SLUDGE PRODUCTION FROM RECIRCULATING SYSTEMS EMPLOYING EXPANDABLE GRANULAR BIOFILTERS

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ABSTRACT

Low density granular bead filters facilitate solids capture and biofiltration in a single unit process, providing an opportunity to reduce the cost of treating recirculating waters. Backflush frequency, a major operational parameter, influences the rate of nitrification and the volume of sludge produced. A mass balance model calibrated on an experimental scale high density catfish system allows the relationship between sludge retention time, sludge production, and nitrification rates to be examined. Frequent backflushing increases waterloss and sludge production, consequently, requiring larger effluent treatment units to protect receiving streams. Nitrification appears to be optimized with sludge retention times in the range of 2-3 days for filters utilized as the primary solids capture device. Nitrification rates decline for extended sludge retention times, probably reflecting the loss in hydraulic conductivity as captured solids and biofloc fill the pores of the bed. The results indicate that recirculating and discharge treatment components should be designed simultaneously so that the overall cost can be minimized.
INTRODUCTION

High density aquaculture production systems allow for systematic optimization of the wide variety of parameters which control the quality and cost of producing the targeted fish, crustacean, mollusc, or reptile. Additionally, they provide an effective means of minimizing the impact of a production unit on the water or environmental resources of an area. In the United States, recirculating technologies are increasingly being adopted to enhance production of highly valued products including tropical fish, ornamental goldfish, and soft-crabs while reducing heating and environmental compliance costs. Researchers have been working to improve the efficiency of recirculating components to the point that recirculating systems can successfully compete in the production of moderate or commodity priced products.

In September 1991, a Workshop entitled "Design of High Density Recirculating Aquaculture Systems", jointly sponsored by LSU Department of Civil Engineering, Louisiana Sea Grant, the National Sea Grant, U. S. Fish and Wildlife Service, and the U. S. Department of Agriculture, was held on the campus of Louisiana State University. This workshop brought together the leading engineers, scientists, and economists involved in recirculating aquaculture systems to discuss current state of the art technologies and determine future research directions. Discussions focused on the need for efficient solids capture, nitrification, and degasification in high density recirculating systems with hydraulic retention times of 10 - 30 days. Several established treatment configurations were compared with emerging technologies, such as the expandable granular biofilter (EGB) which is addressed in this paper. Additionally, concerns about the environmental impact
of sludges produced by the recirculating systems were raised. This paper examines the factors controlling sludge production from recirculating systems with emphasis on the EGB technologies.

BEAD FILTERS
Solids capture and biofiltration is normally accomplished in recirculating systems as sequential unit operations. For example, the most broadly advocated configuration is a settling basin followed by a rotating biological contactor (RBC) (Libey, 1991; Van Gorder, 1991). An EGB effectuates both processes within a single granular bed. Early EGB configurations, such as the upflow sand filter (Burden, 1988; Malone and Burden, 1988), were limited in total ammonia nitrogen (TAN) conversion and solids capture capabilities by the fluidization characteristics of the sand. These short comings were overcome through the use of low density plastic beads which float. These "bead" filters exhibit superior oxygen transport and are more easily cleaned than sand filters. Filtration of suspended solids (TSS) is accomplished by settling, straining, and interception within the granular bead matrix. Simultaneously, the bead bed operates as a fixed film bioreactor. Washing sequences induce the shedding of excessive outgrowths of heterotrophic bacteria and solids accumulating in the interstitial spaces between the beads, thus, assuring good nutrient transport of TAN, nitrite, oxygen, and bicarbonates to the critical nitrifying bacteria.

The method employed to wash (or backwash) the granular bead bed has a direct impact on both the filter's performance and sludge production characteristics. Although both air
injection (Cooley, 1979) and hydraulic wash (Wimberly, 1990) can be utilized to expand and agitate the bed, mechanical washing (Malone, 1992) has proven effective while producing a relatively concentrated sludge stream. The mechanically washed filter has four modes of operation (Figure 1). The significance of this filtration approach stems from the extremely low water loss associated with solids removal. Low density polyethylene

Figure 1: Operational Sequence for a Mechanically-washed Floating Bead Biofilter
beads (3 - 5 mm in diameter) are employed as a filter media in an upflow, pressurized filter configuration. The beads, less dense than water, float above the injection line, and are retained in the filter by an overlying stainless steel screen. The filtration bed is underlain by a cone shaped settling chamber. Embedded in the filter bed is a dual propeller system which is activated for periodic cleaning. The filter physically traps suspended solids, while providing a large specific surface area (1100 m²/m³) for the growth of crucial heterotrophic and nitrifying bacteria.

