

# REDUCING THE ENVIRONMENTAL IMPACT OF HIGH-DENSITY FISH PRODUCTION: AN INTEGRATED APPROACH TO SOLIDS TREATMENT FOR RECIRCULATING AQUACULTURE SYSTEMS USING EXPANDABLE GRANULAR BIOFILTERS<sup>1</sup>

William J. Golz<sup>2</sup>, Shulin Chen, and Ronald F. Malone

Department of Civil & Environmental Engineering  
Louisiana State University  
Baton Rouge, Louisiana 70803-6405  
U.S.A.

## ABSTRACT

*Over the past decade, the environmental impact of wastes discharged from high-density flow-through fish-production systems has been viewed with increasing concern. Recirculating aquaculture systems are gaining wider acceptance because of their ability to reduce waste discharges, improve quality control, and reduce costs. The crucial processes that must be addressed in treating recirculating water are solids capture, biofiltration, aeration, degasification, and ion balance. One of the greatest potentials for cost reduction rests with the development of designs that integrate two or more of these processes. Expandable granular biofilters (EGBs) integrate solids capture and biofiltration in a single unit process, potentially reducing the cost of treatment. Backwash frequency, a major operational parameter, influences the rate of nitrification and the volume of sludge produced. Computer and mass balance models allow the relationship between solids retention time, sludge production, and nitrification rates to be examined. While infrequent backflushing decreases water loss and sludge production, nitrification rates decline for extended solids retention times. Declining nitrification rates reflect ammonification of the accreting solids mass and a decrease in the availability of oxygen due to heterotrophic competition and increased mass-transfer resistance. Nitrification appears to be optimized with solids retention times in the range of 2-3 days, for filters utilized as the primary solids capture device. Studies indicate that biofiltration can be optimized in the presence of solids capture, by manipulating the backwash regime. This paper focuses on the primary in-filter stabilization and the post-discharge, predisposal digestion of aquacultural solids. However, because in-filter stabilization of solids is accomplished concomitantly with nitrification in EGBs, the interplay of these two processes are considered.*

---

<sup>1</sup>For citation, use: Golz, W. J., S. Chen, and R.F. Malone. 1995. Reducing the Environmental Impact of High Density Fish Production: An Integrated Approach to Solids Treatment for Recirculating Aquaculture Systems Using Expandable Granular Biofilters. In *Water Effluent and Quality, with Special Emphasis on Finfish and Shrimp Aquaculture: Proceedings of the Twenty-Fourth U.S.-Japan Aquaculture Panel Symposium*, 157-164.

<sup>2</sup>Author to whom all correspondence should be addressed: wjgolz@verizon.net.

## INTRODUCTION

High density recirculating aquaculture systems (RASs) allow for systematic optimization of the environmental variables that control the quality and cost of producing the targeted aquatic species. Fish culturists in the United States are adopting RASs to enhance the production of highly valued products including tropical fish, ornamental goldfish, and soft crabs. Researchers have been working towards improving the efficiency of recirculating components through integration, so that recirculating systems can successfully compete in the production of even moderate or commodity priced products. As waste discharges from flow-through systems have become the subject of increasing scrutiny by government regulatory agencies, in response to societal values, RASs are increasingly seen as a potentially effective means of minimizing the impact of a production unit on water and environmental resources.

The five processes required to recondition water in a recirculating system are solids capture, biofiltration, aeration, degasification, and ion balance. Solids capture is the removal of feces, uneaten food, and suspended bacteria. Solids capture can be performed by settling tanks, microscreens, or granular filters. Biofiltration is the conversion of dissolved organics and toxic nitrogenous compounds to bacterial biomass. Several common biofilters are rotating biological contactors (RBCs), trickling filters, fluidized beds, and granular beds. Aeration is often provided by blowers and air stones, and it must be sufficient to meet the respiration demands of the culture species and the bacteria in the biofilter. Degasification is the removal of carbon dioxide that results from respiration in the system. Degasification can be achieved concomitantly with aeration by sparging a sufficient volume through air stones, or it can be performed separately in a packed column. Ion balance is necessary to correct potentially harmful chemical imbalances in systems where the water exchange rate is very low. Ion balance may be achieved by increasing the water exchange rate, addition of chemicals, or denitrification for nitrate removal. Each of these crucial processes must be addressed, to provide minimally acceptable water quality for the culture species.

