter media per day; Q_r the flow rate through the filter (Lpm); K_c the unit conversion factor of 1.44; $\mathrm{TAN_I}$ and $\mathrm{TAN_E}$ the influent and effluent ammonia concentration in mg/L and V_b is the volume of filter media (0.28 m^3 for the PWBF and 0.92 m^3 for the FSF).

For solids capture analysis of the swirl separator and PWBF, samples were obtained daily from the collected sludge volume of each unit during the 4-day sampling period. The volume of sludge and data from the total suspended solids (TSS) analysis of the sludge samples were used to determine the dry weight of solids removed from the system by these two components. The TSS analysis of the samples was conducted in triplicate with diluted sample volumes ranging from 10 to 100 mL, depending on the observable solids concentration.

3. Results and discussion

3.1. System water quality

Variations in water quality with changes in feed loading rate, backwash frequency and flow rate are presented in Table 2. The water quality data provided reflects the system sump conditions before the water passes through the PWBF and fluidized sand filter. Acceptable levels of TAN and NO_2-N were attained at all the load rates, backwash frequencies and flow rates evaluated. There was a water temperature range during the filter evaluation period of approximately 7 °C reflecting ambient air conditions in the greenhouse. This was minimized by covering the transparent polycarbonate greenhouse with a 90% shade cloth. Initially, eight 15.2 cm air diffuser stones were used for tank aeration but were replaced with four 1.2 m length bioweave diffuser hoses (Aquatic Eco-Systems, Apopka, FL) to increase the dissolved oxygen concentration of the culture water as the feed rates

Table 2
Mean (± standard deviation) water quality data measured from the system sump during each sampling event

Water quality parameter	Sampling event							
	1	2	3	4	5	6	7	8
DO (mg/L)	7.6 ± 0.3	7.0 ± 0.3	6.2 ± 0.3	5.6 ± 0.4	4.9 ± 0.4	4.2 ± 0.4	4.6 ± 0.4	4.0 ± 0.5
pH	7.8	7.6	7.3	7.2	7.2	7.3	7.2	7.2
Temperature (°C)	22.3 ± 0.9	21.0 ± 0.4	23.1 ± 0.7	24.2 ± 0.9	26.3 ± 0.5	28.7 ± 0.3	27.7 ± 0.6	27.4 ± 0.3
TAN (mg/L)	0.16 ± 0.01	0.28 ± 0.05	0.40 ± 0.03	0.66 ± 0.05	0.73 ± 0.01	0.69 ± 0.07	0.74 ± 0.11	0.73 ± 0.09
NO_2-N (mg/L)	0.021 ± 0.006	0.025 ± 0.006	0.045 ± 0.011	0.056 ± 0.015	0.094 ± 0.052	0.072 ± 0.045	0.143 ± 0.064	0.079 ± 0.034

Table 3
Variation in a 24 h period of the volumetric TAN conversion rate (g TAN converted per m^3 filter media per day) and g TAN removed per day of the propeller-wash bead filter with 0.28 m^3 of media at five daily feed rates with a backwash frequency of 24 h

Time after backflush (h)	Daily feed rates (kg/day)				
	0.9	1.6	2.4	3.45	4.5
6	37.6	45.5	81.2	79.2	129.0
12	59.8	43.9	69.8	53.8	141.5
18	49.4	45.4	65.2	110.7	84.8
24	54.4	38.9	49.3[a]	62.2	48.4
Average	50.3	43.7	67.5	76.5	100.9
Standard deviation	±26.4	±21.1	±27.1	±47.1	±48.4
g Tan removed	14.2	12.4	19.1	21.7	28.6

[a] Values are an average from 4 consecutive days of sampling unless noted where sampling events, N, would equal 3.

increased. At the highest feed rate, 4.5 kg/day, the dissolved oxygen concentration of the water exiting the fluidized sand filter was near 1.0 mg/L. The effluent DO level of the PWBF however, was maintained above the 2.0 mg/L level considered necessary for satisfactory bead filter nitrification performance. System pH was maintained above 7.0 through the addition of sodium bicarbonate at a rate of approximately 0.25 kg per kilogram feed.

