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Evaluation of the nitrification rates of microbead and trickling filters in an intensive recirculating tilapia production facility

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Abstract

Downflow floating polystyrene bead (microbead) and trickling media biofilters were tested simultaneously using common influent water from a 53-m^3 fish rearing tank stocked with tilapia (*Oreochromis Nilotica* × *Aurea*) at a density of 168 kg m^{-3}. The physical characteristics of the two bio-filter media used were: (1) 1.0 mm diameter polystyrene spheres with a density of 16 kg m^{-3} with a specific surface area of 3936 m^2 m^{-3} (referred to as microbeads); and (2) 5.1 cm diameter polyethylene packing material (Norpak) with a specific surface area of 164 m^2 m^{-3}. Nitrification rates increased linearly with influent total ammonia nitrogen (TAN) concentrations up to a concentration of 2.5 mg l^{-1} for both the microbead and trickling filters. There was no further increase in nitrification rate above 2.5 mg l^{-1} that was statistically significant. The trickling filter had a specific nitrification rate 7.5 times higher than the microbead filter, although volumetric nitrification rates were 3.2 times greater for the microbeads than the trickling filter. The study failed to show any relationship for either type of filter between the hydraulic loading rate and the nitrification rate at hydraulic loading rates between 469 and 1231 m^3 m^{-2} day^{-1}.

Keywords: Nitrification; Tilapia; Warm water; Trickle filters; Bead filters

1. Introduction

Raising fish in water recirculation systems requires nitrification treatment systems that maintain acceptable levels of ammonia and nitrite for the species being

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cultured. Wheaton et al. (1994) reviewed the nitrification systems that are commonly used and outlined their characteristic advantages. A common biofilter type is the trickling filter due to its simplicity and non-mechanical nature. The primary disadvantage of the trickling filter is the use of low surface area media that require large volumes and floor space. Such media are also relatively expensive per unit surface area provided.

Fluidized bed reactors offer the advantage of being capable of using smaller media and the associated higher specific surface areas. The high surface area media potentially can result in lower cost nitrification systems. Fluidized bed reactors are currently being used with both floating and sinking media; fluidized sand beds have become increasingly popular in the industry today, especially for larger scale operations (Summerfelt and Cleasby, 1996). The use of floating media in an upflow configuration (Coffin et al., 1992; Drennan and Malone, 1992) and in downflow configurations has been practiced with success (Losordo et al., 1994); the downflow reactor design is also described by Fan et al. (1982) and Karamanev and Nikolov (1992). Again, with the floating media, there is an inherent advantage expected from using smaller media due to the higher specific surface areas obtained. The floating media and downflow configuration offer the added advantage of using high hydraulic loadings without the need for sophisticated mechanical structures in the reactor to retain the media within the reactor vessel.

Hunter (1987) provides the first reference of using a small diameter (0.7 mm) buoyant polystyrene bead as a reactor media. Most bead filters used in aquaculture applications today are using a 3-mm bead with densities only a few percent less than water; this media is also 50–100 times more expensive per unit surface area provided than the 1-mm type floating media that will be used in the present study. For clarity in this paper, the smaller bead media and filters (1 mm diameter) are referred to as microbead filters to distinguish from the 3-mm bead reactors. Use of the term microbead has also been used by others for a 1-mm type bead media (Dean et al., 1988). Microbead filters are currently being used in commercial aquaculture applications and industrial waste treatment[1].

While there is considerable information in the literature on nitrification characteristics for most of the media in current use (Grady and Lim, 1980; Tanaka and Dunn, 1991; Westerman et al., 1993; Wheaton et al., 1994), there is no quantifiable information concerning the use of 1 mm polystyrene floating media (microbeads) presently being used in aquaculture applications. The objective of the present study was to characterize the microbeads and to determine their nitrification characteristics in comparison to trickling filters when used in warm water aquaculture applications.

[1] Canadian Aquaculture Systems, Gloucester, ON; Water Management Technologies, Baton Rouge, LA.

2. Materials and methods

2.1. System description

A pilot scale biofilter system was placed in parallel with a commercial scale water reuse system in operation for raising tilapia (*Oreochromis Nilotica* × *Aurea*). The growout system consisted of a 53-m^3 rearing tank, a 5.7-m^3 settling tank, a Hydrotech screen filter[2] (60 micron screen), two 1.9 m^3 microbead biofilters, two pure oxygen contactors, and an automatic feeder. The tilapia were being carried at a density of 140–168 kg m^{-3}.

