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Low-Cost Biofiltration Systems

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Water for agricultural uses including aquaculture is a limited resource in most places. In Hawaii as in other island locations, water conservation and optimal use of the available resource will be increasingly important as population grows and businesses develop (Leone 2003, New Internationalist 2003).

Biofiltration systems reduce consumptive water use and waste discharge in aquaculture systems, often dramatically, but business operators may lack the capital or otherwise hesitate to make the initial investment. Commercial systems can appear and sometimes be complex. Low cost systems serve to demonstrate principles, structure, and function. They provide encouragement to observers that a system can be operated conveniently and that investment will be recovered within a reasonable time.

This bulletin describes the approaches and demonstration systems developed for aquaculture extension efforts in Hawaii during recent years. The primary purpose of these demonstrations is to show possibilities that are immediately applicable for existing businesses or for readily-envisioned developments among our clientele. No attempt has been made to review this large field of endeavor nor to make a comprehensive test of possible approaches. We welcome information from readers of this bulletin to improve this document for future editions.

Water Use and Conservation Potential

Recirculating biofiltration technology does not aim to completely eliminate addition of new water or discharge of used water during a crop production cycle. The primary purpose is to keep concentrations of total ammonia nitrogen (TAN) low with minimal cost for water replacement. During a recent workshop session in Hawaii, Tom Losordo of North Carolina State University defined "closed" recirculating systems as those in which up to 20% of the water volume is exchanged for new water each day, with 5 to 10% being typical. These percentages are minimal and necessary in systems that remove settleable or filterable solids, in addition to processing ammonia.

Non-recirculating culture systems use various amounts of new water during production, depending on stocking density and the degree of ammonia processing and other support by natural or artificial processes. Fishes and shrimps can be grown in earthen

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ponds without discharge of used water during the entire crop production cycle under some conditions. However, replacement of evaporation losses may require addition of water at a rate of 1 to 3 percent or more of the pond volume per day. In non-recirculating (flow-through) tank systems, considerable water exchange is required to dilute the ammonia produced by the fish at most commercially useful stocking densities. For example, we took a biofilter off-line for a few days' modification during one of our recent trials in Hilo, in which we were maintaining a tilapia stock at 5-6 kg/m^3 in a 2.4 m diameter tank in the greenhouse. The biofilter had been maintaining ammonia concentrations below 0.3 ppm, with water exchange of only about 10% per week. Without the biofilter, a flow rate of about 7 liters per minute of new water (more than 200% per day volume exchange) was necessary to prevent ammonia concentrations from increasing, even at this commercially modest stocking density. Considering only the need for ammonia removal, the biofilter was saving more than 9 m^3 of water per day. At recent public water rates in Hawaii County, this amounts to a cost of $4.23 per day or about $127 per month, which would amount to a significant fraction of the production costs and market value of the crop.

Demonstration Systems in Hawaii

Seven different recirculating biofiltration systems are described here (Table 1). The performance of 5 of these was assessed during support of working culture systems. The designs are mostly adaptations of well-known strategies, made by the authors of this document. In one case, a creative adaptation of a commercial system was given to us by colleagues as noted in the Acknowledgments. These are "small-scale" systems, meaning in this case that the filter container volumes ranged from 20-125 liters (e.g., 5 gallon buckets, 33 gallon plastic trash cans). The supported culture volumes ranged from 0.6 to 8 m^3. The systems are labeled in Table 1 as "Outdoor" and "Indoor," indicating our particular test conditions; the designs are adaptable to many settings.

Quantitative assessments are reported here to lend credence to the workability of these approaches, but the results should not be taken as definitive or limiting. All of the systems can readily be improved upon and adapted to new uses, including use of multiple filter units or much larger containers to support larger culture units.

