
PRODUCTION, CHARACTERISTICS, AND MODELING OF AQUACULTURAL SLUDGE FROM A RECIRCULATING AQUACULTURAL SYSTEM USING A EXPANDABLE GRANULAR BIOFILTER

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ABSTRACT

In an intensive aquacultural operation, a considerable portion of feed input will end up as waste, the majority being in the form of sludge. Aquacultural sludge has a significant pollution potential because of its organic nature and the nutrient content. This paper presents the results of a sludge production and characterization study, along with a mathematical model simulating sludge production from recirculating systems using low density expandable granular biofilters (EGBs). A correlation developed between sludge production and feeding rate showed that 14% of the feed input (on a dry weight basis) ends up as TSS in the sludge discharge. Further characterization of the sludge showed that the percentage of COD, BOD$_5$, BOD$_{pp}$, TKN, TP in TSS were 101.2%, 22.9%, 58.7%, 4%, and 0.7%, respectively. The TSS concentration in the sludge ranged from 631 - 1344 mg/l. The mathematical model which takes fish excretion, solids decay, biofloc production and solids harvest rate into account, was used to estimate the solids production as a function of the operational parameters of a low density media EGB. Model simulation results can be used for filtration system and sludge treatment process design.

INTRODUCTION

While the intensive culture of freshwater and marine finfish is receiving considerable attention from the public and private sectors as a new agribusiness (Losordo, 1991), increasing concern has been raised regarding the environmental impacts of such aquacultural systems (Liao and Mayo, 1974; Mudrak, 1981; Brune, 1991; Iwama, 1991). The discharge of wastes from intensive aquaculture systems into receiving waters can cause eutrophication, oxygen depletion, increased turbidities, and increased solids loads (Iwama, 1991). Although reduced environmental impacts have been realized by using recirculating systems due to their production of concentrated aquacultural wastes (Liao and Mayo, 1974; Iwama, 1991; Chen et al., 1991), sludge from a recirculating system still must be treated prior to discharge into the environment.

The design of a sludge treatment system is determined by the production and characterization of the sludge produced. In recirculating aquacultural systems, suspended solids are typically separated from the culture water by a solids control unit and then discharged from the system in the form of sludge. Because the excreted fecal material is already partially stabilized before it leaves the system, the solids control process employed naturally has an impact on the characterization and rate of sludge

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production. In addition, the feed and feed rate (% body weight/day) are believed to have the strongest influences on the total sludge production from such a system.

The primary methods used to facilitate the removal of solids from recirculating systems are sedimentation and/or filtration processes (Chen and Malone, 1991). Expandable granular biofilters (EGBs) have gained wide acceptance in recent years as both physical and biological filters. These filters offer higher hydraulic loading rates and better removal of small particles (diameters less than 100 microns). An example of EGBs is a newly developed filter which utilizes low-density plastic media and allows for the control of solids residence time (Malone, 1992). This filter has demonstrated a high solids loading capacity and is increasingly gaining acceptance.

The objectives of this paper are (1) to characterize TSS production, (2) to determine the chemical characteristics of the sludge produced and (3) to develop a mathematical model for sludge production from a recirculating system employing an EGB for both solids capture and biofiltration.

MATERIALS AND METHODS

The Experimental System

The investigations on sludge production and characterization were conducted on a recirculating channel catfish (Ictalurus punctatus) culture system in the Spring and Summer of 1992. This system consisted of a low density media EGB, Model BBF-3 (Arment Aquaculture, Inc. of Vacherie, Louisiana), a 1,916 liter rectangular culture tank (2.36 m x 1.16 m x 0.70 m), an aeration system, and a water circulation system (Fig. 1). The aeration was supplied by a 747.5 W regenerative blower coupled with seven inch glass silica air stones. The water circulation was achieved by a 373.8 W horizontal centrifugal pump (American Products) equipped a with strainer. The pump intake was connected by PVC piping to a 3.8 cm perforated inlet manifold on the bottom of the culture tank. A 3.8 cm PVC ball valve was then used to regulate the flow to the filter. The water flowed into the bottom of the filter and exited through the discharge fixture at the top of the filter, where it was returned to the fish tank. The system contained between 90-113 kg (200-250 pounds) of channel catfish during this study. The water level was controlled by an automatic refill connected to a float valve. The water level target was 1,800 liters. The system temperature was maintained by utilizing the laboratory air conditioning and heating systems. The temperature of the system during this research was 25° C +/- 3° C.