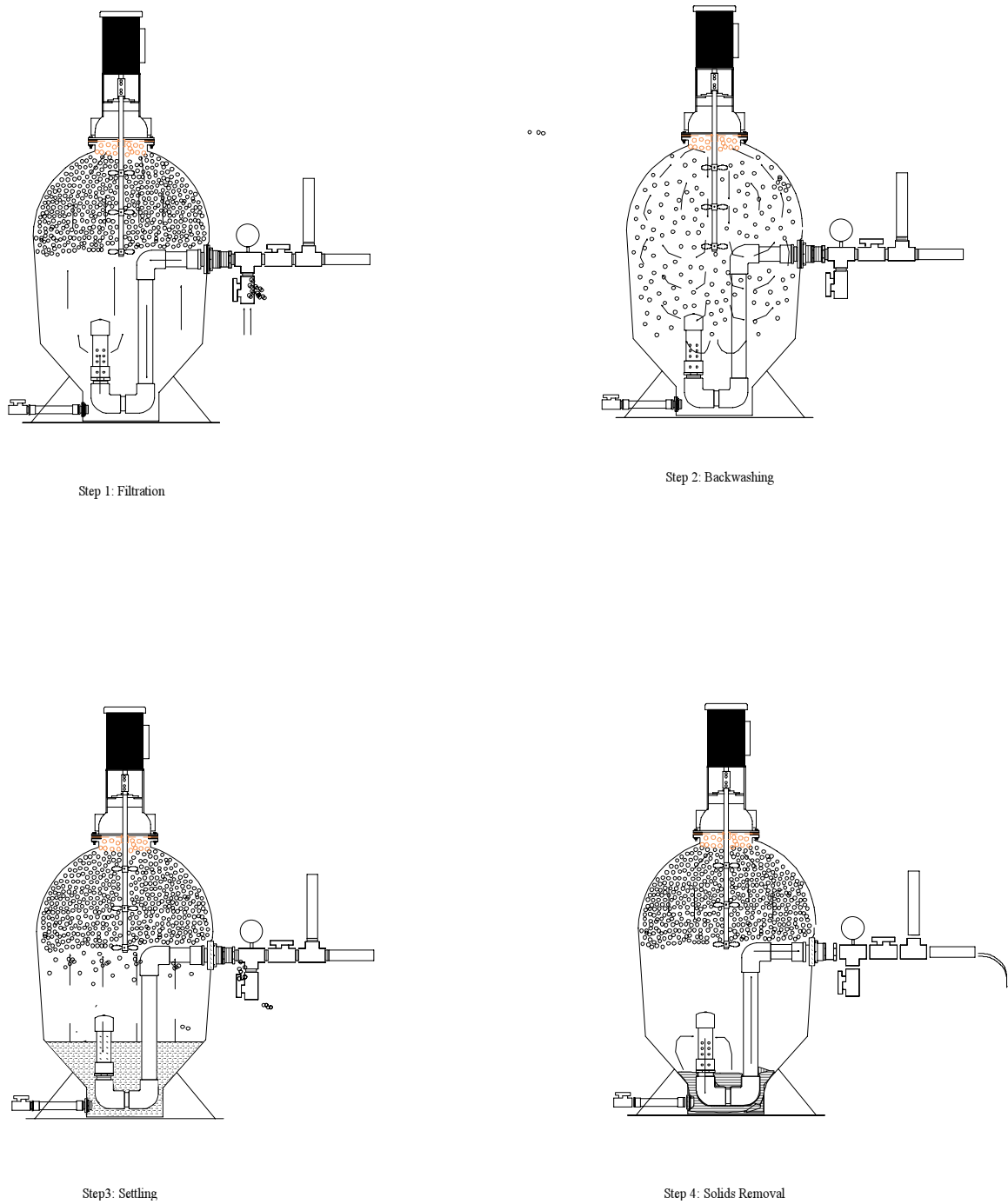
System efficiency can be increased by the addition of optional processes: foam fractionation, ozonation, UV disinfecting, and denitrification. Foam fractionation removes organics that are not easily oxidized by bacteria, which helps control fine solids (<10 microns). A foam fractionator is simply a tube containing air stones, where fine particles form foam at the air-water interface for removal at the surface. Ozone is an effective oxidant used to remove refractory organic material, which contributes to color problems, and bacteria. Ultraviolet (UV) light can be used to control many forms of bacteria, algae, and some viruses, reducing disease outbreaks. Denitrification addresses ion imbalance created by the nitrification process, removing excess nitrate and replenishing alkalinity. These processes, although usually considered optional, may become mandatory if stocking density is very high, the water reuse period is extended, or endemic disease becomes a problem.