An additional pump was added to the biofilter sump of the commercial tank to pump fish tank water to an overhead distribution trough which had six valve-controled outlets. The water flowed by gravity into six pilot-sized biofilters; three trickling filters and three microbead filters. The system setup is depicted in Fig. 1 (note that the microbead filter is patterned after Losordo et al., 1994).

The microbead filters were identical cone-bottomed tanks, each of which had a total volume of 0.1 m^3 and were 40.6 cm in diameter and 81.3 cm high. Each filter was filled with 12 l of acclimated microbeads taken from the commercial tank biofilters. The microbeads for each of the reactors supplied a surface area of 38.5

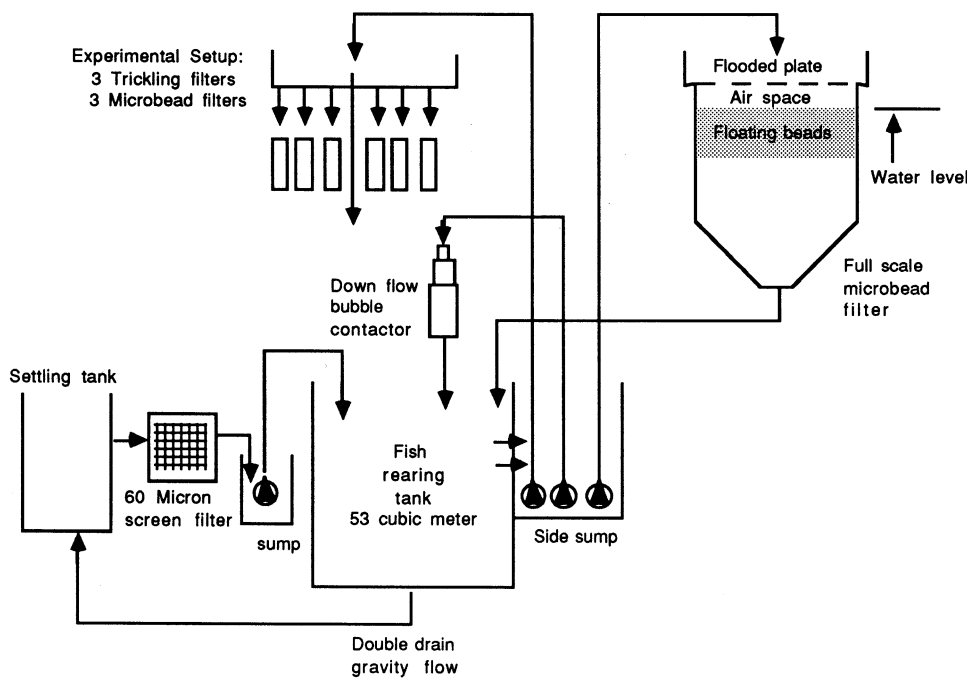

Fig. 1. Commercial scale and pilot scale water reuse systems used to evaluate nitrification rates.

[2] Water Management Technologies, Baton Rouge, LA.

Table 1
Experimental biofilter characteristics

	Microbead filter	Trickling filter
Volume (m^3)	0.1	0.06
Diameter (cm)	40.6	35.6
Height (cm)	81.3	63.5
Hydraulic loading rate ($m^3\ m^{-2}\ d^{-1}$)	424–837	469–1231
Hydraulic retention time (min)	1.2–2.5	0.7–1.5
Media		
Type	Microbeads 1 mm diameter	Norpak 5.1 cm diameter
Volume used (l)	12	28.4
Surface area (m^2)	38.5	4.6
Total surface area available for nitrification (m^2)	39.3	5.2
Specific surface areas ($m^2\ m^{-3}$)	3936	164

m^2. Each microbead filter had a total surface area of 39.3 m^2 when the surface area on the inside of the walls and pipe outlet below the distribution plate of each pilot-scale reactor was included. Influent samples were collected from under the distribution plate to eliminate any ammonia to nitrite oxidation that occurred between the pump box and the distribution plates as being attributed to the pilot reactors. The water was distributed on the top of the filters by a 0.32-cm thick PVC perforated distribution plate which had 936 holes 6 mm in diameter per 1 m^2. The effluent from the filters flowed out a bottom drain; water level in the microbead filters was controled using an outside standpipe.