The EGB filter, which was used for both solids capture and biofiltration, had a bed volume of 0.085 m³ (three cubic feet) of recycled polyethylene beads (pellets). Constructed of fiberglass, the filter had an hourglass configuration that allowed for both bed expansion and consolidation, depending on the mode of operation. In the filter, the plastic media floated, allowing filtration to occur as the upflowing water passed through the bed (Malone and Coffin, 1992). As water flowed through the filter, suspended particles were either strained or deposited on the bead surface, while dissolved organics and nitrogen were consumed by the bacteria growing on the beads' surfaces. Backwashing of the filter was accomplished through bed expansion. Expansion of the media took place when the pump and/or the valve at the inlet side were manually turned off and the sludge valve opened. As the water level dropped, the beads and water were forced through the washing neck of the filter where a combination of water and bubbles scrubbed the beads just before they fell into the expansion chamber. The beads were retained in the filter via a slotted pipe. A detailed description of the backwash operation of the filter can be found elsewhere (Malone and Coffin, 1992).
The resultant sludge was discharged into a small rectangular fiberglass tank to allow for easy sample collection and sludge disposal. Each backwash of the filter generated 151 liters of sludge. No additional water exchange to the system was made except the replacement of that lost during filter backwash.

**Sludge Production Investigation**

The purpose of the sludge production study was to find the relationship between the amount of sludge produced and the amount of feed input to the system. During the investigation, five feeding levels from 0.6 to 1.5% of body weight per day were tested. Each feeding rate was maintained for a week, and a weekly average sludge production was calculated based on the daily sludge production data. The feed was broadcasted into the tank manually. Fish were fed twice a day, immediately after water sampling and between 9:00 and 10:00 a.m. of the next day. The feed used was floating catfish pellets, 32% protein, manufactured by Purina Mills, Inc. Laboratory analyses indicated that the feed had a moisture content of 10.2% (n = 3; std = 0.2%).

During sampling, the bead filter was backwashed, and the sludge was drained into the sludge tank. The sludge volume was measured, then two samples were taken after completely mixing the entire volume of sludge. Sludge samples were collected daily between 2:00 and 3:00 p.m. Samples from the fish tank were also collected to monitor any solids concentration changes in the fish tank which might occur with variations in the feeding rate.

**Sample Analysis**

All samples were collected, preserved, and analyzed in accordance with Standard Methods (APHA, 1989). Parameters measured included biochemical oxygen demands (BOD₅ and BOD₃), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphorous (TP), and total suspended solids (TSS).
Model Development

Sludge Mass Balance

The solids contained in the sludge discharged by an EGB include those produced due to feed input, excretion and bacterial growth. For a given type of feed, the production of the solids in a recirculating system is controlled by several interdependent parameters including: feed rate, feed consumption rate, solids harvesting factor, solids retention time, and solids decay rate. A solids mass balance can be established for the system.

\[
dS/dt = R_E + R_U + R_B + R_N - S_D - S_P
\]

(1)

where

- \( R_E \) = solids mass generation rate from fish excretion, \( R_E = F_r \times M \times E_s \times F_c \).
- \( F_r \) = feeding rate (kg feed/kg fish - day).
- \( M \) = fish mass (kg fish),
- \( E_s \) = solids excreted (kg solids/kg feed),
- \( F_c \) = feed consumption ratio (kg feed consumed/kg fed); \( R_U = F_r \times M \times (1 - F_c) \).
- \( R_B \) = solids mass production rate due to BOD\(_5\) conversion, \( R_B = Y_b \times B \times F_r \times M \). \( Y_b \) = biomass yield coefficient (kg solids/kg soluble BOD\(_5\) consumed),
- \( B \) = soluble BOD generation (kg soluble BOD generated/kg feed fed),
- \( R_N \) = solids production rate due to the growth of nitrifying bacteria, \( R_N = Y_n \times N \times F_r \times M \),
- \( Y_n \) = biomass yield from nitrification processes, \( (kg \; solids \; generated/kg \; TAN \; converted \; to \; NO_3) \).
- \( N \) = total ammonia nitrogen excretion (kg TAN/kg feed consumed),
- \( S_D \) = Solids decay (kg/day), \( S_D = K_d \times S \),
- \( K_d \) = solids decay coefficient (days\(^{-1}\)),
- \( S \) = solids in system (kg solids),
- \( S_P \) = solids removal rate (kg solids/day), \( S_P = H_s \times S \) at backwashing,
- \( H_s \) = sludge harvest factor (kg of solids harvested per day/kg solids in the system).

