

## Application of microbead biological filters

Michael B. Timmons<sup>a,\*</sup>, John L. Holder<sup>b</sup>, James M. Ebeling<sup>c</sup>

<sup>a</sup> *Biological & Environmental Engineering, Cornell University, Ithaca, NY 14853, USA*

<sup>b</sup> *JLH Consulting, Courtenay, BC, Canada*

<sup>c</sup> *The Conservation Fund's Freshwater Institute, Shepherdstown, WV, USA*

### Abstract

The application of floating microbead filters to aquaculture is reviewed and discussed. The microbead filter is distinctly different from the more commonly used floating bead filters that are used today. Conventional bead filters work in pressured vessels and use a media that is only slightly buoyant. The required mass of beads for the volume required make the media a relatively expensive component of a floating bead filter in contrast to sand or microbead media that is much less expensive on a per volume basis. Microbead filters use polystyrene beads (microbead) that are 1–3 mm in diameter (floating bead filters use media approximately 3 mm in diameter also). Microbead have an overall bulk density of 16 kg/m<sup>3</sup> and a specific surface area of 3936 m<sup>2</sup>/m<sup>3</sup> (for 1 mm beads). This material can be obtained commercially in bulk for roughly US\$ 4 kg<sup>-1</sup> of material. Biological filters that use microbeads for their nitrifying substrate can be thought of as a trickling bio-filter in terms of how the flow distribution and collection mechanics are designed and operated. For design purposes, microbead filters can be assumed to nitrify approximately 1.2 kg of TAN/m<sup>3</sup> of media per day for warm water systems with influent ammonia–nitrogen levels from 2 to 3 mg/l. For cool water applications, rates should be assumed to be 50% of warm water rates or use rates similar to those used for fluidized sand beds. Designs and results in several applications are presented. Microbead filters have been used successfully by several commercial growers after being first introduced in the mid 1990s. Effects of capitalization for equipment and buildings upon production costs is discussed and presented in graphical form.

© 2005 Elsevier B.V. All rights reserved.

*Keywords:* Biological filter; Microbead; Data

### 1. Introduction

There is consensus that aquaculture is the environmentally responsible alternative to fishing. It provides a consistent and reliable source of high quality, fresh seafood that is safe to eat, priced

reasonably, and nutritious. Seafood that is produced using recirculating aquaculture system (RAS) technology is potentially the most environmentally friendly and sustainable production system that could be used to produce this needed seafood supply. However, RAS technology is often the most expensive form of production due to the generally higher capitalization costs. A central component of any RAS system is the biological filter system that reduces toxic metabolic products to nitrate, which is fairly innocuous. This

\* Corresponding author. Tel.: +1 60 72 551630;  
fax: +1 60 72 554080.

E-mail address: [mbt3@cornell.edu](mailto:mbt3@cornell.edu) (M.B. Timmons).

paper reviews one such technology, microbead filters, and discusses some of the economic impacts of system capitalization on costs of production.

## 2. Biological filter systems

Maintaining fish in water reuse systems is dependent upon efficient biological filters (nitrifying bacteria) that oxidize the ammonia produced by the fish, which is toxic, into nitrate that is generally non-toxic. There are a large variety of biological filters in use, e.g., rotating biological contactors, trickling filters, and fluidized bed granular filters. Commercial scale production of fish on an economically competitive basis practically forces the use of some type of inexpensive granular filter due to their inherent high surface area to volume ratios for the media employed, e.g., sands that provide 10,000 m<sup>2</sup>/m<sup>3</sup> of material as opposed to trickling media that contains 100–300 m<sup>2</sup>/m<sup>3</sup>. Fluidized sand beds become additionally attractive since they can be scaled to sizes that accommodate the ammonia generated from feeding high levels, e.g., 500 kg of fish feed per day into a single water reuse system that will typically have multiple fish tanks on a closed loop.

Organic nutrients result in heterotrophic bacteria growth and ammonia results in nitrogenous bacterial growth. As with all biological filters, the growth of both the heterotrophic bacteria and the nitrogenous bacteria is proportional to nutrient loads provided to the bacteria. Unfortunately, in water reuse system the organic loadings on bio-filters often result in excessive heterotrophic growth, which can often result in the nitrifiers dying because of being out-competed for necessary nutrients and oxygen. Effective settleable solids removal is critical for effective bio-filter operation. Even with effective settleable solids removal, there are still significant concentrations (5–15 mg/l) of settleable solids that will be transported to the bio-filter area of the water reuse system. Granular filters have the distinct advantage of extracting fine solids from the water column, which greatly enhances water quality by reducing the turbidity of the water column in the fish tank. However, even with very low levels of settleable solids being transported into a biological filter, nitrification performance is negatively impacted. For example, [Zhu and Chen \(2001\)](#) demon-

strated the effect of sucrose carbon on the nitrification rate of bio-filters under steady-state conditions using a reactor series experimental system. They determined at carbon/nitrogen ratios from 1.0 to 2.0, which is where most RAS systems operate; there was a 70% reduction of total ammonia–nitrogen removal rate as compared to C/N ratio of 0.

## 3. Microbead filters: general features

A microbead filter is a combination of trickling and granular type biological filters. A typical configuration of a small-scale microbead filter is given in [Fig. 1](#). Microbead filters are operated in a downflow configuration where influent water is distributed over the top of the media bed and the water then trickles down through the media and gravity flows out of the reactor vessel. The media consists of highly buoyant polystyrene beads that are 1–3 mm in diameter with an overall bulk density of 16 kg/m<sup>3</sup>. Porosity of the media will range from 36 to 40% with newer beads being closer to 40% and acclimated beads being 36% ([Greiner and Timmons, 1998](#)). The beads are the same material that is used for disposable drinking cups. Beads are created by a steam heat treatment of a raw crystal polymer. Trade name of the bead material is Dylite™ and can be obtained from distributors of Nova Chemicals Corporation (Calgary, Alta., Canada). Once a local user is identified, beads will cost around US\$ 4 kg<sup>-1</sup> of material. Beads are identified as Type A, B, C, or T with average diameters of 3, 2, 1.5 and 1 mm, respectively. Originally, microbead filters used Type T beads (1 mm) and more recently users seem to prefer a Type B or C. Type A should be avoided, since the surface area per unit volume is reduced substantially. Surface areas per unit volume of beads can be calculated based upon the surface area of sphere ( $4\pi r^2$ ) and the reported porosity (void space) of 37% for acclimated beads ([Greiner and Timmons, 1998](#)) as 3780, 2520, 1890, and 1260 m<sup>2</sup>/m<sup>3</sup> for the 1, 1.5, 2, and 3 mm bead diameters, respectively.