## **EXPANDABLE GRANULAR BIOFILTERS**

Solids capture and biofiltration are normally performed as sequential unit operations in RASs. For example, a settling basin followed by a rotating biological contactor is a widely-used configuration (Libey, 1991; Van Gorder, 1991). An EGB performs both processes in a single operation. Early EGB configurations, such as the upflow sand filter (Burden, 1988; Malone and Burden, 1988) were limited in TAN conversion and solids capture by the fluidization characteristics of the sand. These limitations were overcome in EGBs through the use of low-density floating plastic beads. 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, and the bead bed operates simultaneously as a fixed film bioreactor. Periodic washing removes excess heterotrophic bacteria and highly-organic solids, which accumulate in the interstitial spaces between the beads. Backwashing mitigates solids ammonification and occlusion of the filter bed, so it is the primary means of optimizing filter performance.

The benefit of this filtration approach stems from the extremely low water loss associated with solids removal, and the large specific surface area ( $1100 \text{ m}^2/\text{m}^3$ ) provided for the growth of bacteria. Low density polyethylene beads (3-5 mm in diameter) are employed as a filter media in an upflow pressurized configuration. The beads are less dense than water, float above the injection line, and are retained in the filter by an overlying stainless steel screen. A propeller, embedded in the filter media, is activated for periodic cleaning. The filtration bed is underlain by a cone shaped settling chamber, and as shown in figure 1, the filter has four operational modes.

During a typical filter operation (Step 1), nitrifiers--which convert toxic ammonia and nitrite to stable nitrate--and heterotrophic bacteria--which remove biochemical oxygen demand (BOD)--become attached to the filter media (Colt and Armstrong, 1981). Heterotrophic bacteria, which grow more rapidly, soon fill the pore spaces between the beads. As solids and bacterial biomass accumulate, solids ammonification increases and the transfer of oxygen and nutrients to the bacteria in the filter is impeded. Triggered by a timer, pressure sensor or computerized control unit, the propeller driven backwash sequence is implemented, homogenizing the bed into the underlying settling chamber (Step 2). When the propellers are turned off, the beads float upward reforming the filtration bed, while the accumulated solids and the bulk of the heterotrophic bacteria become concentrated in the bottom of the settling chamber (Step 3). While a large part of the solids accumulating in the settling cone consist of bacterial biomass that are grown in the intervening filtration cycle, a portion of the nitrifying and heterotrophic bacteria remain attached to the beads. After backwashing, the solids are allowed to compress, forming a concentrated sludge that can be removed with only minimal water loss (Step 4). Since water loss is negligible, the solids can be harvested frequently, and little of the particulate BOD from solids excretion is expressed in the system. Thus, the bead filter is capable of mitigating extremely high waste loadings.



**Figure 1. The four operational modes of an EGB.**

Bead filters compare quite favorably to trickling filters and RBCs, which are clearly effective biofiltration units (table 1). However, trickling filters and RBCs must maintain high porosity to avoid biofouling, which limits their specific surface and thereby their volumetric conversion capacity. On the other hand, fluidized beds display superior volumetric nitrification rates, but they must be used in conjunction with a solids capture device. Use of a bead filter for nitrification, in lieu of a fluidized bed, is predicated on the assumption that integrated treatment is 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.

Filter Type	Aerial TAN Conversion (g/m <sup>2</sup> -day)	Specific Surface Area (m <sup>2</sup> /m <sup>3</sup> )	Volumetric TAN Conversion (g/m <sup>3</sup> -day)	Reference
RBC	0.280	150	41	Mississippi Power and Light demonstration facility, Greenville, Mississippi (1991)
Upflow Sand	0.064	2350	152	Commercial soft-crayfish facility (Burden, 1988)
Hydraulically-Washed EGB	0.231	1230	286	Experimental scale catfish system (Wimberly, 1990)
Mechanically-Washed EGB	0.291	1050	308	Mississippi Power and Light demonstration facility, Greenville, Mississippi (1991)
Fluidized Bed	0.284	2350	633	Experimental scale chemically fed (Thomasson, 1991)