Assuming that (1) all feed was consumed (\( F_c = 1 \)), and (2) biofloc generation resulting from nitrification processes was negligible (Chen et al., 1991), Equation (1) becomes:

\[
dS/dt = (F_r \times M) \times (E_s + Y_b \times B) - (K_d + H_s) \times S
\]

(2)

Evaluation and Simulation

The model was evaluated using the experimental data collected. Data was reported in the same form necessary for inclusion in Equation (1). The evaluation was performed by assuming steady state conditions for Equation (1). For example, Equation (1) was used to calculate the fish excretion rate. Then, knowing the other parameters, the model was considered reasonable if the prediction of the excretion rate was consistent with the reported values.

Once the model was proven reliable, it was used to simulate the behavior of the filter system. A main concern in recirculating systems is solids production/accumulation with respect to feeding rate. Solids accumulation in the system as a function of feeding rate ranging from 1% to 5% was calculated using
the model. Biomass production due to BOD conversion was also calculated under these conditions. The other parameters used in the simulation are listed in Table 1.

Table 1. Parameters used During the Sensitivity Analysis of the Model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Value Used</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved BOD₅ (mg-O₂/l)</td>
<td>0.083 - 0.22</td>
<td>0.178</td>
<td>Page and Andrews, 1973; Gordon, 1974; and Wimberly, 1990</td>
</tr>
<tr>
<td>Biomass Yield (Y₀)</td>
<td>0.36 - 0.65</td>
<td>0.50</td>
<td>Metcalf and Eddy et al., 1979; Chudoba and Tuckek, 1985; Chen, 1992</td>
</tr>
<tr>
<td>Solids Harvest Factor (Hₜ)</td>
<td>0.27 - 0.44</td>
<td>0.362</td>
<td>Coffin, 1993</td>
</tr>
<tr>
<td>Solids Decay Rate (Kₜ)</td>
<td>0.28 - 0.71</td>
<td>0.405</td>
<td>Metcalf and Eddy, 1979; Reynolds, 1982</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Sludge Production

Total solids generation in the system was directly related to the feeding rate of the fish as demonstrated in Fig. 2. Linear regression of data in Fig. 2 resulted in the following equation:

\[ S_p = 0.124 \, F \left( r^2 = 0.78, \, SE = 20.5, \, SB = 0.008, \, N = 5 \right) \]  
(3)

where

\[ F = \text{feed input rate, } F = F_r \, M; \]
\[ SE = \text{standard error of the regression model}; \]
\[ SB = \text{standard error of the coefficient estimated by regression}; \]
\[ N = \text{number of observations}. \]

The coefficient of regression indicates that approximately 12.4% of the feed (with a moisture content of 10%) input was expressed as TSS and discharged from the system as sludge. On a dry weight basis, this coefficient becomes 14%. It should be noted that the TSS concentration in the fish tank did not change considerably with changes in the feeding rate. Therefore, the variation of solids production due to solids accumulation in the fish tank can be neglected. The resultant solids production rate from a bead filter can be compared with solids production from other solids control processes. Mudrak (1981) reported that clarifiers and settling basins employed as solids removal devices in trout raceway systems recovered 0.032 to 0.258 kg solids/kg of feed (dry weight basis). McLaughlin (1981) found a range of 0.044 to 0.38 kg TSS/kg feed fed in trout raceway settling basins and attributed the large variation to digestion occurring in the settled sludge prior to removal. The research results illustrated in Fig. 2 also suggest that the solids production from a filter is lower than the reported fish excretion (Wimberly, 1990). This is mainly due to solids decay in the filter system. It needs to be pointed out that solids decay requires oxygen; it is therefore important to consider this oxygen consumption when one designs an aeration unit for such a system.
Waste Characteristics