Outdoor Green Water Biofilters

Systems A, B, and C were developed at the University of Hawaii's freshwater aquaculture research facility at Windward Community College on the island Oahu. They were aimed at facilitating increased production capacity (stocking density) and water conservation on freshwater ornamental fish farms (Asano et al. 2003). All were made in 20 liter white plastic buckets and deployed on the edge or submerged in cylindrical plastic tanks of water volume 2080 liters (Figure 1). Each bucket contained 0.028 m^3 (1 ft^3) of pvc ribbon (Bio-Fill, Aquatic Ecosystems, *www.aquaticeco.com*) for bacterial substrate. System A (trickling filter) had water pumped to the open top of the bucket, through homemade spray bars, from where it trickled to the bottom and returned to the culture tank through a short pipe. Water was lifted from the culture tank by a 15 W electric pump set to deliver 9 liters per minute, which amounted to about 6 culture tank volumes per day. System B (submerged filter, similar to the box filters familiar to aquarium hobbyists) was driven by air lift of tank water out of the center of the submerged bucket, which had small holes drilled in its sides to admit tank water. Water flow was 3 liters per minute, about 2 tank volumes per day. Air was provided by the facility's blower system. System C was similar to system A, but was driven by air lift.

A demonstration system on Maui Island (System G) is based on a trickling filter in a bucket like System A, but is undergoing continuing development of added functions by Aecio D'Silva of the University of Arizona. Water passes from the culture tank to a settling basin (55 gallon drum) to remove solids. Water goes from there to the biofilter and then through a hydroponic vegetable production system. One of the innovative developments was to remove solids to an

Table 1. Seven recirculating biofiltration systems demonstrated in Hawaii. Approximate materials costs reflect prices in Hawaii during the late 1990's – early 2000's. Costs of air pumps for air lifts are not included; research facility air systems were used in these cases.

System	Filter Container	Culture System	Biofilter Materials Cost
A. Outdoor Green Water Trickling Filter (pump driven)	plastic bucket 20 liters (5 gal)	cylindrical plastic tank 2080 liters	$ 60*
B. Outdoor Green Water Submerged Filter (air lift driven)	plastic bucket 20 liters	cylindrical plastic tank 2080 liters	$ 45**
C. Outdoor Green Water Trickling Filter (air lift driven)	plastic bucket 20 liters	cylindrical plastic tank 2080 liters	$ 45**
D. Indoor Trash Can Up-flow Filter (air lift driven)	plastic trash can 125 liters (33 gal)	cylindrical plastic tank 4700-8000 liters	$ 110**
E. Indoor Shelf System Up-flow Filter (pump driven)	plastic water bottle 20 liters	75 liter (20 gal) glass aquaria x 8: 600 liters	$ 150*
F. Indoor Fluidized Bed Sand Filter (pump driven)	12" dia. pvc pipe 60 liters	cylindrical plastic tank 4700 liters	$ 300***
G. Outdoor Green Water Trickling Filter (pump driven)	plastic bucket 20 liters	cylindrical plastic tank 2500 liters	$ 50*

* Includes small (15-25 W AC) submersible water pump.
** Does not include an air pump to drive air lift.
*** Includes 186W (0.25 hp) AC electric water pump.

Figure 1. Outdoor green water biofilters at Windward Community College. Top: trickling filter mounted on tank rim. Bottom: submerged filter in tank. Photos by K. McGovern-Hopkins.

anaerobic digestion container to produce an additional by-product, methane. The biofilter used non-biodegradable packaging "peanuts" as a substrate which substantially reduced costs. Although quantitative test results are not available, this inexpensive biofiltration unit performed comparably to biofilters using much more expensive substrates such as bio balls.

The performance of systems A and B was assessed in a controlled experiment in which 9 tanks were stocked with juvenile koi (ornamental carps) at an initial density of 1 kg/m^3, with fish added later to attain 3 kg/m^3, which finally grew to 4.6 kg/m^3. Three tanks each were allocated to 3 treatments: support by systems A and B, and a set of unsupported controls. Details are presented by Asano et al. (2003). Initial fertilization of the tanks and the waste produced by the initial stocks of fish fostered dense green water blooms, which kept the concentrations of total ammonia, nitrite, and nitrate at nearly undetectable levels through 16 days. It was presumed that the filters were conditioned by that time. Upon tripling of the fish biomass on day 17, concentrations of nitrogen rose in all tanks. The biofilters in general held the nitrogen concentrations at lower levels than were seen in the control tanks, but required some time to become conditioned to the new biomass and N-loading. Between days 17-75, all biofilter systems reduced total ammonia to 2 mg/l or less, and nitrite to low levels. The controls were taken down on day 76, when ammonia had reached high levels and some fish died. One of three submerged filter systems had a partial mortality event. The trickling filters marginally outperformed the submerged filters, with better ammonia removal and some advantage in oxygen concentrations. New water was added only to make up evaporation until day 76, after which water was exchanged at about 30% per week. The value of these results for the farming of freshwater ornamental fish in Hawaii is that the supported densities are much higher than those typical of local farming practices, and this was done with minimal water exchange.