During the filter evaluation period the feed rate was steadily increased in response to fish growth. This caused a steady increase in the TAN production, P_{TAN}. However, when the feed was increased from 3.45 to 4.5 kg/day, the protein of the feed was dropped to 32% versus the original 45% crude protein, CP, in all tanks. As a result, the P_{TAN} only increased 1.7%. Thus, the organic loading increased by 30% dramatically increasing the C/N (carbon to nitrogen) ratio but there was only a minute increase in the P_{TAN}.

3.2. Biofilter nitrification performance

The variation in a 24-h period of the volumetric nitrification rate (VTR) of the PWBF and FSF for the five daily feed rates when the backflush frequency for the PWBF was 24 h and system flow was 305 Lpm is presented in Tables 3 and 4. Values in the tables are the average measured value from 4 consecutive days of sampling. The PWBF was backwashed at 06:00 and first feeding was at 09:00 or 3 h after filter backwashing. The second and third feedings were 6 and 12 h after the backwash event and water samples for TAN analysis during these periods were collected before the feeding event.

Numerous studies have indicated that increasing the TAN concentration in biofilters results in proportional improvements in a filter's conversion ability (Rogers and Klemetson, 1985; De Los Reyes and Lawson, 1996; Malone et al., 1999; Sandu et al.,

Table 4
Variations in a 24-h period of the volumetric nitrification rate (g TAN converted per m^3 biofilter media per day) and g TAN remover per day of the fluidized sand filter with approximately 0.92 m^3 of media at five daily feed rates

Time after backflush (h)	Daily feed rates (kg/day)				
	0.9	1.6	2.4	3.45	4.5
6	24.9	34.0	49.2	71.7	97.3
12	21.4	42.8	77.7	90.0	134.4
18	24.9	38.8	73.4	82.5	106.9
24	20.3	34.0	44.8	55.5	87.1
Average	23.1	36.8	59.2	72.2	100.1
Standard deviation	±7.2	±10.2	±18.1	±16.3	±25.7
g TAN removed	21.3	33.9	54.6	66.6	92.3

Values are an average from 4 consecutive days of sampling.

2002). This was evident throughout the study except on a single occasion. At the 1.6 kg/day feed rate, the VTR nitrification performance of the PWBF decreased approximately 13% with a P_{TAN} increase of 80% and an actual measured TAN concentration increase of 75%, from 0.16 to 0.28 mg/L. The water temperature during that sampling period was the lowest during the evaluation period but not believed to have been the dominant factor resulting in a decreased VTR for the PWBF. Usually variable temperatures have little effect on the performance of biofilters except at extreme temperatures and mainly lower temperatures (Haug and McCarty, 1972; Harremoes, 1982; Fdez-polanco et al., 1994). Perhaps the PWBF had not fully acclimated to the 75% feed load increase (thereby changing the C/N ratio) although over 5 weeks was provided for the system to attain a steady state. Noticeably, the FSF VTR increased almost 60% with the increase feed load. However, the FSF was not the first biological treatment unit in line as the water had passed through two solid removal devices before entering the FSF. Thus, the C/N ratio of the water entering the PWBF was higher than the water entering the FSF. A higher C/N ratio changes the ratio of autotrophs and heterotrophs in the system and can hinder the nitrifiers (Belser, 1979; Bovenduer et al., 1990; Manem and Rittmann, 1992; Zhu and Chen, 2001b). Consequently, one would expect an increase carbon load by increasing the feed rate would have more effect on the PWBF than the FSF resulting in lower nitrification performance or perhaps an impediment.