The waste characteristics of the sludge, as summarized in Table 2, shows that TSS is the major component of the sludge. The majority of BOD$_5$, COD, and TKN are associated with particulate matter. Once the suspended particles are removed from the sludge, the effluent quality is greatly improved. Therefore, the data in Table 2 can be used to assist in sludge treatment system design by making TSS control the first priority. The fact that TSS control is the limiting factor makes the treatment process simpler, since suspended solids removal is typically easier than biological filtration.

Table 2 shows that the majority of phosphorous is in dissolved form. Therefore, in case where phosphorous discharge is a concern, the sludge effluent needs to further treatment.
Table 2. Waste and Waste Components in the Sludge Effluent (N = 5).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Concentration (STD)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Particulate and Dissolved form (mg/l)</td>
</tr>
<tr>
<td>TS</td>
<td>2389.0 (376.8)</td>
</tr>
<tr>
<td>BOD(_5)</td>
<td>242.5 (91.9)</td>
</tr>
<tr>
<td>COD</td>
<td>1149.0 (383.6)</td>
</tr>
<tr>
<td>TKN</td>
<td>52.0 (18.0)</td>
</tr>
<tr>
<td>TP</td>
<td>19.4 (5.3)</td>
</tr>
</tbody>
</table>

\(^a\)STD = Standard deviation.

Another important fact determining sludge treatment design is the pollutant potential of the suspended particles discharged from the biofilter. For example, the BOD value of the TSS determines if a stabilization process is necessary. The TKN and TP contents determine the land application rates, if the land treatment option is chosen. Table 3 demonstrates the relative magnitude of other parameters to TSS concentration in the sludge. The nitrogen results (Table 3) compare well with that reported by Olson (1991) who analyzed organic nitrogen in trout manure collected in settling basin as 3.7% of TSS on dry weight bases. The phosphorous, on the other hand, is lower in this study. Olson (1991) reported TP/TSS as 2.6%; whereas, the present study was only 0.7%. The difference can be caused by difference in initial phosphorous concentration in fish feed, or different solids control methods causing different dissolution rate of phosphorous in water. It has been summarized that the TP content of salmonid diets range from 1.14 to 2.2%, while the range of TP content for tilapia and carp diets are 1.3% to 2.52%, and 0.93 to 3.06%, respectively. Given the fact that the majority of TP will be dissolved in water (Table 2), the percentage of TP to TSS given in this study is considered reasonable.

Table 3. Ratios of BOD\(_5\), COD, BOD\(_{20}\), TKN, TP to TSS in Suspended Particulates from Sludge Effluents (%).

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>TSS</th>
<th>BOD(_5)/TSS</th>
<th>COD/TSS</th>
<th>BOD(_{20})/TSS</th>
<th>TKN/TSS</th>
<th>TP/TSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>631</td>
<td>25</td>
<td>122</td>
<td>52.3</td>
<td>4.2</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>866</td>
<td>24.7</td>
<td>83</td>
<td>84.7</td>
<td>4.9</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>1344</td>
<td>16.3</td>
<td>116</td>
<td>51.0</td>
<td>2.9</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>976</td>
<td>16.4</td>
<td>100</td>
<td>40.6</td>
<td>3.9</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>1047</td>
<td>32</td>
<td>85.0</td>
<td>64.9</td>
<td>3.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Mean</td>
<td>972.8</td>
<td>22.9</td>
<td>101.2</td>
<td>58.7</td>
<td>4.0</td>
<td>0.7</td>
</tr>
<tr>
<td>STD</td>
<td>260.5</td>
<td>6.6</td>
<td>17.7</td>
<td>16.9</td>
<td>0.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>
The results in Table 3 can also be used to evaluate the stability of the TSS in the sludge. It has been reported that the ratio between ultimate BOD and fecal matter was 1:1 (Speece, 1973); whereas, Table 2 indicates a lower value, averaging 0.6:1. Given the fact that COD/TSS is about 1:1, the actual ultimate BOD value should be lower than one (kg BOD/Kg TSS), at least under the conditions given in this study. Nonetheless, the TSS from the discharged sludge was partially stabilized when considering BOD_5 and BOD_{20}.