Although being easily mistaken for a physical filter, the bead filter was specifically designed to facilitate rapid growth of both nitrifying and heterotrophic bacteria. During a typical filter operation (Step 1), heterotrophic bacteria rapidly grow in the pore spaces between the beads, extracting dissolved organics (BOD) from the circulating waters. Slower growing nitrifiers, coat each bead providing for the conversion of the toxic ammonia and nitrite to the stable nitrification end product, nitrate (Colt and Armstrong, 1981). As solids and bacterial biomass accumulate, the bed begins to clog, impeding the transfer of oxygen and nutrients to the bacteria in the filter. Triggered by a timer, pressure sensor, or computerized control unit, the propeller driven backwash sequence (Step 2) is implemented, homogenizing the bed into the underlying settling chamber. When the propellers are turned off, the beads float upwards reforming the filtration bed, while the accumulated solids and the bulk of the heterotrophic bacteria accumulate in the bottom of the settling chamber for removal (Step 3). The slow growing nitrifying bacteria benefit from their attachment to the beads and are retained in the bed. A large part of the solids accumulating in the settling cone consist of bacterial biomass grown in the
intervening filtration cycle. These solids are allowed to compress, forming a concentrated sludge that can be removed (Step 4) just prior to the next backwash cycle. The water loss is negligible, permitting frequent backwashing. If the solids are harvested several times a day, little of the particulate (excreted solids) BOD demand is expressed in the system. Thus, the bead filter is capable of mitigating extremely high waste loadings.

Bead filters compare quite favorably to fixed media nitrification filters which are exposed to the air (Table 1). High recirculating flow rates dictated by ammonia mixing constraints, in combination with the low substrate regimes, eliminate concerns about oxygen transport. Trickling filters and RBC's are clearly effective biofiltration units. However, the need to maintain high porosity to avoid biofouling limits specific surface area, thus, controlling their volumetric conversion capacity. On the other hand, fluidized beds are clearly superior nitrification units, displaying volumetric nitrification rates double that of bead filters. Use of a bead filter for nitrification in lieu of a fluidized bed is predicated on the assumption that integrated treatment with a bead filter will prove to be more cost effective. That is, a bead filter sized for nitrification will be less costly than a properly sized solids capture device and a fluidized bed.

SLUDGE PRODUCTION

All the sludge generated from a recirculating aquaculture system originates from the feed. Assuming a typical feed conversion ratio of 1 to 2, and neglecting the impact of uneaten food, 80% of feed (on a dry mass basis) input to an aquaculture system will eventually be wasted as fish excretion products (Hopkins and Manci, 1989). Sludge volume is a
<table>
<thead>
<tr>
<th>Description</th>
<th>No Observations</th>
<th>Specific Surface Area (m²/m³)</th>
<th>Mean pH</th>
<th>Mean Effluent TAN (mg-N/l)</th>
<th>Areal TAN Conversion (g/m²-day)</th>
<th>Volumetric TAN Conversion (g/m³-day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upflow sand</td>
<td>6</td>
<td>2350</td>
<td>7.15</td>
<td>0.31</td>
<td>0.064</td>
<td>152</td>
</tr>
<tr>
<td>Hydraulic washed bead filter</td>
<td>32</td>
<td>1230</td>
<td>7.54</td>
<td>0.62</td>
<td>0.231</td>
<td>286</td>
</tr>
<tr>
<td>Mechanical washed bead filter</td>
<td>7</td>
<td>1050</td>
<td>7.38</td>
<td>1.1</td>
<td>0.291</td>
<td>308</td>
</tr>
<tr>
<td>Rotating biological contactor</td>
<td>6</td>
<td>150</td>
<td>7.51</td>
<td>0.53</td>
<td>0.280</td>
<td>41</td>
</tr>
<tr>
<td>Fluidized bed</td>
<td>40</td>
<td>2350</td>
<td>7.47</td>
<td>0.30</td>
<td>0.284</td>
<td>633</td>
</tr>
</tbody>
</table>