**Table 1.** A comparison of the TAN conversion rates of common biofilter types.

### SLUDGE PRODUCTION

All the sludge generated from a recirculating aquacultural system can be equated to the feed. Assuming a typical feed conversion ratio of 1-2 lbs feed/lb fish, and neglecting the impact of uneaten food, 80% of the feed (on a dry mass basis) put into an aquacultural system will eventually be wasted as fish excretion products (Hopkins and Mancini, 1989). Sludge volume is a 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 from soluble BOD excretion. The 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 that considers the major solids fluxes:

$$\frac{d}{dt}(M_s) = F M_o (E_s + E_B Y_H) - k_s M_s S_v - H_s M_s \quad (1)$$

Where:  $M_S$  is the mass of solids in the filter bed (mass);

$M_O$  is the mass of cultured species (mass);

$E_S$  is the solids excretion ratio (mass TSS/mass-feed);

$E_B$  is the dissolved  $BOD_5$  excretion ratio (mass  $BOD_5$ /mass-feed);

$Y_H$  is the heterotrophic yield per mass of  $BOD_5$  consumed (mass VSS/mass- $BOD_5$ );

$k_S$  is the solids decay rate ( $d^{-1}$ );

$S_V$  is the volatile solids fraction (unitless); and

$$H_S = h_f f_b \quad (2)$$

Where:  $H_S$  is the solids harvest rate ( $d^{-1}$ );

$h_f$  is the solids harvest fraction (unitless); and

$f_b$  is the backwash frequency ( $d^{-1}$ ).

The direct solids excretion ratio ( $E_S$ ) has been observed as 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  $E_S$  in the range of 0.3 to 0.5 are common.

The soluble  $BOD_5$  excretion rate can also be expressed as a fraction of the feeding rate. Based upon a study of 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 soluble  $BOD_5$  excretion ratio was 0.05 kg  $BOD_5$ /kg feed, or about 23% of the total  $BOD_5$  excreted.

The first-order solids-decay rate at 20°C has been reported as varying from  $0.124 \text{ SRT}^{-0.594}$  (Ning 1995) to  $0.278 \text{ SRT}^{-0.518}$  (Wang 1995). The volatile fraction of catfish excretions has been reported as about 0.9 by Wimberly (1990) and as about 0.7 for Kemp's Ridley sea turtles (Malone & Guarisco 1988), red swamp crawfish (Cange 1987), and blue crabs (Burden 1988).

The solids production from biofiltration depends on the growth of bacterial biomass during the breakdown of dissolved organics ( $BOD_5$ ) and nitrification. Considering ammonia nitrogen excretion rates of 1.8 to 4.6% of the feeding rate (Page and Andrews, 1974; Gordon, 1974; Ruane *et al.*, 1977; Wimberly, 1990) and the stoichiometry of nitrification cited by Wheaton (1977), biomass production due to nitrification is negligible at 0.3% to 0.9% of the feeding rate. The biomass production due to dissolved  $BOD_5$  consumption, on the other hand, is more significant. For example, if the soluble  $BOD_5$  excretion is 0.05 kg  $BOD_5$ /kg feed, as reported by Wimberly (1990), biofloc production will be about 6% of the feed rate.

$H_S$  can be related to the solids retention time (SRT) by:

$$\text{SRT} = 1/H_S \quad (3)$$

The solids harvest rate for a given bead filter can be determined by washing the filter repeatedly and estimating the harvest fraction. By this method, SRT can be estimated for a variety of backwashing sequences. With a backwash frequency of once per day, propeller-washed bead filters with a harvest fraction of 0.57 display a  $H_S$  of 0.57 and a SRT of about 1.75 d.

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

$$S_p = H_S \times M_S \quad (4)$$

The concentration of the sludge stream ( $S_C$ , kg/m<sup>3</sup>) is determined by the efficiency of the sludge separation process and the amount of flushing or wash down water ( $Q_S$ , m<sup>3</sup>/day) required for the sludge removal.

$$S_C = S_p / Q_S \quad (5)$$

Calibration of Equations 1 through 5 against a computer model resulted in  $k_S = 0.065 \text{ d}^{-1}$  for a SRT of 3 days. Because aquaculture sludge is partially digested in the filter,  $k_S$  values for sludge with a high SRT are usually lower than those observed for municipal waste ( $0.48 \text{ SRT}^{-0.415}$ , Rich 1982).

Equations 1 through 5 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 recirculating aquacultural systems for catfish or trout generate sludge volumes comparable to other commercially raised animals on a live weight basis.