The dominant design features of all microbead filters are illustrated in [Fig. 1](#):

- Water distribution system over the top of the bead bed.
- Floating bed of beads.

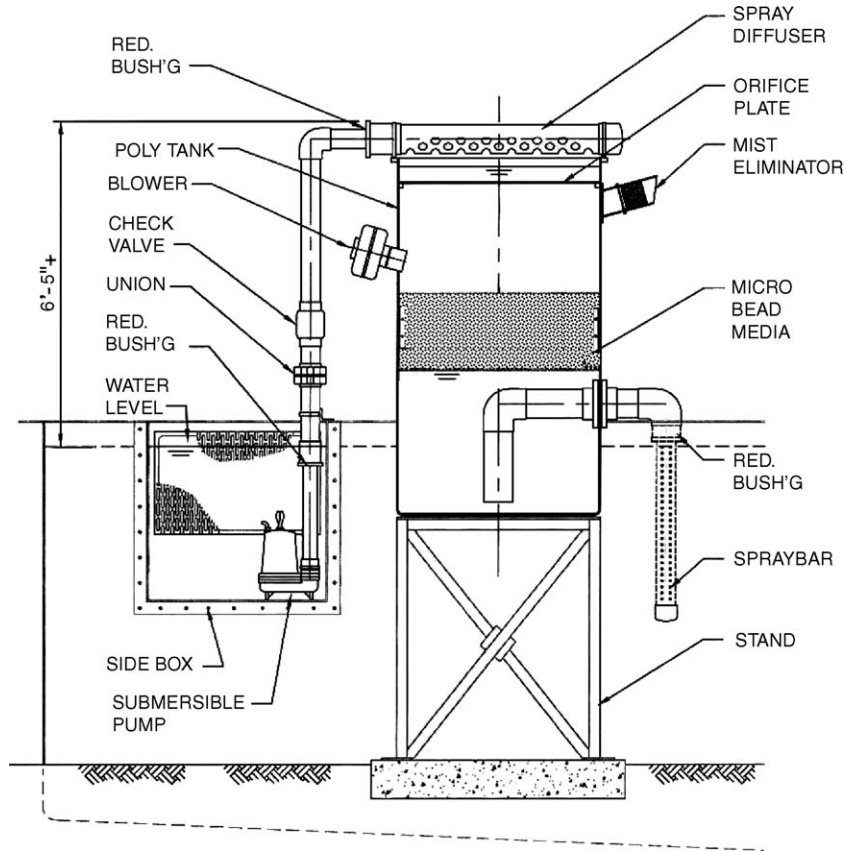


Fig. 1. Generic microbead filter design (drawing courtesy of JLH Consulting, Courtenay, BC, Canada, 2004).

- Adequate water depth below the floating beads (retention vessel).

Variations on microbead filters will be the manner in which the water is distributed over the beads. In Fig. 1, a spray diffuser is shown. Other applications use flooded perforated plates and create a water head of a few centimeters on top to create the water distribution. Some applications actually use the orifice plate to “hold down” the beads and force the beads to be submerged into the retention vessel of the bio-filter. Other designs intentionally create a gas space between the top of the beads and the water spray so that gas stripping can be forced. The ultimate embellishment in this arrangement is where the gas space is ventilated at 3–10 times the hydraulic loading rate to provide CO<sub>2</sub> stripping. All approaches can be made to work, but limitations imposed by specific designs need to be

recognized. For example, a traditional trickling filter will result in gas stripping due to the high void area of the media. Microbeads will not provide gas stripping unless it is via the process of distributing the water over the top of the bead surface and additional design features are incorporated to flush high CO<sub>2</sub> laden air from the space above the bead surface.

#### 4. Performance characteristics of microbead filters

Greiner and Timmons, 1998 reported the first performance data on a microbead filter and compared its performance to a trickling filter:

$$R = k_1 C_i \quad C_i < 2.5 \text{ mg/l} \quad (1)$$

where  $R$  is ammonia–nitrogen oxidation rate,  $g/(m^2 \text{ day})$ ;  $C_i$  the ammonia–nitrogen influent concentration,  $mg/l$ ;  $k_1 = 0.19$  for microbead filter ( $SE_{\text{coeff}} = 0.005$ ,  $R^2 = 0.93$ ,  $n = 11$ ) 1.43 for trickling filter ( $SE_{\text{coeff}} = 0.108$ ,  $R^2 = 0.58$ ,  $n = 11$ ).

The reaction rate in Eq. (1) goes to zero order for ammonia concentrations above 2.5  $mg/l$ . Nitrification rates given by Eq. (1) were developed for a water temperature of 26.4 °C; effects of water temperatures can be predicted using the relationship presented by Wortman and Wheaton, 1991 and as discussed further by Timmons et al. (2002).

In the Greiner and Timmons study, the specific surface areas for the two medias were 3936 and 164  $m^2/m^3$  for the beads and the trickle media, respectively. The trickle filter media was 5 cm diameter Norpak media (NSW Corporation, P.O. Box 2222, Roanoke, VA 24009) that had been cut into pieces 7–10 cm long. Using Eq. (1) and an influent ammonia concentration of 1  $mg/l$ , the volumetric removal rate is predicted to be 0.75 and 0.23  $kg \text{ TAN per } m^3 \text{ per day}$  for the microbead and trickling filter, respectively. For the tests conducted, the influent water had an average temperature of 26.4 °C (S.D. = 0.3), dissolved oxygen >5.0  $mg/l$ , a pH of 6.7 (S.D. = 0.2), total suspended solids (TSS) conditions 6.4  $mg/l$  (S.D. = 3.6) and an alkalinity of 90  $mg/l$  (S.D. = 18). The Greiner and Timmons data was based upon small-scale reactors, 0.1  $m^3$  microbead and 0.06  $m^3$  trickle filter. For both the microbead filter and the trickling filter, the average removal percentage of ammonia across the filters was 9%. Note that for typical tilapia systems that have influent ammonia–nitrogen levels of 2–3, the volumetric removal rate would be predicted to be 1.9  $kg \text{ TAN}/m^3/d$ . Also, note that the TSS levels in the Greiner–Timmons research experiments were very low, thus maximizing nitrification performance in the bio-filters.