Commercial soft-crayfish facility (Burden, 1988)
Experimental scale catfish system (Wimberly, 1990)
Mississippi Power and Light demonstration facility, Greenville, Mississippi (1991)
Mississippi Power and Light demonstration facility, Greenville, Mississippi (1991)
Experimental scale chemically fed (Thomasson, 1991)
major factor in designing a waste treatment system for effluents. Sludge volume generated from
a recirculating system is controlled by the amount of solids produced (measured as kilograms of
dry weight solids) and the degree to which the solids are concentrated in the effluent stream.
Total sludge production from a recirculating system can be estimated by considering direct fish
excretion, solids breakdown, and biofloc production during biofiltration. Sludge concentration is
controlled by the solids removal technique employed to capture solids from the recycled stream.
Solids production can be quantified through a mass balance analysis which considers the major solids fluxes:

\[
dS/dt = (F \times P) - [(1 - E) \times F \times P/W_f] - [K_d \times S] + [B_f (F \times P)] - h_s S
\]  

(1)

where,

\[
\begin{align*}
F & = \text{Feed rate (kg feed/kg fish-day)} \\
P & = \text{Fish in system (kg)} \\
E & = \text{Solids excretion rate (kg excreted/kg feed consumed)} \\
W_f & = \text{Feed waste factor (kg fed/kg consumed)} \\
K_d & = \text{Solids biological decay constant (day}^{-1}) \\
S & = \text{Solids in system (kg)} \\
B_f & = \text{Biofloc production factor from soluble BOD (kg biofloc produced/kg feed)} \\
h_s & = \text{Sludge harvest fraction (kg solids harvested/kg solids in system-day)}
\end{align*}
\]

Assuming steadystate conditions and solving for S:

\[
S = \frac{[1 - \frac{1 - E}{W_f} + B_f] \times F \times P}{(K_d + h_s)}
\]  

(2)
Neglecting the impact of uneaten feed (i.e. $W_f = 1$), Equation 2 can be simplified, clearly identifying the major factors controlling sludge accumulation in a recirculating system:

$$S = \frac{[E + B_I] \times F \times P}{(K_d + h_s)}$$  (3)

The direct solids excretion rate ($E$) has been estimated at 0.40 (Speece, 1973) to 0.52 kg/kg-feed (Liao and Mayo, 1974) for trout and 0.43 kg/kg-feed for catfish (Wimberly, 1990). Other reported TSS excretion rates for catfish ranged from 0.18 to 0.69 kg/kg-feed (Page and Andrews, 1974; Gordon, 1974, Ruane et al., 1977). Solids excretion rates clearly vary with species, temperature, and feeding rates. However, values of $E$ in the range of 0.3 to 0.5 appear to be typical.

The BOD$_5$ excretion rate can also generally be expressed as a fraction of the feeding rate. The BOD$_5$ is excreted in soluble and particulate forms. Based upon the study on channel catfish, Murphy and Lipper (1970) reported the soluble BOD$_5$ as 58% of the total BOD$_5$ excreted; whereas, BOD$_5$ in particulate matter was 42%. Wimberly (1990) found that 23% and 77% of the BOD$_5$ excreted was in the soluble and particulate forms, respectively.

The solids production from biofiltration depends on the growth of bacterial biomass during the breakdown of dissolved organics (BOD$_5$) and nitrification. Considering TAN excretion rates of 1.8 to 4.6% of the feeding rate (Gordon, 1974; Page and Andrews, 1974; Ruane et al., 1977; Wimberly, 1990) and the stoichiometry of nitrification cited by Wheaton (1977), biomass production due to nitrification is negligible at 0.03% to 0.09% of the feeding rate. The biomass production due to dissolved BOD$_5$ consumption, on the other hand, is more significant. For example, if 23% of the BOD$_5$ (0.22 kg BOD$_5$/kg-feed) is produced in the soluble form as reported by Wimberly (1990), the total soluble BOD$_5$ production will result in a biofloc production which
averages 5% of the feeding rate. This portion of BOD$_5$ is absorbed during biofiltration, producing TSS levels equivalent to 9% of the feeding rate based on the stoichiometry of BOD$_5$ removal. Assuming the BOD has a composition similar to typical municipal sludge, values for the biofloc production constant, $B_f$, in the range of 0.08 to 0.12 can be reasonably assumed.

The sludge harvest faction, $h_s$, can be related to the rate of solids retention time (SRT) by Equation 4:

$$\text{SRT} = \frac{1}{h_s}$$  \hspace{1cm} (4)

This sludge loss characteristics for a given bead filter configuration can be determined by sequential washing, thereby, allowing the SRT to be estimated by dynamic modelling. By this method, $h_s$ can be estimated for a variety of backwashing sequences. Bubble washed bead filters display $h_s$ values of about 0.35 (SRT = 2.9); whereas, the more vigorously washed mechanical bead filters display $h_s$ values as high as 0.75 (SRT = 1.33) for once a day wash sequences.