The microbeads were 1 mm diameter polystyrene balls with a bulk density of 16 kg m^{-3}.[3] The diameters of new microbeads were measured using a 100 × microscope. The void space ratio of the microbeads was calculated by using a known volume of dry microbeads and adding water to determine the void volume. The void space ratios were determined for new, old/acclimated microbeads (air-dried and biofilm removed), and for old/acclimated air-dried microbeads but with the biofilm present.

The trickling filters were round tanks with a total volume of 0.06 m^3 and were 35.6 cm in diameter by 63.5 cm high. Each filter was filled with 15.2 lineal meters of used 5.1 cm diameter Norpak media (NSW Corporation, Roanoke, VA) which had been cut into pieces 7–10 cm long. The media had a total surface area of 4.6 m^2. Including the surface area on the inside of the walls below the distribution plate resulted in each trickling filter having a total surface area of 5.2 m^2. The water was distributed on the top of the filter using the same distribution plate as used for the microbead filters. The effluent from the filters also flowed out a bottom drain. The physical characteristics of both filters are summarized in Table 1.

[3] Daylite, Type T Beads, Arco Chemical, Philadelphia, PA.

2.2. Bed expansion

Acclimated microbeads (approximately 300 l) were removed from the active biofilters on the commercial scale growout system and placed into an identical biofilter with a diameter of 1.4 m and a volume of 1.9 m^3, on a system without fish. The hydraulic loading rate to this biofilter was between 762 and 938 m^3 (m^2 filter cross-section)$^{-1}$ day^{-1}. The depth of the microbeads was measured while the system was running (water was flowing through the filter). The pumps were then turned off and the depth of the microbeads 'at rest' was measured. The pumps were then turned back on and after 30 min the measurements were repeated to determine the amount of expansion that occurred due to hydraulic loading. Three sets of measurements were taken in total. Clorox was then added to the system to kill the bacteria. After allowing the system to flush itself for a week, the same sets of measurements were taken and this data was considered to represent new microbeads. Together, these tests using microbeads from a specific filter are referred to as Trial 1. The process was repeated using twice the volume of acclimated microbeads from a different operating filter on the commercial scale rearing system and is referred to as Trial 2. Trials 1 and 2 were performed to estimate the expansion effects due to biofilm growth and fluidization and so that an estimate of specific surface area could be made for acclimated microbeads.

2.3. Nitrification rates

The pilot biofilter system was started and time was given to allow the trickling filters to develop bacteria populations; the trickling filter media had been used previously for over 2 years of continuous operation. The ammonia removal rate was monitored until a quasi steady state condition for nitrifying populations were established after approximately 8 weeks.

After the trickling filters were acclimated, 36 l of microbeads were removed from one of the well acclimated biofilters on the commercial scale unit and 12 l placed into each of the three pilot microbead filters. Eighteen hours later the first data was collected. It should be noted that during all pilot scale tests, the commercial scale system from which the influent water was obtained had been operating under fairly high fish feeding rates for several months of continuous operation; thus the influent water supplied to the pilot scale biofilters is considered typical of influent conditions under commercial scale and feeding conditions.

The flow rates were measured for each of the six pilot filters and the influent and effluent samples were collected and analyzed for TAN. This process was repeated 2–3 times a day over a 2–3-day period. The flow rates were measured using a 20-l bucket and a stopwatch, the reported flowrate is the average of three measurements. The TAN concentrations were determined based upon Standard Methods 4500-NH_3 B and C for wastewater (APHA, 1992). The nitrification and hydraulic loading rates were calculated for each filter at each time point. This process was repeated two more times, restocking the microbead filters each time with microbeads from the commercial-scale biofilters. For the tests conducted, the influent

water had an average temperature of 26.4°C (SD = 0.3), a dissolved oxygen greater than 5.0 mg l^{-1}, a pH of 6.7 (SD = 0.2), total suspended solids (TSS) conditions 6.4 (SD = 3.6) mg l^{-1} and an alkalinity of 90 mg l^{-1} (SD = 18).

A fourth run was performed to determine if there was any volatization of ammonia through the filters, which might occur due to aeration and gas stripping. All six of the filters were placed in Clorox for 2 weeks to eliminate the presence of any bacteria. The filters were then put back into position without any media in either of the two types of filters. The system was then operated as before and the flow rates and influent/effluent TAN concentrations were measured over a period of 3 days.