Indoor Biofilters

Systems D, E, and F were developed and tested on Hawaii Island in the aquaculture laboratory greenhouse at the research and teaching farm of the University of Hawaii at Hilo College of Agriculture, Forestry, and Natural Resource Management. The primary purpose was to provide demonstrations of workable systems that are applicable to a variety of products and farm situations. Quantitative assessments of performance were made, but no formal experiments were performed.

The up-flow biofilter contained in a plastic trash can (system D), is an adaptation of a traditional design described by Szyper (1989; Figure 2 here), with the current ver-

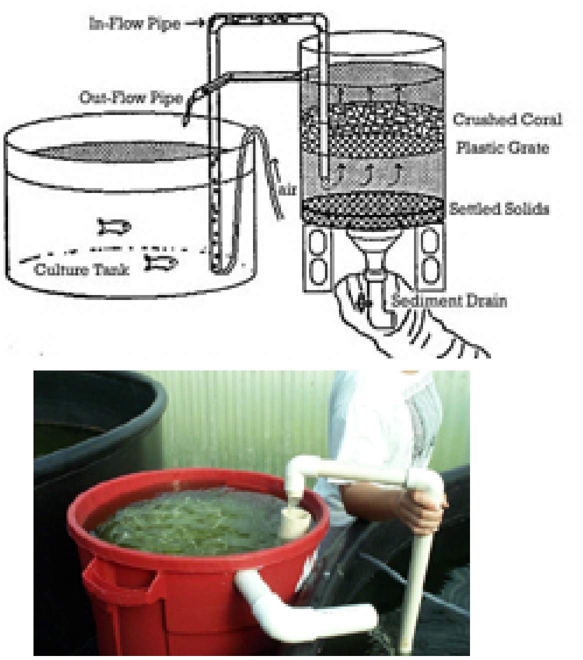

Figure 2. Trash can biofilter. Top: diagram from Backyard Aquaculture in Hawaii. Bottom: working biofilter at UH Hilo farm. Photo by J. Szyper.

sion shown in detailed photographs at *www.uhh.hawaii.edu/~pacrc/bigisaquapg/* (Select Education and Training from the home page). Tank water is air-lifted in a 4 cm (1.5 in) pvc pipe into the filter body alongside the tank. A larger open tube delivers the water to the bottom dead space where solids can collect for manual drainage through a bottom valve. Water fills the can moving upward through a 5-10 cm thick layer of crushed coral for pH control and alkalinity addition, then through a layer consisting of 0.04 m^3 (1.5 ft^3) of the plastic ribbon used in systems A, B, and C. These layered materials are supported above the dead space by a plastic grate resting on pipe sections of 15-20 cm length. Water returns from the top of the filter to the culture tank by passive overflow. This system has supported cylindrical tanks of 4.5 to 8 m^3 volume containing tilapia stocks up to 5 kg/ m^3 for more than two years' nearly continuous operation. For maintenance of modest fish stocks, minimal water exchange and infrequent cleaning are sufficient, with total ammonia concentrations kept well below 1 ppm. The facility water's relatively low alkalinity (30-40 ppm) is maintained or slightly increased. This biofilter was able to replace and match the performance of the sand biofilter in a trial described below. Nitrogen processing is discussed quantitatively in a separate section below.