The sludge production constant $S_p$ (kg/day) from the system is defined simply as:

$$S_p = h_s \times S$$  \hspace{1cm} (5)

The concentration of the sludge stream or $S_c$ (kg/m$^3$) is determined by the efficiency of the sludge separation process and the amount of flushing or washdown waters ($Q_s$ in m$^3$/day) required for the sludge removal.

$$S_c = \frac{S_p}{Q_s}$$  \hspace{1cm} (6)

Calibration of Equations 2 through 6 using an experimental system in the author's laboratory resulted in $K_d = 0.36$ day$^{-1}$ for a bead filter with an SRT of about 3 days. The obtained $K_d$ value is within the range of municipal waste (0.28 - 0.71 day$^{-1}$, Reynolds, 1982). Given the refractory
nature of aquaculture sludges, it can be anticipated that $K_d$ values for sludges with high SRT's will decline below that observed in the author's laboratory.

Equations 2 through 6 can be used to estimate sludge production from a proposed recirculating configuration. Assuming a feeding rate of 2% of body weight per day, Table 2 illustrates that a recirculating aquaculture system for catfish or trout generate sludge volumes comparable to other commercially cultured animals on a live weight basis.

Table 2. Waste Generation (day/1000 kg-Live Weight) Comparison Between Catfish and Other Commercial Animals.

<table>
<thead>
<tr>
<th>Animals</th>
<th>BOD (kg)</th>
<th>TSS (kg)</th>
<th>TKN (kg)</th>
<th>Sludge Volume (liter)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish (1)</td>
<td>1.1-3</td>
<td>3.9-6.3</td>
<td>0.2-0.32</td>
<td>65-630$^{(2)}$</td>
<td>Present study$^{(3)}$</td>
</tr>
<tr>
<td>Beef Cattle</td>
<td>1.6</td>
<td>9.5</td>
<td>0.32</td>
<td>30</td>
<td>Middlebrooks et al., 1982;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Overcash et al., 1983a</td>
</tr>
<tr>
<td>Dairy Cows</td>
<td>1.4</td>
<td>7.9</td>
<td>0.51</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Poultry</td>
<td>3.4</td>
<td>14</td>
<td>0.74</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Swine</td>
<td>3.1</td>
<td>8.9</td>
<td>0.51</td>
<td>76</td>
<td></td>
</tr>
</tbody>
</table>

(1) Calculated at the feeding rate of 2% body weight per day
(2) Calculated based on 1-6% TSS concentration in sludge
(3) Calculated according to the excretion value in Table 1, and assuming $K_1 = 0.36$, $h_s = 0.35$.

**DISCUSSION**

Direct discharge of untreated backwash waters to receiving streams can cause a variety of problems including oxygen depletion, nutrient enrichment, loss of water clarity, and destruction of important benthic communities through the formation of sludge deposits. Generally, effluent streams should be clarified to separate and concentrate settleable solids prior to discharge. The sludge itself must be disposed of through land application or landfilling. Although sludge
produced by recirculating systems is high in organics, with volatile solids content around 80 percent, the material is at least partially stabilized having passed through the gut of the fish and having been attacked by the bacteria which flourish in the system. High nitrogen contents (4 - 6%), phosphorus levels of about 2 percent, and the absence of contaminants, such as heavy metals, make aquaculture sludges attractive as fertilizers (Mudrak, 1981; Willett and Jakobsen, 1986; Olson, 1991). Direct land application has proven feasible in areas with dry climates where the high moisture content of the sludge is considered beneficial. In wet climates, additional stabilization of sludges (Table 3) may be required to avoid odor problems.

Table 3. Features of Sludge Stabilization Options.

<table>
<thead>
<tr>
<th>Option</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Anaerobic Lagoon</td>
<td>High organic loading</td>
<td>Odor</td>
</tr>
<tr>
<td></td>
<td>Low maintenance</td>
<td></td>
</tr>
<tr>
<td>2. Aerated Lagoon</td>
<td>Space efficient</td>
<td>Energy consumption</td>
</tr>
<tr>
<td></td>
<td>High organic loading</td>
<td>Moderate maintenance</td>
</tr>
<tr>
<td>3. Aerobic Digesters</td>
<td>High loading</td>
<td>Energy consumption</td>
</tr>
<tr>
<td>4. Anaerobic Digesters</td>
<td>High loading</td>
<td>Complex</td>
</tr>
<tr>
<td></td>
<td>Methane generation</td>
<td>High maintenance</td>
</tr>
<tr>
<td>5. Composting</td>
<td>Useful end product</td>
<td>Dewatering required</td>
</tr>
</tbody>
</table>

As can be seen in Equation 5, the mass of sludge produced from a recirculating system, \( S_p \), is the product of the solids content of the system and the sludge harvest factor. These two parameters are, however, inversely related through Equation 3. Decreasing \( h_s \) tends to decrease sludge production as the importance of \( K_d \) increases with SRT, but at the cost of increasing the solids content of the system.