A linear regression analysis with the y-intercept assigned as zero was performed on the data points for each type of filter. Also, a series of regressions was performed by removing the data point for the highest influent TAN concentration, and performing a new linear regression with the reduced data set. The slopes of the two regressions were compared using a one-tail t-test to determine if the regression slopes were statistically different. Data points were removed one at a time and the corresponding linear regression was compared to the regression for all data points using the one-tailed t-test to determine if the response correlation was affected by the ammonia influent concentration.

3. Results and discussion

3.1. Bead characteristics

The diameters of new microbeads averaged 0.949 mm (SD = 0.016, $n = 100$). The void space ratio of new microbeads was 40% and that of old/acclimated microbeads (air-dried and biofilm removed), was 36.5%. Similarly, for old/acclimated air-dried microbeads but with the biofilm present, the void space ratio was 36.0%. All the characteristics of the microbeads are summarized in Table 2.

Table 2
Characteristics of the microbeads

Material	Polystyrene
Diameter	0.949 mm (SD = 0.016; no biofilm present)
Specific surface area	3936 m^2 m^{-3}
Specific weight	16 kg m^{-3}
Porosity	40% = new beads
	36.5% = acclimated with biofilm removed dry beads
	36.0% = acclimated with biofilm present dry beads

Table 3
Acclimated and new (no biofilm) microbead expansion

	Trial #	
	1	2
Acclimated microbead depth		
At rest (cm)	17.8	42.5
Expanded (cm)	29.2	50.2
% Expansion	64	18
New microbead depth		
At rest (cm)	13.3	37.5
Expanded (cm)	15.9	40.0
% Expansion	20	7

Inside diameter of microbead biofilter = 134.6 cm

3.2. Bed expansion

The expansion effects related to both biofilm growth and fluidization are shown in Table 3. This table shows that the acclimated microbeads expanded an average of 41% under flow conditions while the brand-new microbeads expanded an average of 13%. However, on an absolute basis the new bead beds both expanded nearly the same, 2.5 cm, while the acclimated bead beds expanded differently on an absolute basis with the shallower bed (Trial 1) expanding nearly 50% more even though the bed was only 42% as deep. Note that the beads were from different bio-reactors.

In Trial 1, the volumetric expansion was over twice that of the beads in Trial 2 (Table 4: 1.32 vs. 1.15). The increased biofilm growth would result in the beads being less buoyant and thus exhibit greater expansion under fluidization as is demonstrated by the data in Table 3. The initial volume of new microbeads increased by an average of 23% (15–32%) due to biofilm growth after acclimation. Thus, specific surface area of new microbeads decreased from a total surface area of 3936 $m^2\ m^{-3}$ to a surface area of 3208 $m^2\ m^{-3}$ for acclimated microbeads.

Table 4
Comparison of the volume required between acclimated and new microbeads

	Trial #	
	1	2
Volume (at rest)		
Acclimated microbeads (m^3)	0.25	0.61
New microbeads (m^3)	0.19	0.53
Ratio: acclimated/new	1.32	1.15

The number of acclimated and new microbeads is the same.

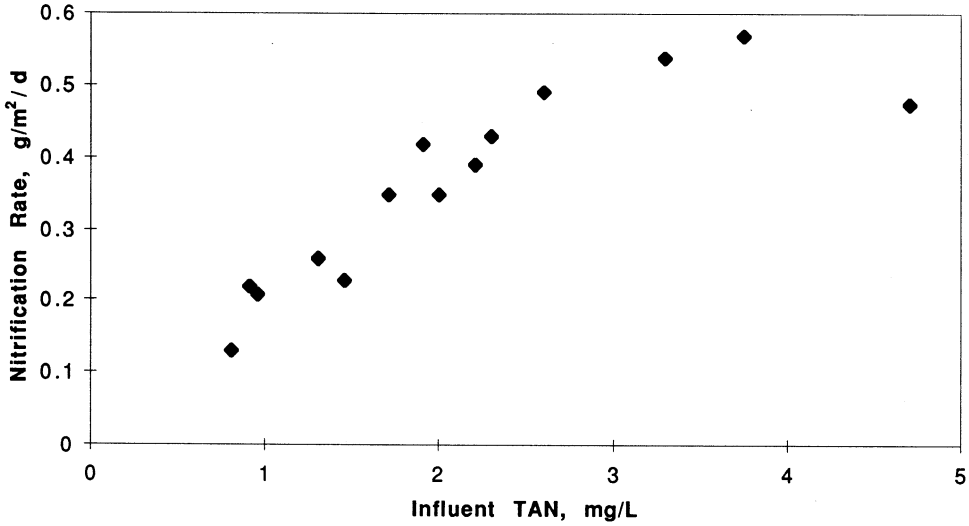

Fig. 2. Influent TAN versus nitrification rate for microbead filters.