Performance of a commercial microbead filter system provided similar performance data over an 8-year-period of continuous operation. Chapman (2004, Personal Communication, Northern Tilapia Inc., Lindsay, Ont., Canada) reported that eight microbead filters, using a Type T bead 1.0 mm diameter, each being 0.4  $m^3$  in bead volume, had an average TAN removal rate of 1.2  $kg \text{ TAN}/(m^3 \text{ day})$ . This was for a system that was fed 100  $kg$  of 42% protein feed on a daily basis. The ammonia–nitrogen ( $P_{\text{TAN}}$ ) produced

from 100  $kg$  of 42% protein feed can be predicted to be 3.9  $kg$  of TAN per day using accepted equations as presented by Timmons et al. (2002) that reflect the feed protein levels. Removal rates were also calculated based upon influent ammonia reduction across the filter only on a given day. For these tests across the day ( $n = 4$ ), the average ammonia influent was 1.4  $mg/l$  and 95% of the ammonia produced by the fish was removed by the bio-filter. Average removal rates were 0.46  $kg \text{ TAN}/(m^3 \text{ day})$ . If the ammonia levels were 3  $mg/l$ , the predicted removal rates would be roughly doubled. In a separate test, the bead filters removed ammonia at a rate of 3.1  $kg \text{ TAN}/(m^3 \text{ day})$  when the biological filters were used to reduce excessive ammonia levels from 7.3 to 2.2  $mg/l$  over a 6.5 h period. Remember that the Chapman system had very low turbidity and this allowed most of the nitrification to occur in the biological filter as opposed to the water column of the fish tank (activated sludge).

The unit TAN removal rate was calculated by dividing the production rate of ammonia–nitrogen ( $kg/\text{day}$ ) by the volume of microbeads ( $m^3$ ). For a limited set of data, TAN removal rate was also calculated based upon the change in ammonia concentration across the filter in order to exclude any nitrification that occurred in other parts of the system. Water quality conditions were 27 C, 2.5  $mg/l$  TAN,  $NO_2-N < 1.0 \text{ mg/l}$  and TSS  $\sim 10 \text{ mg/l}$ . Overall water exchange rates are 2–3% per day (extremely good water quality for this low of an exchange rate). The author has visited this facility multiple times over this 8-year-period and the water has been very clear with a dark tea color. Fish feeding behavior is aggressive at each feeding that occurs over a 16 h feeding periods with hourly frequency for feed distributions.

## 5. Large scale commercial microbead filters

Producing food fish on an economically competitive basis requires large production scales, e.g., >500 metric tonnes/year. Fillet operations will require production levels exceeding 2500 metric tonnes/year and preferably 5000 metric tonnes/year or greater. At such scales, a key element is that the biological filter can be designed to oxidize ammonia loads resulting from the associated large daily fish feedings, e.g., daily feedings in excess of 500–1000  $kg$  feed per day,

so that overall system costs can be reduced per unit of fish produced. The TAN resulting from this fish-feeding load is approximately 3% of the fish-feeding rate. Based upon the data presented in this paper, warm water nitrification systems using well managed bead filters can be assumed to assimilate ammonia at a rate of 1 kg TAN/m<sup>3</sup> of media per day. Thus, the mentioned 1000 kg/day fish-feeding rate would require a bio-filter with a 30 m<sup>3</sup> media volume. Bead filters as originally developed and demonstrated successfully at such farms as Northern Tilapia were roughly a single cubic meter in bead volume or less. The first attempts at scaling microbead filters by simply making their footprint larger failed to provide a proportional increase in nitrification capacity.

A successful design modification to the original microbead filter concept that was patented by Cornell University (Patent Number 6,666,965 “Cellular microbead filter for use in water recirculating system”, awarded December 23, 2003) was to subdivide a large bead bed into smaller subsections all within the same filter vessel. Large scale applications of microbead filters using single reactor vessels has been implemented by Fingerlakes Aquaculture LLC (Groton, NY) under a license from the Cornell Research Foundation. Performance characteristics of such a system are shown

in Fig. 2 (Belcher, 2003). Fingerlakes Aquaculture is a 500 metric tonnes/year tilapia farm.

The Fingerlakes Aquaculture farm consisted of six independent production systems or pods; four of the pods employed CycloBio™ filters (Marine Biotech, Beverly, MA), and one pod was under construction during the study. Design feeding loads per production pod were approximately 270 kg of feed per day. The data shown in Fig. 2 is approximately 7 months after start-up of the microbead filter, which was on Pod 5. The microbead filter had a bead depth of 21 cm, a filter bead volume of 6 m<sup>3</sup>, and used a Type B bead 1.85 mm diameter. The hydraulic loading rate of the Aquafilter was 1108 m<sup>3</sup>/(m<sup>2</sup>day) (18.9 gpm/ft<sup>2</sup>). Measured performance characteristics for the Fingerlakes Aquaculture bead filter were: 1.1 kg TAN/(m<sup>3</sup>day), average influent TAN 1.9 mg/l, average system nitrite–nitrogen 0.6 mg/l, water temperature 26 °C, and average feed per day into the system was 239 kg/d. Note that the nitrification rate is based upon assuming that all nitrification occurs in the biological filter. This may over-estimate substantially the actual performance of any biological filter. For example, after the data shown in the figures was collected, an additional test showed that the ammonia removal across the microbead filter resulted in only 4% of the ammonia produced by the