The major concerns in disposing agricultural wastes are increased nutrient availability, metals content, and solids runoff. Olson (1991) found that fish wastes had a higher percentage of nitrogen content than cattle, pig, and sheep wastes. This finding has been confirmed by the results of this study. Chen et al. (1991) compared the discharges of fish wastes with other manures, and found that fish wastes discharged less BOD and TSS on a per weight basis. However, recirculating fish systems could very easily discharge more effluent volume than the other animal production systems such as poultry and dairy operations.

The characterization results can be also used as a reference in determining sludge treatment methods. Olson (1991) reported on the use of land application of sludge collected in settling basins of commercial trout facilities in Idaho. The findings were that the trout waste had significantly lower levels of metals than other sludges and had more nitrogen available for plant uptake, which made it an excellent soil conditioner/fertilizer. The conclusion from Olson (1991) was that fish manure is a viable fertilizer source, is low in heavy metals content, has 3 - 4% nitrogen by weight, and is easily applicable to land farming when in a slurry form (approximately 10% solids). Chen et al. (1991) discussed other potential designs and options available for disposal and treatment of recirculating system sludges.

**Model Evaluation**

The model has been evaluated against the production data. According to the regression relationship indicated by Equation (3), solids production from the filter based on dry weight can be expressed as

\[ S_p = Hs \times F = 0.14 \times Fr \times M \]  

(4)

It can be obtained from (4) that:

\[ S = S_p / Hs \]  

(5)

The solids removal rate due to decay can be calculated as

\[ S_d = Kd \times S = 0.14 \times Fr \times M \times Kd / Hs \]  

(6)

Substituting Equations (2), (4) and (5) into (6), at steady-state conditions, we obtain a simplified relationship

\[ 0.14 \times (Kd / Hs) + 0.14 = Es + Y \times B \]  

(7)

Substituting the values of Kd, Hs, Y, and B given in Table 1, the Es value can be determined as 0.22. Excretion studies reported a range of the ratio of TSS production to feed consumed of 0.08 to 0.52 (Speece, 1973; Liao and Mayo, 1974; Page and Andrews, 1973; Gordon, 1974; Wimberly, 1990). Given the fact that caution was taken to minimize uneaten food during the solids production investigation in this study, the excretion rate, as predicted by the model (Equation 1), is considered
reasonable. It is evident a similar model can also be developed for solids control processes such as sedimentation.

**Solids Accumulation under Different Conditions**

In a recirculating system design and operation, it is important to know the rate of solids and biomass accumulation in the system, since such accumulation can significantly affect the nitrification capacity of the filter and exert oxygen demands on the system. Fig. 3 describes the relationships between solids and biomass accumulation in the system and the feeding rate. This prediction, based on Equation (1), can be used in oxygen mass balance calculations in recirculating system design. It is evident from Fig. 3 that solids and biomass accumulations are significant at high feeding rate. Aeration system design must consider the decay of the accumulated solids in the system to assure a necessary safety factor. It should be pointed out that the calculation was conducted on the assumption that the filter was backwashed daily. Variation in the backwashing frequency leads to a change in solids production rate, as well as solids accumulation in the system (Coffin, 1993).

![Diagram showing solids accumulation vs. feeding rate](image)

**Figure 3. Sludge and Steady-State Biomass Accumulations in the Recirculating System as a Function of Feeding Rate**

**SUMMARY**

Solids production rate of a recirculating catfish system using a EGB was found to be about 14% of the feeding rate. Reductions in the environment impact of such sludge can be realized through TSS control, the only exception being phosphorous. Although the solids had been partially treated when it
was discharged from the filter, additional stabilization is necessary. The production of sludge from the EGB can be mathematically described. Simulation of the model can provide the necessary information for sludge treatment system design and operation.

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