Animal	BOD (kg)	TSS (kg)	TKN (kg)	Sludge Vol. (kg)	Reference
Fish	1.13	3.90-6.30	0.20-2.32	65-630	Chen (1993)
Beef Cattle	1.60	9.50	0.32	30	Middlebrooks, <i>et al.</i> 1982; Overcash <i>et al.</i> 1983a
Dairy Cows	1.40	7.90	0.51	51	“
Poultry	3.40	14.00	0.74	37.00	“
Swine	3.10	8.9	0.51	76.00	“

**Table 2.** A comparison of the waste generation rates of various commercial animals.

## DISCUSSION

Direct discharge of untreated aquacultural solids to receiving streams, e.g. in flow-through systems, can cause a variety of problems including oxygen depletion, nutrient enrichment, loss of water clarity, and destruction of benthic communities by the formation of sludge deposits. However, in recirculating systems, water discharge rates are negligible, e.g. 5-10% per day, and effluent streams can be clarified, separating and concentrating settleable solids prior to discharge. Although the sludge itself must be disposed of through land application or landfilling, the material has been partially oxidized by biofilter bacteria. The two issues most important to successful aquacultural solids management are (1) understanding the impact that primary in-filter solids stabilization has on other critical system functions and (2) selecting the most appropriate post-discharge treatment option.

As can be seen in equation 4, the mass of sludge produced from a recirculating system ( $S_p$ ) is the product of the solids content of the system ( $M_s$ ) and the sludge harvest rate ( $H_s$ ). However,  $H_s$  and SRT are inversely related through equation 3. Decreasing  $H_s$  tends to decrease sludge production as the amount of solids decay increases with SRT, but solids ammonification and mass-transfer constraints also increase with SRT, causing apparent nitrification to decline. Chen *et al.* (1993) applied equations 1 through 3 to a model of a hypothetical finfish system of a 1000 kilogram capacity. Utilizing constant values for  $E_s=0.4$ ,  $E_B=0.05$ ,  $Y_H=0.4$ , and  $k_s=0.36$ , a reduction of about 50% in discharged sludge mass was achievable by manipulating the bead filter backwash frequency. However, the corresponding increase in sludge mass held in the system ultimately increases aeration and degasification burdens on the recirculating system and causes the apparent nitrification rate to decline. This phenomenon constrains efforts to manipulate SRT for purposes of sludge volume reduction. Naturally, the SRT-nitrification relationship will define the optimum sludge reduction, and the backwash frequency should be manipulated to optimize nitrification.

Sludge management policies should focus on increasing  $S_c$  (Equation 5), since the concentration of solids varies dramatically with the type and management of the solids control device employed in the recirculating loop (table 3).

Source	Sludge TSS Concentration	Reference
Upflow Sand Filter	0.005-0.015%	Malone & Burden 1988
Sand Filtration	0.01-0.02%	Metcalf & Eddy 1979
EGB	0.05-0.5%	Chen <i>et al.</i> 1993
Primary Sedimentation	1-6%	Kugleman & Van Gorder 1991; Chen <i>et al.</i> 1993

**Table 3.** A comparison of sludge TSS concentrations from several sources.

Additionally, the sizing criteria and cost of the stabilization and disposal options depend upon the volume of sludge produced. If the solids capture device in the production system is not capable of concentrating the solids, then an external clarifier should be used to achieve the desired sludge density. Consideration should be given to partitioning sludge stabilization between internal and post-discharge treatment processes. Integrated design allows for overall minimization of treatment costs, reduction of the potential for adverse environmental impact, and enhanced RAS efficiency.

Bead filters are designed with internal settling cones, to facilitate single stage sludge concentration (figure 1). Additionally, the sludge retention time can be controlled by the frequency, duration, and vigor of the backwash. Higher sludge retention times (2-5 days) tend to encourage the biodegradation of solids concomitant with enhanced nitrification rates and decreased water losses. Increasing settling times following the backwash sequence is another means of significantly increasing sludge density. These factors are important in the context of their linkage with an external sludge treatment processes.

High nitrogen contents (4-6%), phosphorus levels of about 2% and the absence of contaminants, such as heavy metals, make aquacultural sludge attractive as a fertilizer (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 sludge may be required to avoid odor and runoff problems. Table 4 lists some of the more common methods for digesting sludge, along with some of their important advantages and disadvantages.