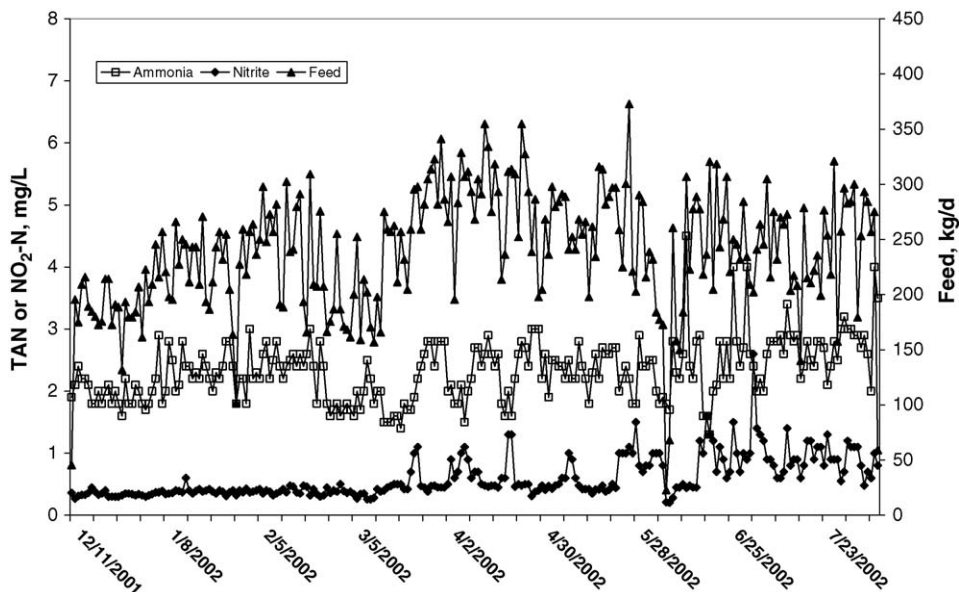


Fig. 2. Performance of a large-scale microbead filter (Belcher, 2003).



fish was being removed by the microbead filter (ammonia reduced from 2.5 to 2.4 mg/l). While the accuracy of this data could be questioned, it certainly indicates that there was substantial nitrification occurring outside of the bio-filter. The Fingerlakes systems (true for both the sand filter systems and the microbead) were also typified by very high TSS ( $\sim 50$  mg/l) in the fish tanks. These levels clearly were supporting high bacterial concentrations and as a result, it appears could have provided the majority of the nitrification. This is in contrast to the Chapman systems where it was demonstrated that 95% of the nitrification was occurring in the biological filter.

For comparison purposes with the microbead filter, performances of two CycloBio™ filters are shown in Figs. 3 (Pod 1) and 4 (Pod 4) (Belcher, 2003). These filters had been in operation for at least two years. The filters were 3.5 m (11.5 ft) in diameter and 4.9 m (16 ft) tall and were loaded with 1.8 MT of washed graded sand (0.45–0.55 mm) from Best Sand Company (Chardon, OH). Bed expansion for each of the bio-filters averaged 40%. Fig. 3 for Pod 1 shows a very stable, textbook type performance. In contrast, the Pod 4 performance shown in Fig. 4 is extremely erratic and plagued by high nitrite levels. This is an example of the frustration of working with bio-filters in general (and not just sand filters). The two bio-filters shown in Figs. 3 and 4 were as identical in design and operation

as possible, yet performance is dramatically different between the two during this particular time frame. Overall performance characteristics are summarized in Table 1, which also includes performance of the other two CycloBio™ filters.

The average feeding level in Pod 1 (Fig. 3) during the 240 days time period was 245 kg (540 lb) of feed per day with 80 days exceeding 316 kg/day (700 lb/day). There are several shifts in feeding that can be observed as waves in Fig. 3. Total ammonia nitrogen concentrations were relatively stable during this time (mostly between 1.5 and 2.0 mg/l) with slightly higher concentrations occurring when higher feeding rates were being applied to the system. The average TAN concentration during this time was 1.9 mg/l. The average TAN removal rate by the Pod 1 bio-filter was calculated to be 0.7 kg TAN/(m<sup>3</sup>day) with a 10% water exchange rate. Nitrite–N concentrations were relatively stable during the first half of this time, experienced a spike to approximately 1.5 mg/l during the spring of 2002 (coinciding with increased feeding), and then decreased shortly afterwards to below 1 mg/l for the remainder of the period. The average nitrite–N concentration during this period was 0.7 mg/l.

The average feed concentration in Pod 4 during 240 days time period (Fig. 4) was 268 kg (588 lb) of feed per day with over 110 days exceeding 316 kg/day

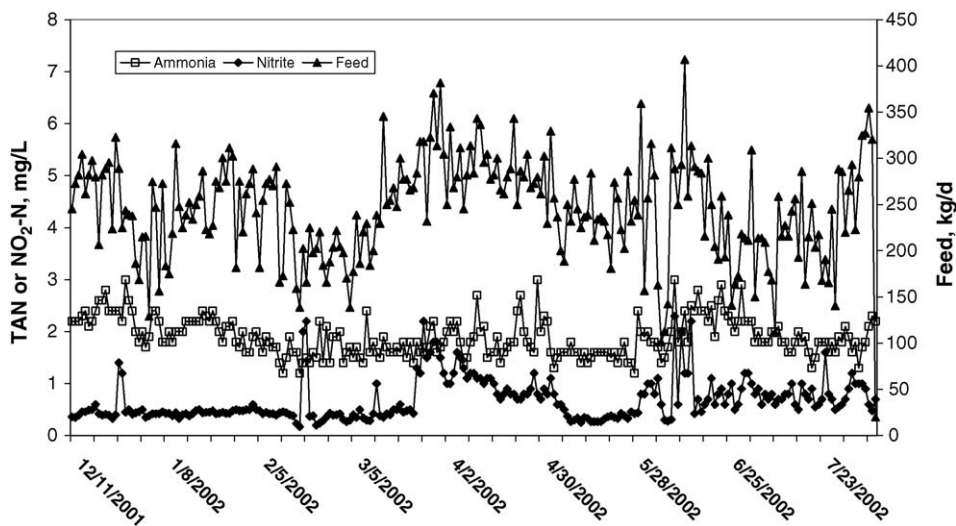


Fig. 3. Performance of a CycloBio™ filter, referred to as Pod 1 (Belcher, 2003).