A smaller biofilter of similar design strategy (system E, Figure 3) was assembled in an inverted 20 liter plastic drinking water bottle. A valve was installed in the neck of the bottle for solids removal. A bottle with this feature was originally obtained commercially, but later filters were made in house. Used water is delivered by a 1.3 cm (1/2 in) pipe passing through a bulkhead fitting placed about 10 cm above the bottom of the filter. Water fills the system passing upward through a 5 cm thick layer of crushed coral and 0.01 m^3 (0.33 ft^3) of plastic ribbon supported on a plastic grate as in system D, exiting through a bulkhead fitting near the top into a 75 liter reservoir tank. From there, a 15 W electric pump delivers water to an overhead 5 cm (2 in) pipe running lengthwise over the aquarium shelf. Taps from this pipe deliver water by gravity to each of eight 75 liter (20 gallon 'high') glass aquaria. Used water leaves each aquarium near the bottom, through a bulkhead fitting to an outside standpipe, from which water falls into a lengthwise, down sloping 5 cm pipe that returns water to the filter by gravity. An important feature of

Figure 3. Aquarium shelf biofilter system. Left: close-up of filter vessel showing layers of Bio Fill and crushed coral. Right: system overview. Photo by J. Szyper.

the water pathway is the prevention of siphoning in case of pump failure: there is a lack of continuous pipe connection when 1) water enters the aquaria, and 2) used water enters the return pipe.

This shelf system was filled with fresh water and stocked with juvenile (2.5 - 5 cm length) pink convict cichlids, which were available on the facility from earlier work. Each aquarium was stocked initially with 3 small fish; when the filter took total ammonia concentrations to nearly undetectable levels after 10 days, fish were added every few days in an attempt to approach the processing capacity of the system. Fish additions after about 30 days caused brief ammonia spikes; earlier additions did not. An addition at about 40 days' operation caused a large ammonia spike, a reduction after a few days, followed by rising concentrations. At this point, fish stocking densities were about 2 kg/m^3, the aquaria appeared heavily stocked, the water had notable color and suspended particulate matter (though aquarium bottoms were siphoned manually daily), and the first two fish mortalities were found over two days. The trial was terminated at this point. This relatively small and inexpensive filtration system supported fish biomass densities reasonable for commercial production of ornamental fishes when aquarium systems are appropriate. In addition, these densities are higher than a commercial shop would display, and so the system could be used in that setting.

An identical system was installed on a nearby shelf, and filled with artificial seawater (Instant Ocean). After conditioning, the filter held total ammonia at genuinely undetectable levels with low to modest fish stocks, in contrast with the low but detectable levels at low fish densities in the freshwater system. This difference was consistent over a two year period. The seawater system kept clownfish pairs for nearly two years, and a variety of other marine fishes (e.g., reef grouper, white ulua (jack crevalle), Pacific threadfin, greater amberjack) for periods of days to months. In order to test a less expensive artificial seawater formula, the freshwater shelf was drained and refilled with the new seawater, called “Five Comp” for its five components (Table 2). Reef grouper and white ulua were stocked at low densities and kept for 16 days. The biofilter adapted to Five Comp, taking TAN levels below 1 ppm for the last 5 days.

Finally for Hawaii Island systems, a fluidized bed sand biofilter (System F, Figure 4) was built in an upright 1.2 m (4 ft) length of 30 cm diameter (12 in) pvc pipe, capped on one end, and having 44 kg (100 lb) of No. 20 graded sand as substrate for bacterial growth. The sand was kept in motion by injection of water to the bottom of the sand bed by a 186 W (0.25 hp) AC water pump through a 0.4 cm (1.5 in) pipe ending in a homemade spray head. The pump was installed in and near the top of a trash can that was set up similarly to System D above, but without plastic ribbon. This vessel served as pump reservoir, clarifier (discussed below), and water conditioner with its layer of crushed coral. Pumped water was directed to the bottom of the sand biofilter vessel, filled it, and overflowed into the fish tank (a 2.4 m diameter (8 ft) cylindrical plastic tank containing about 4.6 m^3 of water. Water completed its cycle by returning from the fish tank to the trash can by passive overflow through an exit port near the top of the tank wall. This system was stocked (with hybrid tilapia) and monitored similarly to the aquarium shelf system in the trial described above. The time course of TAN concentrations showed a qualitatively similar pattern of performance for the sand biofilter. After conditioning, the filter kept TAN at low levels until total fish biomass

Table 2. Ingredients for “Five Comp” artificial salt water. Weights of salts used to make 100 liters and 50 gallons of salt water are given.