Method	Advantages	Disadvantages
<b>Anaerobic Lagoon</b>	High organic loading capacity Low maintenance	Odor
<b>Aerated lagoon</b>	High organic loading capacity Low area requirement	Large energy consumption Moderate maintenance
<b>Composting</b>	Useful end product	Dewatering required Moderate capital expense
<b>Anaerobic Digester</b>	High organic loading capacity Methane generation	Complicated management High maintenance

**Table 3.** A comparison of sludge stabilization options.

Although anaerobic lagoons are inexpensive and easy to operate, they are seldom suited for any but the most remote locations because of their nefarious odor. Aerated lagoons have an organic loading capacity similar to anaerobic lagoons with no offensive odor, but aeration equipment is initially expensive with continuing operations and maintenance costs. Composting yields soil conditioner, which is a commercially valuable end product. However, composting requires mechanical dewatering prior to stacking in static piles or windrows, and static piles must be aerated while windrows require periodic mixing. Anaerobic digestors are very popular for stabilizing sludge from municipal waste treatment plants, but they are expensive and their management requires specialized knowledge of their microbiology.

## SUMMARY

Recirculating aquaculture systems provide better quality control and can mitigate the negative environmental impact caused by the continuous discharge of organic solids from large-scale aquaculture production systems. An integrated approach to solids treatment permits the synergy between processes to reduce costs. Manipulation of bead filter backwashing characteristics can result in a substantial reduction in sludge mass discharged through biodegradation, without adversely affecting nitrification. Dilute sludge produced by backwashing or wash down operations can be concentrated by internal settling or by external clarification processes prior to stabilization and disposal. 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. As a final disposal option, land application appears most feasible for rural areas, whereas landfilling may be most appropriate for urban areas.

In this paper, we have focused on solids discharge, because it presents the greatest threat of environmental degradation, particularly oxygen depletion and destruction of crucial benthic communities. However, the discharge of nutrients, i.e. nitrate and phosphorous, can cause eutrophication of the receiving water. The major problem associated with nutrient enrichment is an algal bloom, providing the basis for an oxygen crash when water quality or environmental conditions change. Nitrate removal can be accomplished by denitrification within or external to the RAS. If denitrification is provided within the RAS, some of the alkalinity lost in the nitrification process will be replenished. Because phosphorous removal methods are expensive, the reformulation of aquatic feeds to increase metabolically available phosphorous is the most promising means of reducing the phosphate discharge.

## REFERENCES

- Burden, D.G., 1988. Development and Design of a Fluidized Bed/Upflow Sand Filter Configuration for use in Recirculating Aquacultural System, Ph.D. dissertation, Louisiana State University, Baton Rouge, Louisiana, 140pp.
- Cange, K. M., 1987 Waste Characterization Methodologies and Results. Personal Communication. Louisiana State University. Cited by D. M. Wimberly (1990): p. 40, Tbl. 4A.
- Chen, S. D. E. Coffin, & R. F. Malone, 1993. Production, Characteristics, and Modeling of Aquacultural Sludge from a Recirculating Aquaculture System Using a Granular Media Biofilter. *Techniques for Modern Aquaculture*: 16-25. American Society of Agricultural Engineers, St. Joseph Michigan.
- Colt, J.E. and D.A. Armstrong, 1981. Nitrogen Toxicity to Crustaceans, Fish and Mollusks, *Proceeding of the Bio-Engineering Symposium for Fish Culture* 1:34-47.
- Cooley, P.E., 1979. Nitrification of Fish-Hatchery Reuse Water Utilizing Low-Density Polyethylene Beads as a Fixed-Film Media Type, M.S. Thesis, University of Idaho, Moscow, Idaho.
- Gordon, J.A., 1974. Water Characterization Studies for High-Density Raceway Production of Catfish - The Galatin Project, *Proceedings of the 29th Purdue Industrial Waste Conference*, Lewis Publishers, Chelsea, Michigan.
- Hopkins, T.A. and W.E. Mancini, 1989. Feed Conversion, Waste and Sustainable Aquaculture, the Fate of the Feed, *Aquaculture Magazine*, 15(2):30, 32-36.
- Kugelman, I.J. and S. Van Gorder, 1991. Water and Energy Recycling in Closed Aquacultural Systems, *Engineering Aspects of Intensive Aquaculture*, pp. 80-87, *In* *Proceedings from the Aquaculture Symposium*, Cornell University, Ithaca, New York, April 4-6, 1991. Northeast Regional Agricultural Engineering Service, NRAES-49.
- Liao, P.B. and R.D. Mayo, 1974. Intensified Fish Culture Combining Water Reconditioning with Pollution Abatement, *Aquaculture*, 3:61-85.
- Libey, G.S., 1991. Maximizing Nitrification with Rotating Biological Contractors, Paper presented at the Workshop on Design of High Density Recirculating Aquacultural Systems, Louisiana State University, Baton Rouge, Louisiana, September 25-27, 1991.
- Malone, R. F. & M. Guarisco, 1988. Waste Characterization Study for the Kemp's Ridley Sea Turtle. NOAA Technical Memorandum NMFS-SEFC-200. Cited by D. M. Wimberly (1990) p. 39, Tbl. 3A.
- Malone, R.F. and D.G. Burden, 1988. Design of Recirculating Soft Crawfish Shedding Systems, Louisiana Sea Grant College Program, Louisiana State University, Baton Rouge, Louisiana.
- Malone, R.F., 1982. Floating Media Biofilter, U.S. Patent No. 5,126,042, June 30th.
- Metcalf and Eddy, Inc., 1979. *Wastewater Engineering: Treatment, Disposal, Reuse*, 2nd Edition, McGraw Hill, New York, 922pp.
- Middlebrooks, E.J., C.H. Middlebrooks, J.H. Reynolds, G.Z. Watters, S.C. Reed and D.B. George, 1982. *Wastewater Stabilization Lagoon Design, Performance and Upgrading*, Macmillan Publishing Co., Inc., New York, 356pp.
- Mudrak, V.A., 1981. Guidelines for Economical Commercial Fish Hatchery Wastewater Treatment Systems, Allen, J.L. and C. Kinney (editors, *Bio-engineering Symposium for Fish Culture*, American Fisheries Society.