Figure 2 illustrates an application of Equations 3 through 5 to a hypothetical finfish system of a 1000 kilogram capacity. Utilizing typical constant values \( (E = 0.4, B_I = 0.1, F = 0.02, K_d = 0.36) \),
Figure 2. Increasing the Solids Retention Time Decreases Sludge Production but Increases the Solids Mass in the Recirculating Loop.

A reduction of about 50 percent in discharged sludge mass is achievable by manipulation of the bead filter backwashing sequence. However, there is a corresponding increase in sludge mass held in the system which increases aeration and degasification burdens within the recirculating system. Additionally, excessive sludge accumulations may interfere with the biofilter's nitrification performance.

The relationship between sludge accumulation and nitrification capacities can be inferred from Figure 3 which illustrates a typical nitrification pattern for a heavily loaded bead filter operated without backwashing. Initially, the nitrification rate constant (normalized to surface area) increases as the mass of nitrifying bacteria increases. But, as the pore spaces of the filter begin to clog the nitrification capacity declines. This phenomenon constrains efforts to manipulate SRT
Figure 3. Nitrification Rates Displayed by Bead Filters is Influenced by the Backwash Interval.

for purposes of sludge volume reduction. Common sense dictates that the biofilter should be manipulated to optimize nitrification. The resulting SRT's limit sludge reduction to about fifty percent as illustrated in the example (Figure 2).

Sludge management policies should focus instead on increasing $S_C$ (Equation 6). The concentration of solids varies dramatically with the type and management of the solids control device employed in the recirculating loop (Table 4). Additionally, the sizing criteria and cost of the stabilization and disposal options are controlled by the volume of sludge produced. If the solids capture device controlling the TSS levels in the production system can not be operated to minimize the waters discharged, then an external clarifier should be used to achieve the desired sludge density. Clearly, integrated design allows for overall minimization of treatment costs.
Table 4. Total Suspended Solids Concentrations in Sludge Generated by Three Typical Solids Removal Processes.

<table>
<thead>
<tr>
<th>Techniques</th>
<th>TSS Concentration in Sludge</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upflow sand filter</td>
<td>0.005 - 0.015%*</td>
<td>Malone and Burden, 1988</td>
</tr>
<tr>
<td>Primary sedimentation</td>
<td>1 - 6%</td>
<td>Kugelman and Van Gorder, 1991; present study</td>
</tr>
<tr>
<td>Low-density media filter</td>
<td>0.05 - 0.5%</td>
<td>Present study</td>
</tr>
<tr>
<td>Sand filtration</td>
<td>0.01 - 0.02%</td>
<td>Metcalf and Eddy, 1979</td>
</tr>
</tbody>
</table>

* Calculated for 1 - 3 minute backwashing time

Consideration given to the partitioning of the sludge stabilization burden between internal and discharge treatment processes can reduce the potential for conflicts with environmental regulatory agencies while enhancing production methodologies.

Bead filters should be designed with internal settling cones, as was illustrated in Figure 1, to facilitate single stage sludge concentration. Additionally, the sludge retention time can be easily controlled by frequency, duration, and vigor of backwashes. Higher sludge retention times (2 - 5 days) tend to encourage biodegradation of sludges, while enhancing nitrification capacities and decreasing waterloss. Increasing settling times within the backwash sequence can significantly increase sludge density. These capabilities can facilitate linkage with external sludge treatment processes.

SUMMARY

Integrated design of recirculating and discharge treatment processes can eliminate potential environmental impacts of sludges generated from large scale aquaculture production systems. Manipulation of bead filter backwashing characteristics can result in about a 50 percent reduction in sludge mass discharged through encouragement of biodegradation. Dilute sludges produced
by backwashing or washdown operations should be concentrated by internal settling lines or by external clarification processes prior to stabilization or disposal. Both aerobic and anaerobic processes with extensive track records are available to reduce the easily biodegradable portion of discharged sludge, minimizing the volume of sludge for final disposal. Direct sludge disposal through land application appears feasible for rural areas; whereas, landfilling of stabilized sludges may be most appropriate for urban areas.
LITERATURE CITED