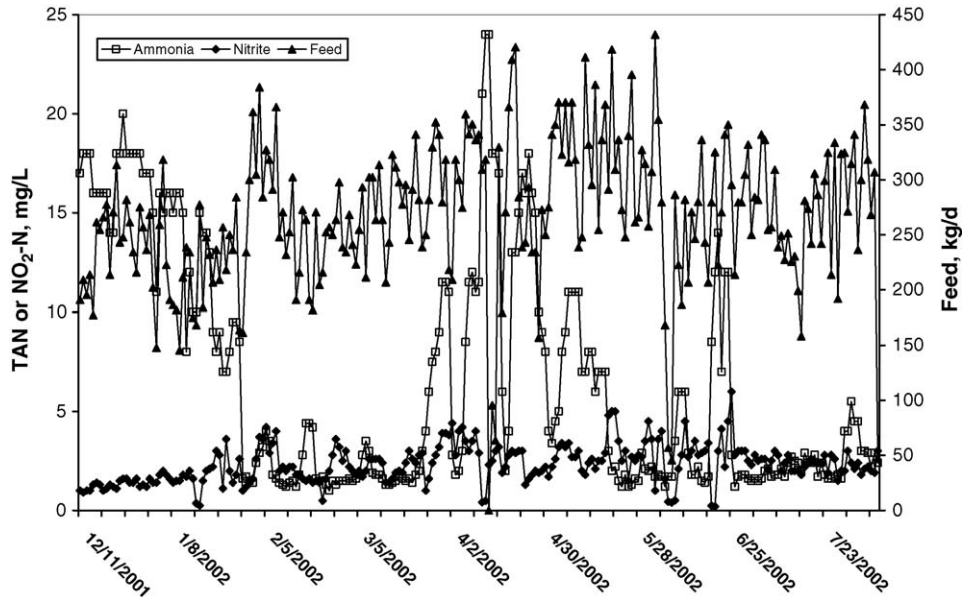


Fig. 4. Performance of a CycloBio™ filter, referred to as Pod 4 (Belcher, 2003).

(700 lb/day). In general, feeding levels ranged between 204 and 340 kg/day (450–750 lb/day). Total ammonia–nitrogen concentrations were mostly between 1.5 and 3.5 mg/l during this time period however there were several significant spikes during this time, TAN > 20 mg/l. The average TAN concentration during this sampling period was 6.6 mg/l. The average TAN removal rate by the bio-filter was calculated to be 0.7 kg TAN/(m<sup>3</sup>day) with a 10% water exchange rate. Nitrite–N concentrations typically ranged between 1 and 3 mg/l during this sampling period with smaller spikes following the TAN spikes. The average nitrite–N concentration during this period was 2.3 mg/l. Summary performance data is provided in Table 1 for the four CycloBio™ filters (Belcher, 2003) and the microbead filter for comparative purposes.

### 5.1. Coolwater application

Microbead filters were applied to an Atlantic salmon smolt operation during the fall of 2004 using an average hydraulic loading rate of 984 m<sup>3</sup>/(m<sup>2</sup>day) (16.8 gpm/ft<sup>2</sup>). Over a 30 days period, the average feeding rate was 56 kg (45% protein feed) for two bio-filters (similar to Fig. 1) with a media volume per bio-filter of 0.93 m<sup>3</sup>. Sodium bicarbonate was added daily at a rate of 135 kg/d, and makeup water averaged 567 lpm (150 gpm). The average removal rate was 1.25 kg TAN/(m<sup>3</sup>day) with a removal efficiency per pass of 29% (S.D. = 12%) across the filter. The water quality parameters in the fish tanks were TAN 1.2 (S.D. = 0.9) mg/l, NO<sub>2</sub> 1.4 mg/l (S.D. = 0.3), water temperature 13.6 °C, hardness 72 mg/l, pH 7.3, turbidity 11.7 mg/l, CO<sub>2</sub> 10 mg/l, and chloride concentrations 400 mg/l.

Table 1

Performance Data of CycloBio™s and a microbead filter (Pod 5) at Fingerlakes Aquaculture's Groton Facility from 12/11/01–8/8/02 (Belcher, 2003)

Pod system #	Pod 1	Pod 2	Pod 3	Pod 4	Pod 5 microbead
Average fish feeding rate (kg/day)	245	262	281	268	239
Average TAN concentration (mg/l)	1.9	3.0	2.5	6.6	1.9
Average nitrite–N concentration (mg/l)	0.7	2.3	2.4	2.3	0.6
Average TAN removal rate (kg TAN/(m <sup>3</sup> day))	0.7	0.7	0.8	0.7	1.1

## 6. Carbon dioxide removal using microbead filters

Microbead filters can be designed to include a CO<sub>2</sub> stripping function. This can be an advantage by reducing the overall operating costs of the system, since CO<sub>2</sub> removal will be a necessary component in most intensive systems. The airflow requirements for successful stripping (generally about 5–10 times the volumetric water flow) can be coupled with overall building ventilation requirements for minimal air exchanges to control air quality and moisture levels. Wintertime ventilation requirements will require 2–3 building air exchanges to maintain adequate air quality (relative humidity below 85% and CO<sub>2</sub> levels <2000 ppm; OSHA maximum 8 h exposure is 5000 ppm (Timmons et al., 2002)). The CO<sub>2</sub> stripping ventilation requirements will be similar to the building air exchange requirements, thus a convenient coupling of design and operational requirements. Air high in CO<sub>2</sub> leaving the bio-filter can either be vented directly from the building or dispersed into the general airspace where the building's ventilation system will control overall air quality. Surprisingly, the choice of venting directly or through the overall building ventilation system has minimal impact on the overall heating requirements for the operation. Venting directly can be attractive and provide opportunities for using heat exchangers to conserve heat.

In the Northern Tilapia system, the CO<sub>2</sub> levels in the water column are maintained between 20 and 50 mg/l by maintaining pH between 6.7 and 7.1 and alkalinities between 75 and 150 mg/l. Approximately 50% of the total flow through the microbead filters is first stripped through a 1 m high packed column placed above the microbead filter. There is additional CO<sub>2</sub> removal through the bead filters but is estimated to be a small percentage of the total removal since there is no forced air movement through the gas space between the beads and the distribution plate. Without the active forced air removal in the microbead filters, one should design for an active removal mechanism. Based upon the Northern Tilapia experience, approximately 50% of the flow should be actively stripped for CO<sub>2</sub> removal. The degree of stripping required will be species dependent.

For the Fingerlakes Aquaculture microbead system, there was no active CO<sub>2</sub> removal other than

what was provided by the spraying the bio-filter influent water onto the top of the bead bed. However, this was an uncovered bed and there was good air movement, although not forced, around the top of the bead bed. The average pH for the data shown in Fig. 2 was 6.7 and the average alkalinity was 111 mg/l. Using the pH–alkalinity–CO<sub>2</sub> relationships presented by Timmons et al. (2002), the dissolved CO<sub>2</sub> can be predicted to be approximately 48 mg/l. While this level of CO<sub>2</sub> may be satisfactory (marginal) for tilapia, other fish species that are more sensitive to CO<sub>2</sub> would require more complete CO<sub>2</sub> stripping. Stripping after a bio-filter provides greater potential for stripping CO<sub>2</sub> since the water will be higher in CO<sub>2</sub> since the nitrification process produces CO<sub>2</sub>.