The VTR data obtained for the PWBF is higher than that obtained by De Los Reyes and Lawson (1996) in their study of a PWBF clarifier and a rotating biological contactor. The solids loading on this unit (neglecting the hydrocyclone impact) is comparable to the grow-out category described by Malone and Beecher (2000) and the system's water quality also falls within the targeted TAN and Nitritie-N criteria of <1.0 mg-N/L. However, given the presence of the fluidized bed within the treatment loop a much lower TAN level would have been expected. Although the PWBF exhibited a greater VTR than the FSF at all five feed rates, the FSF actually removed a greater percentage of the TAN because the FSF has over three times the volume of media. Using the average VTR values in Tables 3 and 4, the grams of TAN removed by each the PWBF and FSF was calculated (g TAN removed per m^3 media-day $\times$ m^3 media) at the five different feed load rates and presented in each of the tables. At the lowest feed load rate of 0.9 kg/day, the PWBF accounted for approximately 40% of the total TAN removed by both filters. At the other feed load rates, the amount of TAN removed by the PWBF was relatively steady ranging from 26.8% at a feed load rate of 1.6 kg/day down to 23.7% at the highest feed load rate of 4.5 kg/day. From the estimated P_{TAN} information provided in Table 1, the filters accounted for 65% to over 90% over the TAN removal in the system. At the lowest daily feed rate, 0.9 kg/day, the combined TAN removal amount was greater the P_{TAN}, indicating ammonia substrate concentration for the filters was potentially limiting. Peak PWBF nitrification performance, 100.1 g TAN removed per m^3 of media per day, at the 4.5 kg daily feed rate was in the same range of TAN removal performance for a same size PWBF used for tilapia production reported by Westerman et al. (1996), but the mean influent TAN concentration was 0.47–0.49 mg/L versus the 0.74 mg/L reported in this paper. Daily feed rates in the study by Westerman et al. (1996) were not presented.

Since the observed VTR numbers for the PWBF were on the low end of the performance range for a grow-out operation, a couple of filter management strategies were evaluated to focus on improving the nitrification capacity of the PWBF. One strategy was to change the PWBF backwashing protocol. At the two higher feed loading rates, 3.45 and 4.5 kg/day (12.3 and 16.1 kg feed/m^3 of media-d, respectively) the backwash interval was increased from 24 to 36 h. Studies have shown that aggressively-washed filters require longer backwash intervals. (Chitta, 1993; Malone et al., 1993; Golz et al., 1999). Increasing the backwash interval at these two feed load rates did not improved PWBF performance, Table 5. In fact, at the 3.45 kg/day feed loading rate, the VTR of the PWBF decreased 50%, while the FSF VTR increased 24% and accounted for over 80% of the TAN removed from the system. At the 4.5 kg/day feed loading rate, there was no significant VTR difference in either the PWBF or FSF. Longer backwash intervals at the lower feed rates (<2.4 kg/day) may be beneficial in optimizing nitrification by providing a longer hydraulic residence time for substrate utilization but, at the higher daily feed rates ($\geq$3.5 kg/day) system flow rate dropped 10% after 24 h due to solids accumulation in the media

Table 5
Variations in a 24-h period of the volumetric nitrification rate (VTR, g TAN converted per m^3 biofilter media per day) and g TAN removed per day of the propeller-wash bead filter (PWBF) with 0.28 m^3 of plastic bead media and the fluidized sand filter (FSF) with 0.92 m^3 of sand media at two daily feed rates with a 36 h backwash frequency

Time after backflush (h)	VTR (g TAN/m^3-day)			
	3.45 (kg feed/day)		4.50 (kg feed/day)	
	PWBF	FSF	PWBF	FSF
0	70.5	107.1	99.9	82.0
12	38.1	90.5	132.6	82.5
24	46.2	73.9	95.5	79.3
36	41.6	87.8	69.5	115.7
Average	50.7	89.8	99.4	92.4
Standard deviation	±31.1	±13.6	±45.3	±16.6
g TAN removed	14.4	82.8	28.1	85.2

Values are an average from 3 consecutive days of sampling.

bed. The longer backwash intervals also increased the operating pressure (dynamic head) of the filter an additional 2–3 psi (1.4–2.1 m). With a decrease in system flow rate, greater operating pressure, and no apparent improvement in PWBF performance, the backwash interval was reset for 24 h.