The total surface area available for nitrification at any given time can be calculated by momentarily turning off the flow to the biofilter, measuring the bead depth and calculating the volume; the volume measured might best be adjusted to a clean bead basis based upon the above data so as to better estimate whether or not original bead volume and surface area has been lost due to bead migration from the biofilter. This is especially important when calculating anticipated nitrification rates that are based upon total surface area available; a loss of beads could result in an undersized biofilter to meet the nitrification needs of the system.

The results of Tables 3 and 4 indicate that the design engineer should assume that the required biofilter volume will have to allow for a minimum increase in volume of 32% due to biofilm growth and that fluidization can increase overall bed depth by 11 cm on an absolute basis. Based upon our experiences, the design engineer must also recognize that uncontroled biofilm growth due to heterotrophic growth and/or poor solids management may result in extreme bed expansion during fluidization. Under such conditions, microbeads may be flushed from the reactor due to their loss of buoyancy.

3.3. Biofilter performance

Figs. 2 and 3 show the nitrification rates as related to the influent TAN concentration for the microbead and trickling filters, respectively; effects of hydraulic loading rate have been neglected for the initial analysis. Each data point is the average rate of three filters at a specific time. The nitrification rates ranged from 0.13 to 0.57 g m^{-2} day^{-1} (microbead filter) and 0.94 to 3.92 g m^{-2} day^{-1} (trickling filter) for influent TAN concentrations between 0.81 and 4.63 mg l^{-1}. The

average reductions of TAN across the two types of filters were 8.6% (SD = 2.6) and 9.3% (SD = 4.6) for the microbead and trickling filters, respectively. There was no measurable drop in ammonia across the reactors due to air or gas stripping when the reactor vessels were operated without media.

For both types of filters, the slopes were determined to be statistically different, 95% confidence level for the microbead data and 90% confidence level for the trickling filter data, after the removal of the three highest influent data points. This result indicates that the response function became a zero order response for ammonia-N concentrations above 2.5 mg l^{-1}. The linear regression on the remainder of the data is as follows:

$$R = k_1 C_i \quad C_i < 2.5 \text{ mg } l^{-1} \tag{1}$$

where: R = ammonia-nitrogen oxidation rate, g m^{-2} d^{-1}; C_i = ammonia-nitrogen influent concentration, mg l^{-1}; and $k_1 = 0.19$ for microbead filter ($SE_{coeff} = 0.005$, $R^2 = 0.93$, $n = 11$), and 1.43 for trickling filter ($SE_{coeff} = 0.108$, $R^2 = 0.58$, $n = 11$.

Similar removal of data points did not result in any further correlation difference between the nitrification rate and influent ammonia concentration which indicates a first order correlation for the lower concentrations or that the reaction rate is substrate limited up to around 2.5 mg l^{-1} of ammonia-nitrogen as has been shown by others (Bovendeur et al., 1987; van Rijn and Rivera, 1990). Nijhof (1995) demonstrated that nitrification rates decrease through a biofilter, with the lowest rate near the effluent outlet, which also clearly suggests nitrification rates are substrate limited below some concentration level. Through our filters, however, the