## 7. Other design considerations for microbead filters

### 7.1. Coolwater applications

The data presented in this paper has been from warm water, tilapia applications. Microbead filters are equally applicable to coolwater applications, but rates should be reduced based upon the lower temperatures (see Wortman and Wheaton, 1991). Microbead filters have been installed into multiple salmonid operations more recently. Reports from commercial users are positive. However, adjustments need to be made for design applications. For warmwater applications and influent ammonia levels of 2–3 mg/l, the reported data indicates a safe value for design purposes is 1.2–1.9 kg TAN/(m<sup>3</sup>day) of media. Adjusting nitrification rate from 30 to 10 °C based upon Wortman and Wheaton, 1991 predicts a 45% reduction in rate. Coolwater systems are generally for species that require higher water quality standards than tilapia systems, e.g., lower suspended solids and ammonia levels at or below 1 mg/l. Nitrification rates can be assumed to be proportional to influence ammonia levels over a range of 0–2.5 or 3 (Greiner and Timmons, 1998; Ebeling, 2000). Combining temperature effects and expected lower ammonia levels, a design value of 0.5 kg TAN/(m<sup>3</sup>day) could be assumed for design purposes for coolwater applications.



## 7.2. Hydraulic loading

The hydraulic loading of any bio-filter is often a critical design parameter. For fluidized sand beds (FSB's), the hydraulic loading determines the amount of bed expansion and ensures full mixing of the sand column; the design principles of fluidized sand beds are well reviewed by Summerfelt and Cleasby (1996). In microbead filters, the hydraulic loading rate is less critical than for FSB's, yet it is still a very important design criterion. Greiner and Timmons, 1998 reported a range of 424–837 m<sup>3</sup>/(m<sup>2</sup>day) (7.2–14.3 gpm/ft<sup>2</sup>). The Northern Tilapia Inc. farm used a rate of 1056 m<sup>3</sup>/(m<sup>2</sup>day) (18 gpm/ft<sup>2</sup>) while Fingerlakes Aquaculture's large-scale bed uses a slightly higher loading rate of 1108 m<sup>3</sup>/(m<sup>2</sup>day) (18.9 gpm/ft<sup>2</sup>). We currently recommend minimum loading rates of 1290 m<sup>3</sup>/(m<sup>2</sup>day) (22 gpm/ft<sup>2</sup>). The bead bed will not act like a FSB in terms of seeing the media being well mixed. The bead bed almost appears to be a static mass, but when loaded at the higher loading rates, one will observe movement of beads from the upper portion of the bed into the lower portions. To some degree, the bead bed acts like a slowly eroding sand castle, where outer portions of the bed bead column finally fall away from the walls back into the main portion of the bed where they are then re-mixed with other beads. This constant yet slow turnover of beads in the bed is what provides the overall volumetric nitrification of roughly 1 kg TAN/(m<sup>3</sup>day) of bead volume.

## 7.3. Bed expansion, loss of beads, and bead depth

A microbead is operated in a down flow mode. The beads because of their high buoyancy effectively float on top of the water column with minimal submergence. During operation, Greiner and Timmons, 1998 reported bed expansions of 3 cm (for new beads) and 8–9 cm for acclimated beads with fully developed bio-films. These expansions were independent of bead bed depth.

Some operations have noted a loss of beads from the bio-filter vessel. Loss of beads is obvious, since the beads reappear somewhere else in the system floating on top of the water column. Most bead loss is observed with new beads, which will have some small percentage of undersized beads that can be hydraulically flushed from the bio-filter vessel. It is extremely important to maintain at least 60 cm of water depth separation

between the bottom of the bead bed that is "floating" on the water column and the invert of the pipe or outlet port. Note in Fig. 1 how the outlet pipe is elbowed downward to provide much of this separation difference. Some thought should also be given to how to minimize any turbulence or mixing action on the solids that might settle in the bio-filter vessel. Generally, providing some means to gravity discharge the vessel to remove any collected solids should strongly be considered. Regardless of how efficient the solids removal system is for the overall system, any vessel with retention time will collect solids. A microbead vessel is no different.

Smaller beads are also more subject to flushing out of the bio-filter vessel since the biofilm on a smaller bead has more of an impact on the beads relative buoyancy than a larger bead. For this reason, a Type B or C beads with diameters of 1.5–2.0 mm are recommended, as opposed to the Type T bead with a diameter of 1.0 mm.

Bead depths in microbead filters are limited to around 50 cm. It is unclear why, but the limited depth requirement is probably related to eventual channeling of water flow as the water trickles through the bead column. As the bed depth is increased, the opportunity for water channelling increases. Hence, the need to either limit bed depth or to provide some type of additional mixing or stirring of the bed.

## 7.4. Nitrification efficiency

The percent removal of ammonia across a biological filter or efficiency is mostly dependent upon the hydraulic retention time across the media. Fluidized sand beds with fine sands and long vessel retention times will remove almost all the ammonia of the entering water. Conversely, fluidized sand bio-filters using large sands will have somewhat proportionally less removal efficiency. The removal rate is the product of mass flow and change in concentration. Using efficiency as a single criterion to rate bio-filter performance is not valid, since what is important is the rate of ammonia mass removal. A microbead filter will have a very short retention time through the bead column and as a result, the efficiency of removal will not be high. The authors recommend using 20% as a design value for removal per pass through the bed. Data supplied by Northern Tilapia indicates an

efficiency of removal of 20% while the data supplied by Fingerlakes Aquaculture had an average efficiency of removal of 11%. The bead depth in the Northern Tilapia system was 0.45 m versus 0.21 m for the Fingerlakes Aquaculture bead filter. Nitrification efficiency is similar to the ratio of bead depths. Greiner and Timmons, 1998 reported a 9% removal efficiency for a bed depth of 9 cm and a bead volume of 12 l. Shallow bed depths do not contribute to high removal efficiency.