The other effort to improve the PWBF VTR performance was made by increasing the system recirculation flow rate. The flow delivered to this filter (305 Lpm) was within the oxygen based transport guidelines defined by Malone and Beecher (2000) for grow-out situations (225 Lpm) but well below the flow capacity of the unit (757 Lpm). Zhang and Bishop (1994) describe the severe inhibition that can occur when low turbulence adjacent to biofilms allows the development of a thick water boundary layer. Zhu and Chen (2001a) more formally quantified the turbulence effect with their plots of nitrification capacity versus Reynolds number. Replacement of the centrifugal pumps in the system water recirculation loop increased the hydraulic flux rate through the filter from 1.09 to 1.25 m^3 min/m^3 of media, a 15% increase. The increased flux rate improved PWBF VTR over 25% as well as increasing the VTR performance of the FSF approximately 17%, Table 6. However, the distribution of the grams of TAN removed by the PWBF and the FSF was still approximately 25/75%. These results indicate that the PWBF's nitrification capacity was inhibited by the low recirculation flow and perhaps by the extended duration (1 min) of the propeller-wash. However, the inability of the fluidized bed to compensate in the presence of a relatively high substrate concentration suggests that both units were impaired by secondary water quality factors most probably a borderline pH reflecting a CO_2 buildup and secondly, low oxygen delivery. Both of these factors stem from the need for more aeration in the rearing tanks.

3.3. Biofilters clarification performance

Several reports have stated that organic particle accumulation on a biofilm surface can reduce the nitrification efficiency of biofilters (Sarner and Marklund, 1984; Wheaton et al., 1994; Zhu and Chen, 2001b). In the existing system, a swirl separator was

Table 6
Variations in a 24-h period of the volumetric nitrification rate (VTR, g TAN converted per m^3 biofilter media per day) and g TAN removed per day of the propeller-wash bead filter (PWBF) with 0.28 m^3 of plastic bead media and the fluidized sand filter (FSF) with 0.92 m^3 at a daily feed rate of 4.5 kg, a system flow rate of 350 Lpm, and a 24 h backwash frequency

Time after backflush (h)	PWBF VTR (g TAN/m^3 media-day)	FSF VTR (g TAN/m^3 media-day)
6	137.8	112.7
12	128.2	158.2
18	130.0	135.2
24	112.0	63.4
Average	127.0	117.4
Standard deviation	±42.0	±37.4
g TAN removed	36.0	108.3

Values are an average from 4 consecutive days of sampling.

Table 7
Dry weight of solids removed from the swirl separator and propeller-wash bead filter at five daily feed rates (kg/day) and a backflush frequency of 24 h

System component	Daily feed rates (kg/day)				
	0.9	1.6	2.4	3.45	4.5
Bead filter					
Solids (g)	89.0 ± 6.6	207.8 ± 25.3	225.6 ± 7.8	510.2 ± 93.4	576.6 ± 47.6
Water volume (L)	98.4 ± 1.3	87.9 ± 0.5	91.4 ± 3.0	88.4 ± 9.8	83.8 ± 9.3
Swirl separator					
Solids (g)	5.8 ± 1.7	22.5 ± 7.8	69.0 ± 10.5	97.8 ± 40.5	4.2 ± 3.6
Water volume (L)	11.7 ± 7.8	37.1 ± 7.1	60.5 ± 11.8	32.3 ± 7.3	33.3 ± 10.1

implemented to capture the heavy solids via the low-volume flow from the tank bottom (approximately 10% of total system flow) prior to flowing into the PWBF. This was done for a couple of reasons. Capturing the larger particles reduced the organic load into the PWBF thereby minimizing filter clogging, reducing filter backwashing frequency and ultimately lowering water usage. Also, by reducing the solids load, the C/N ratio is lower, and the PWBF's nitrification efficiency should improve. Tables 7 and 8 provide the data on the daily solids removal amount from the swirl separator and PWBF during the evaluation period for the various feed loading rates, backwashing intervals and flow rates.