- Murphy, J.P. and R.I. Lipper, 1970. BOD Production of Channel Catfish, *The Progressive Fish-Culturist*, 32:195-198.
- Ning, Z. (1995) Louisiana State University. Personal Communication, 19 July 1995.
- Olson, G.L., 1991. The Use of Trout Manure as a Fertilizer for Idaho Crops, Paper presented at National Livestock, Poultry and Aquaculture Waste Management Workshop, July 29-31, 1991, Kansas City, Missouri.
- Overcash, M.R., F.J. Humenik and J. R. Miner, 1983a. *Livestock Waste Management, Volume I*, CRC Press, Inc., 255pp.
- Page, J.W. and J. W. Andrews, 1974. Chemical Composition of Effluents from High Density Culture of Channel Catfish, *Water, Air, and Soil Pollution*, 3:365.
- Reynolds, T.D., 1982. *Unit Operations and Processes in Environmental Engineering*, Brooks/Cole Engineering Division, Monterey, California, 576pp.
- Rich, L. G., 1982. A Cost Effective System for the Aerobic Stabilization and Disposal of Waste Activated Sludge Solids. *Wat. Res.*, 16:535-542.
- Ruane, R.J., T.Y.J. Chu and V.E. Vandergriff, 1977. Characterization and Treatment of Waste Discharged from High-Density Catfish Cultures, *Water Research*, 11:789-800.
- Speece, R.E., 1973. Trout Metabolism Characteristics and the Rational Design of Nitrification Facilities for Water Reuse in Hatcheries, *Transactions of American Fisheries Society*, 102(2):323-334.
- Thomasson, Mark P., 1991. Nitrification in Fluidized Bed Sand Filters for Use in Recirculating Aquaculture Systems, Master's Thesis, Louisiana State University, Baton Rouge, Louisiana.
- Van Gorder, S., 1991. Optimizing Production by Continuous Loading of Recirculating Systems, Presented paper at the Workshop on of High Density Recirculating Aquaculture Systems, September 25-27, 1991, Louisiana State University, Baton Rouge, Louisiana.
- Wang, L. (1995) Louisiana State University. Personal Communication, 10 May 1995.
- Wheaton, F.W., 1977. *Aquacultural Engineering*, Wiley-Interscience, 708pp.
- Willett, L.R. and Jakobsen, P., 1986. Fertilizing Properties of Trout Farm Waste, *Agricultural Wastes*, 17:7-13.
- Wimberly, D.M., 1990. Development and Evaluation of a Low-Density Media Biofiltration Unit for Use in Recirculating Fish Culture Systems, Masters Thesis, Louisiana State University, Baton Rouge, Louisiana.