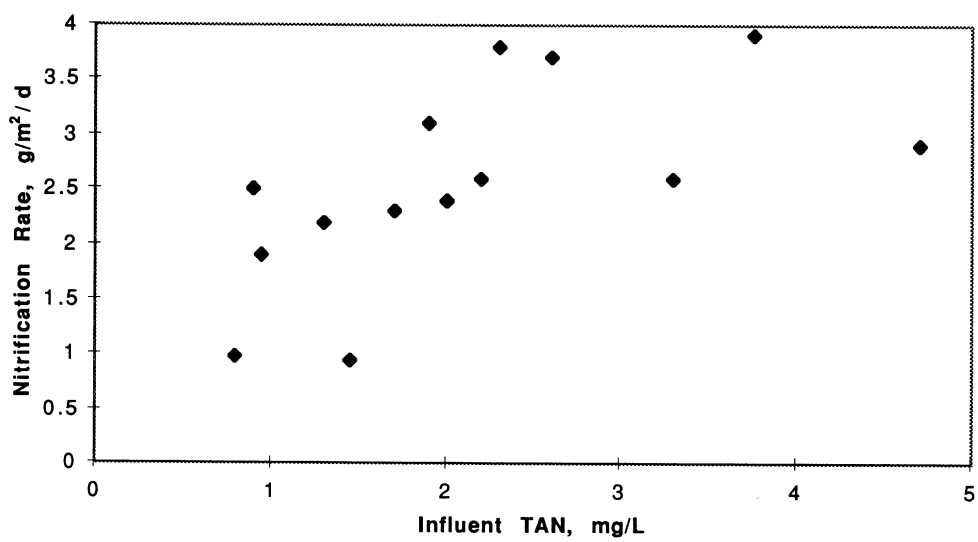

Fig. 3. Influent TAN versus nitrification rate for trickling filters.

fraction of TAN removed was small, averaging 8.6% for the microbead filters and 9.4% for the trickling filters. For this reason, we compared nitrification rates to the influent TAN concentration and not the effluent or average TAN concentration. Note that the flow rates used in this study are for very high hydraulic loading rates (HLR); the effect of HLR is discussed later in this section.

The nitrification rates of the two full-scale microbead biofilters which support the 53 m^3 (14000 gallons) rearing tank have been monitored over several months. Comparing the observed rates to the calculated rates (using Eq. (1)) showed that the model predicted the nitrification rate within 13.0% (SD = 21.6) of the actual performance.

While the nitrification rates for the microbead filters showed more consistency, the trickling filters had rates that were on average 7.5 times higher for any given influent TAN concentration. However, for the same volume, the microbeads would contain over 24 times more surface area (3936 compared to 164 $m^2\ m^{-3}$) than the trickling filter media in this study. The microbead filter could then remove TAN at a higher rate based on reactor volume than the trickling filter. However, a conservative approach to using a microbead filter is to allow twice as much volume as is required for the initial volume of new beads; the additional volume is also so that the microbeads are not flushed out of the reactor during operation. Thus, effective nitrification rates per unit of volume for a microbead filter would be approximately 1.5–2 times that of a comparably sized trickling filter.

The general water quality appearance of the commercial tank was very dark water but high clarity. The presence of fine solids appeared to be minimal. TSS data taken across the pilot scale microbead reactors was 7.3 (4.3 SD) effluent TSS which is not statistically different than the influent conditions (6.4 $mg\ l^{-1}$). There may be a size difference in the solids coming into the microbead filter and leaving it. More TSS data and size distribution data should be taken to further describe the removal characteristics of TSS from a micro-bead filter. Nothing conclusive can be said at this time.

3.4. Hydraulic loading rate (HLR)

There was no significant effect of HLR (m^3 (m^2 filter cross-section)$^{-1}$ day^{-1}) on nitrification rate in either the microbead or trickling filters over the range of the data analyzed for either type of filter. The trickling filters in this study operated at media surface loading rates of 9–24 m^3 (m^2 of media)$^{-1}$ day^{-1}, compared to a typical surface media loading rate for rotating biological contactors (similar in principle to a trickling filter) of 0.04–0.1 m^3 (m^2 of media)$^{-1}$ day^{-1} (Metcalf and Eddy, 1991). Thus, the filters in this study were loaded much higher hydraulically than those rates reported in the literature. Other research (Nijhof, 1995; Nijhof and Klapwijk, 1995) has shown increased nitrification rates with increased hydraulic loading rates. Our data would suggest that there is a limit to this benefit, due to lack of correlation in our study between nitrification rate and hydraulic loading. Also, the higher than normal HLRs on our trickling filters may partly explain why their nitrification rates (0.92–3.92 $g\ m^{-2}\ day^{-1}$) were much higher than rates

previously reported in the literature (0.1–0.8 g m^{-2} day^{-1}; Miller and Libey, 1985; Bovendeur et al., 1987; Nijhof, 1995). These high HLRs would have eliminated any substrate feeding limitation or lack of oxygen for the biofilms in the present study.