Of the feed quantity fed to fish, approximately 25% of that quantity will be produced as suspended solids or total suspended solids, TSS (Timmons et al., 2001). The solids removal ability of the swirl separator was variable in reducing the particulate load into the biofilters. Periodically, the swirl separator was inefficient due to blockage of the tank bottom drain line by skeletal remains of dead fish. At the 0.9, 1.6 and 4.5 kg/day feed rates the percent of theoretical TSS removal was less than 10%. At the 2.4 and 3.5 kg/day feed rate, TSS removal was approximately 11% theoretical TSS values (i.e. 25% of feed load). Increasing the system flow from 305 to 350 Lpm considerably improved the TSS removal by the swirl separator. At the 4.5 kg/day feed rate with the high flow, Table 8, the separator removed over 25% of the theoretical TSS. Water flow through the swirl separator was approximately 10% of the system flow rate. The swirl separator targets the larger particulate matter, potentially reducing the solids load on the bead filter. This should present some benefit by lowering the C/N ratio and through extension of the backwashing interval widow. These potential benefits were not evident here, overshadowed by the other management issues.

For the PWBF the range of the estimated TSS captured was from 37 to 60% per backwash event. There was no effective difference in the sludge production rate of the PWBF by extending the backwash cycle from 24 to 36 h. In fact, the solids capture rate decreased 20% at the 3.5 kg/day feed rate with the 36 h backwash interval compared to a 24 h

Table 8
Dry weight of solids removed from the swirl separator and propeller-wash bead filter at two daily feed rates, backflush intervals and flow rates

Daily feed rate (kg/day)	3.45	4.5	4.5
Backflush frequency (h)	36	36	24
System flow rate (Lpm)	300	300	350
Bead filter			
Solids (g)	516.0 ± 58.4	934.0 ± 25.2	679.1 ± 75.1
Water vol. (L)	87.1 ± 10.9	85.0 ± 1.0	104.1 ± 13.4
Swirl separator			
Solids (g)	ND	66.3 ± 10.8	309.0 ± 165.7
Water vol. (L)	ND	32.6 ± 3.8	52.8 ± 4.5

Note: ND = no data.

backwash cycle. These observations may be an artifact of the experimental design. Chen et al. (1997) discusses the aerobic degradation rate of solids in warmwater systems. They cite total solids degradation rates of the order of 10% per day. Extending the backwash interval by 50% induced a proportional increase in sludge residence of the bead bed, and thus, could allow a substantial reduction in the volume of sludge produced by the unit.

The water loss from the PWBF per backwash event was approximately 90 L. A higher system flow rate (350 Lpm) resulted in an increase of the PWBF backwash volume, 104 L per event. The backwash volume was also high (>100 L) at the lowest daily feed rate (0.9 kg/day). The low solids capture and high backwash volume at this feed load in addition to the low filter VTR performance indicates that a longer backwash interval (36–48 h), could be implemented. Not only would water be conserved by limiting filter backwashes but the additional carbonaceous matter accumulated in the filter media between backwash cycles may help improve nitrifying assimilation of the autotrophic bacteria in the filter (Rogalla and Payraudeau, 1988).

The solids were removed from the PWBF via the drain valve rather than back through the filter inlet screen. A richer sludge is removed by purging the drain valve versus removing effluent through the inflow port per the filter design protocol. This method is not recommended by the manufacturer because filter media or system water can be lost if closure of the sludge valve fails. However, this method has been incorporated by others without reported valve failure and incorporation of a manual ball valve on the front side of the actuator valve allows closure in case of failure or repairs are needed.

4. Summary

The data presented in this paper provides field data to supplement the existing published information regarding nitrification and solids removal performance of the propeller-washed bead filters as well as combination treatment systems with a fluidized sand filter. The PWBF nitrification performance in this field setting was satisfactory, but less than that reported from laboratory scale studies. However, Malone and Beecher (2000) in discussing the use of bead filters for warmwater aquaculture production systems did mention that bead filters nitrification performance can vary widely with loading and management. And for bead filters operated mainly for clarification, as in the system setup presented, nitrification performance will largely be supplemental. It is the intent of this manuscript to provide practical performance data for the PWBF in combination with a FSF that aquaculturists will find useful when utilizing these filters in a recirculating aquaculture production system. The opportunity exists to strive for better nitrification field performance of the PWBF through management strategies or design enhancement. The performance data presented is a supplement to the already established specific threshold values for the propeller-washed bead filter and should be used with best management practices to optimally maintain a recirculating system for production of foodfish.

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