### 7.5. Operating expense

The microbead filter used by Fingerlakes Aquaculture (Belcher, 2003) was designed to treat the ammonia resulting from up to 300 kg (660 lb) of feed per day or approximately 100 metric tonnes/year of fish growth at feed conversion ratio of 1.1. While capitalization costs of a microbead filter should be one of the least expensive biological filters to install, e.g., similar to large-scale fluidized sand beds, the greatest savings associated with microbead filters are in operating costs. Specifically, by using a low head, low profile microbead design, significant savings in pumping costs are realized. In the case for Fingerlakes Aquaculture, a total of 27 hp was required to operate the entire microbead filter system (biofiltration, solids separation and oxygenation) pumping 15,100 lpm (4000 gpm) compared to the 41 hp required to operate the CycloBio™ system for these same unit processes pumping 11,400 lpm (3000 gpm). A system operating on a 27 hp continuous draw will consume 1,77,000 kWhs of electrical energy per year.

Expressing the electrical energy used for pumping on a per unit of fish produced from a 100 metric tonnes/year system yields an operating cost for electrical pumping of 1.8 kWh/kg of fish produced for the microbead filter and 2.7 kWh/kg for the CycloBio™ system or 33% less energy costs. Summerfelt et al. (2004) reported that CycloBio™ systems reduced overall operating pressure by 19–23% compared to a conventional fluidized sand bed. Thus, a conservative estimate would be that a microbead filter compared to a traditional fluidized sand bed system would use roughly 1/3 less energy for pumping costs. This advantage would also require the proper selection of pumps for a microbead filter so that the low head advantage would be realized.

### 7.6. Scale of production

RAS produced seafood must lower current production costs to compete successfully against other commodity type seafoods and against the other meat choices. Salmon farms produce 1000–2000 metric tonnes per site. Catfish farms are similar in production capacity. RAS farms will also need to be similarly scaled and need to focus on improved productivity per unit worker. Labor savings obtained from converting from outdoor production to indoor farming was a primary factor that drove the poultry industry to confinement housing. The productivity per unit worker in the broiler industry has increased from 95 metric tonnes of broilers per year in 1951 (Watt Publishing, 1951) to 950 metric tonnes/year in 1991 (Perry, 1991) and is now 1480 metric tonnes/year per full-time worker (Cunningham, 2003). The current labor productivity for indoor broiler production is roughly 15 times more productive than the current 100 tonnes/year per worker for large scale indoor tilapia farms (500 tonnes/year) and still seven times that of the best current salmon farms that produce 130–200 tonnes per worker per year.

Ultimately, indoor RAS fish production has two distinct advantages over poultry production: better feed conversion efficiency and higher productivity per unit area of building. The yearly meat output per unit floor area from a large-scale tilapia farm is approximately 150–250 kg/m<sup>2</sup>, depending upon floor coverage utilization and tank depth, compared to 122 kg/m<sup>2</sup> from a broiler house. Broiler production has feed conversion efficiencies of approximately 2.00 (2.09 bird weight, feed to gain ratio on feed energy levels of 3170 kcal/kg and protein levels of 19.5%), while tilapia conversions range from 1.1 to 1.4 for feed energy levels of approximately 2500 kcal/kg and high protein contents, e.g., greater than 38%.

US broiler production is based upon vertical integration with the broiler grower being the contract farmer. The farmer owns the building, provides husbandry, and pays the majority of the utilities. Total capitalization or investment for a broiler building and equipment is US\$ 0.42 kg<sup>-1</sup> of yearly broiler production capacity (Cunningham, 2003); capital recovery costs will be from 0.06 to 0.09 kg<sup>-1</sup> of broiler produced. For these services and capital investment, the farmer is paid US\$

0.11 kg<sup>-1</sup> of broiler produced (Cunningham, 2003). All costs associated with building ownership, depreciation of capital equipment, labor and utilities (electric and water and generally about 50% of the fuel heating costs) are borne by the farmer. Broiler contracts are based upon 15 years bank loans and the same equipment and building depreciation periods used for the RAS analysis in this paper (7 years on equipment and 10 years on buildings). A broiler grower reaps most of the financial benefit once the building has been fully depreciated and the bank loan has been paid off.

In contrast to the low capital costs of broiler production, capital costs in fish production systems are much higher. Currently, the most cost competitive systems being reported have equipment costs in the US\$ 1.00–2.00 range kg<sup>-1</sup> of yearly production capacity and building costs will add an additional US\$ 25–150 m<sup>-2</sup> of building floor area provided or an additional US\$ 0.16–0.94 when expressed on a per kg of yearly production capacity. The impact of these investment costs on capital recovery cost per unit of fish produced are demonstrated in Fig. 5, assuming a fish rearing tank depth of 2 m, a floor utilization of 40% (percentage of floor that is covered by rearing tanks,

excludes bio-filters, settling systems, etc.), and an interest rate of 8%. Capital recovery (annual) costs are shown over a range of building and equipment costs. Note that the capital recovery costs is affected by the assumed annual interest and the number of years that the initial capital cost is amortized (recovered) over.

As shown in Fig. 5, producing food fish in RAS's will require continued improvements in the cost efficiency of the equipment and building systems if these capital recovery costs are to become comparable to those associated with broiler production, e.g., US\$ 0.06–0.09 kg<sup>-1</sup> of broiler produced. For RAS production, a realistic target over the next 10 years is to reduce the capital recovery costs to US\$ 0.15 kg<sup>-1</sup> of fish produced. This could be achieved if for example the equipment capital investment costs were US\$ 0.53 kg<sup>-1</sup> of yearly production capacity (US\$ 0.10 kg<sup>-1</sup> capital recovery cost) and building costs were US\$ 50 m<sup>-2</sup> (US\$ 0.05 kg<sup>-1</sup> capital recovery cost), using an 8% interest rate and capital recovery periods of 7 years for equipment and 10 years for buildings (same assumptions used to develop Fig. 5). Most of the cost improvements will need to come in the equipment area and some improvements in building costs, since insulated buildings are currently