4. Conclusions

Based upon the results of this study using microbead and trickling biofilters and commercial fish farm influent waters, the following conclusions are drawn: (1) hydraulic loading rate did not affect ammonia nitrification rate for hydraulic loading rates between 469 and 1231 m^3 m^{-2} day^{-1} for both types of biofilters; (2) the nitrification rates were first order up to an influent TAN concentration of 2.5 mg l^{-1} for both types of biofilters; (3) trickling filter ammonia nitrification rates were 7.5 times higher per unit area of media than the microbead media, but the microbeads removed approximately 3.2 times more TAN (by weight) per day per unit volume of reactor; and (4) biofilm growth on a well established microbead filter increased the media volume between 15 and 32%. Allowances should be made for microbead volumetric expansion due to biofilm growth and fluidization. These additional volumetric requirements are not necessary in trickling filters.

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References

APHA, 1992. Standard Methods for the Examination of Water and Wastewater, 18th ed. Washington, DC.

Bovendeur, J., Eding, E.H., Henken, A.M., 1987. Design and performance of a water recirculation system for high-density culture of the African catfish, *clarius gariepinus* (Burchell 1822). Aquaculture 63, 329–353.

Coffin, D.E., Chitta, B., Malone, R.F., 1992. Biofiltration for Recirculating Finfish Culture Systems. Presented at Louisiana Aquaculture Conference and Trade Show, Baton Rouge, Louisiana, January 30–31.

Dean, R.C., Karkare, S.B., Ray, N.G., Runstadler, Jr., P.W., Venkatasubramania, K., 1988. Large scale culture of hybridoma and mammalian cells in fluidized bed reactors. In: Bioreactor Immobilized Enzymes and Cells: Fundamental and Applications. London: Elsevier Applied Science, p. 128.

Drennan, D.G., Malone, R.F., 1992. Design of Recirculating Systems for Intensive Tilapia Culture. Paper presented Louisiana Aquaculture Conference and Trade Show, Baton Rouge, LA, January 30–31.

Fan, L.-S., Muroyama, K., Chern, S.-H., 1982. Hydrodynamic characteristics of inverse fluidization in liquid–solid and gas–liquid–solid systems. Chem. Eng. J. 143–150.

Grady, C.X.P.L., Lim, H.C., 1980. Biological Wastewater Treatment. New York: Marcel Dekker.
Hunter, J.S. III, 1987. Recent developments in buoyant media liquid filtration. Filtration Separation 1 (November/December), 399–406.
Karamanev, D.G., Nikolov, L.N., 1992. Bed expansion of liquid-solid inverse fluidization. AIChE J. 38, 1916–1922.
Losordo, T.M., Westerman, P.W., Liehr, S.K., 1994. Water treatment and wastewater generation in intensive recirculating fish production systems. Bull. Natl. Res. Aquacult. (Suppl. 1), 27–36.
Metcalf, Eddy, 1991. Wastewater Engineering, 3rd ed. New York: McGraw-Hill.
Miller, G.E., Libey, G.S., 1985. Evaluation of three biological filters suitable for aquacultural applications. J. World Maricul. Soc. 16, 158–168.
Nijhof, M., 1995. Bacterial stratification and hydraulic loading effects in a plug-flow model for nitrifying trickling filters applied in recirculating fish culture systems. Aquaculture 134, 49–64.
Nijhof, M., Klapwijk, A., 1995. Diffusional transport mechanisms and biofilm nitrification characteristics influencing nitrite levels in nitrifying trickling filter effluents. Water Res. 29 (10), 2287–2292.
Summerfelt, S.T., Cleasby, J.L., 1996. A review of hydraulics in fluidized-bed biological filters. ASAE Trans. 39 (3), 1161–1173.
Tanaka, H., Dunn, I.J., 1991. Kinetics of biofilm nitrification. Bioengineering 24, 669–689.
van Rijn, J., Rivera, G., 1990. Aerobic and anaerobic biofiltration in an aquaculture unit-nitrite accumulation as a result of nitrification and denitrification. Aquacult. Eng. 9, 217–234.
Westerman, P.W., Losordo, T.M., Wildhaber, M.L., 1993. Evaluation of various biofilters in an intensive recirculating fish production facility. Proceedings of an Aquacultural Engineering Conference, 21–23 June 1993. Spokane, Washington, ASAE Publication 02-93, St. Joseph, MI, pp. 326–334.
Wheaton, F.W., Hochheimer, J.N., Kaiser, G.E., Krones, M.J., Libey, G.S., Easter, C., 1994. Nitrification filter principles. In: Timmons, M.B., Losordo, T.S. (Eds.), Aquaculture Water Reuse Systems: Engineering Design and Management. Amsterdam: Elsevier, Chap. 4.