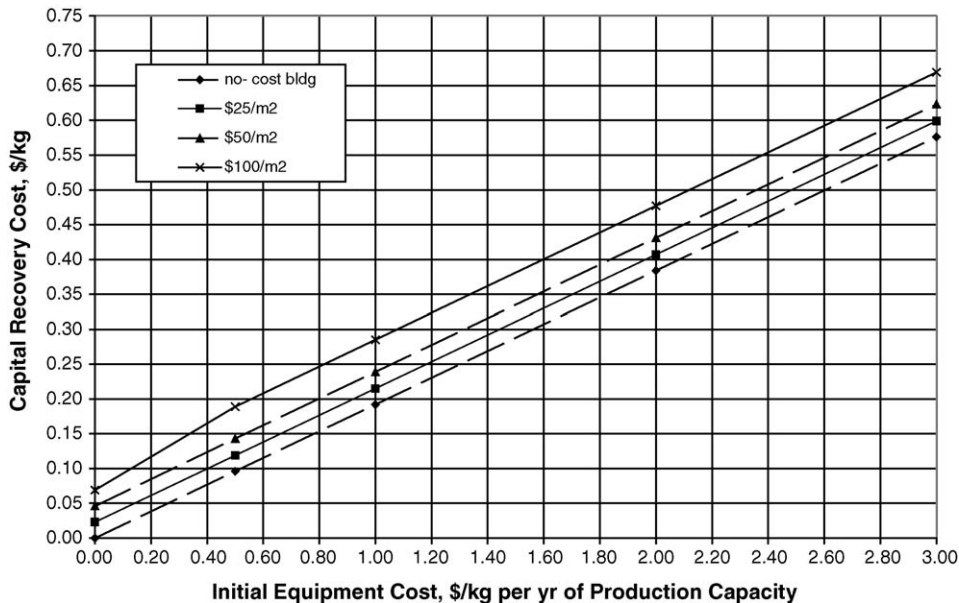


Fig. 5. Capital recovery costs as affected by combined capitalization costs for building and equipment (for a tank depth of 2 m, floor utilization of 40%, interest rate of 8%).

installed in the broiler industry for the price noted. Uninsulated buildings can be installed for the US\$ 50 m<sup>-2</sup> cost noted currently.

## 8. Summary and conclusions

The application of floating microbead filters to aquaculture are reviewed and discussed. The microbead filter is distinctly different than the more commonly used floating bead filters that are widely used today. Floating bead filters work in pressured vessels and use a media that is only slightly buoyant, thus the media is a relatively expensive component of the overall filter design. In contrast, microbead filters use a polystyrene bead (microbead) that is 1–3 mm in diameter with a bulk density of 16 kg/m<sup>3</sup> and a specific surface area of 3936 m<sup>2</sup>/m<sup>3</sup> (for the 1 mm beads). This material can be obtained commercially in bulk for roughly US\$ 4 kg<sup>-1</sup> of material. Microbead filters are considered a low-cost design alternative similar to fluidized sand filters because of their ability to be scaled to large production systems. A key advantage of microbead filters is that their cost of operation will be approximately 50% of a fluidized sand bed due to the ability to use low head high volume pumps for their operation. For design purposes, microbead filters can be assumed to nitrify approximately 1.2 kg of TAN/(m<sup>3</sup>day) of media for warm water systems with influent ammonia–nitrogen levels from 2 to 3 mg/l. For cool water applications, rates should be assumed to be 50% of warm water rates. These rates are similar for design purposes with fluidized sand beds. Microbead filters will have low nitrification efficiencies of 10–20% primarily because of the low hydraulic retention time within the bead bed volume. Bead filters are limited in depth to approximately 50 cm; this will increase the required footprint of the bio-filter as compared to a fluidized sand bed that can be made several meters tall.

Effects of capitalization for equipment and buildings upon production costs is discussed and presented in graphical form. RAS produced seafood remains compromised by the high capitalization costs. Producing food fish in RAS's will require continued improvements in the cost efficiency of the equipment and building systems if capital recovery costs are to become comparable to those associated with broiler

production, e.g., US\$ 0.06–0.09 kg<sup>-1</sup> of broiler produced. Most of the cost improvements will need to come in the equipment area and some improvements in building costs.

## Acknowledgments

Appreciation is expressed to Gary Chapman (Northern Tilapia Inc., Lindsay, Ont., Canada) and Dr. Shivaun Leonard (Fingerlakes Aquaculture, Groton, NY, USA) who provided performance data on bio-filters from their commercial tilapia operations. Appreciation is also given to Dr. Brian Brazil (USDA-ARS National Center for Cool and Cold Water Aquaculture (NCCCWA, Kearneysville, WV)) who provided data on a coolwater system and to Mr. David Belcher (Biological & Environmental Engineering, Cornell University) who edited the paper.

## References

- Belcher, D.M., 2003. Final Report: Improved Indoor Fish Management System, Phase II. USDA SBIR Agreement No. 00-33610-9943, April 24.
- Cunningham, D.L. 2003. Cash Flow Estimates for Contract Broiler Production In Georgia: A 20-Year Analysis. The University of Georgia Cooperative Extension Service, Bulletin #1228, March.
- Ebeling, J.M., 2000. Kinetic reaction rate analysis of nitrifying bead filters in aquaculture. Ph.D. Thesis, University of Maryland.
- Greiner, A.D., Timmons, M.B., 1998. Evaluation of the nitrification rates of microbead and trickling filters in an intensive recirculating tilapia production facility. *Aquacult. Eng.* 18, 189–200.
- Perry, C., 1991. Manpower Management on Large Broiler Farm. *Poultry Digest* July Issue. Watt Publishing, Cullman, AL, pp. 20–26.
- Summerfelt, S.T., Cleasby, J.L., 1996. A review of hydraulics in fluidized-bed biological filters. *ASAE Trans.* 39 (3), 1161–1173.
- Summerfelt, S.T., Davidson, J., Helwig, N., 2004. Evaluation of a full-scale CycloBio™ fluidize-sand biofilter in a coldwater recirculating system. In: *Proceedings, 5th International Conference on Recirculating Aquaculture*, June 22–25, Roanoke, VA, pp. 227–237.
- Timmons, M.B., Ebeling, J.M., Wheaton, F.W., Summerfelt, S.T., Vinci, B.J., 2002. *Recirculating Aquaculture Systems*, second ed. Cayuga Aqua Ventures, LLC, Ithaca, NY, p. 760.
- Watt Publishing, 1951. *Broiler Growing Statistics*. Broiler Grower Magazine. Watt Publishing, Cullman, AL.
- Wortman, B., Wheaton, F.W., 1991. Temperature effects on biodrum nitrification. *Aquacult. Eng.* 10, 183–205.
- Zhu, S., Chen, S., 2001. Effects of organic carbon on nitrification rate in fixed film biofilters. *Aquacult. Eng.* 25, 1–11.