Ingredient	Formula	Weight for 100 liters g	Weight for 50 gal oz
Sodium chloride (table salt)	$NaCl$	2500	167
Magnesium sulfate (Epsom salt)	$MgSO_4$	600	40
Potassium chloride	KCl	60	4.0
Calcium chloride	$CaCl_2$	120	8.0
Sodium bicarbonate (baking soda)	$NaHCO_3$	20	1.3
Total		3300	230

exceeded 50 kg (>10 kg/m^3). A major difference from the shelf system is that the sand biofilter adapted, presumably by an increase in bacterial population, to the last biomass addition and reduced total ammonia to low levels. At this point, the sand biofilter was taken off line, and a conditioned trash can biofilter (System D) was installed on the fish tank. This filter took the remaining total ammonia concentration of about 1 ppm to nearly undetectable over 1.5 days (including two daily feedings), at which time the trial was terminated.

Figure 4. Fluidized bed sand biofilter system including trash can clarifier / pump sump. Photo by J. Szyper.

System Performance: Solids, Oxygen, & pH

Recirculating biofiltration systems must deal with solid wastes produced in any culture system of substantial intensity. None of the demonstration systems described here was designed to remove solids efficiently; the primary consideration was to demonstrate low cost ammonia processing. The performance of the systems with ammonia is discussed in further detail below. Neither were the systems designed for optimal maintenance of dissolved oxygen concentrations. In general, modest levels of air bubble aeration and the aerating effect of air lifts was relied upon to support oxygen demand in the systems. Similarly, maintenance of pH is somewhat addressed by aeration, in that high concentrations of carbon dioxide are degassed by aeration at lower pH values, providing a partially effective negative feedback. That is, more carbon dioxide is removed when systems are producing higher amounts, and this works to increase pH. This factor was handled differently between the indoor and outdoor filter systems, the latter having some carbon dioxide taken up by the blooms. All of these factors can be improved with available low cost technology, and we have continued to expand and improve some of these systems.

The *Outdoor Green Water Biofilters* were manually cleaned of solids every two weeks during the latter, highest-stocking-density stage (day 76 onward) of their formal trials (Asano et al., 2003). This was sufficient to keep the systems working well. The culture tanks contained some settled solids, mainly clumped microalgae from the active blooms, which were not removed. The aeration was not intended to, and did not, keep all solids well mixed in the water. Settling of solids in a culture vessel is benign up to a point because they are readily removed by siphoning. In general, manual solids removal is an effective strategy in small scale systems. Automating the process is an important effort to save personnel costs for commercial settings. The green water blooms acted to increase dissolved oxygen and pH levels during the day, and to lower them at night, resulting in greater extremes than would be seen in clear water systems. Nonetheless, the systems maintained with few exceptions, dissolved oxygen above 4 ppm and pH above 6.0.

The *Indoor Biofilters* were different in each case. The trash can filter (System D), in its original deployment on the tilapia tank, became a green water system like the outdoor systems. Solids were occasionally emptied through the bottom valve, and other parts of the system were cleaned only infrequently, mainly by manual siphoning of solids from the bottom of the culture tank. Air stone aeration and the effect of air lift maintained the system for several years with great stability. Solids were manually siphoned from the aquarium systems (System E) daily during the stocking density trial. This was adequate to support the trial, but left enough solids suspended in the water (by fish activity and the single bubble stream from a pipette) to have the aquariums look dirty (with turbidity and larger particles) during later stages. Aeration maintained dissolved oxygen levels above 5 ppm in the reservoir at all times, and above 4 ppm in the aquaria until the last 2 weeks. The crushed coral layer in this system provided notable advantages. The pH never fell below 6.9, and only rarely below 7.0. Total alkalinity increased during the trial from about 40 to 80 ppm. The sand biofilter system (System F) was taken to higher fish stocking densities than any other system, greater than 10 kg/m^3. Dissolved oxygen levels declined steadily during the trial, but did not fall below 4 ppm. The crushed coral layer effectively maintained total alkalinity, increasing it from an initial 30 ppm to 50 ppm. The aeration effectively mixed suspended solids throughout the water, which means that solids were being sent to the clarifier quantitatively. Very little settled on the culture tank bottom; the fish being somewhat underfed may have contributed to this condition. Solids were removed nearly daily from the bottom port of the clarifier trash can. However, the clarifier design permitted too much of suspended solids to reach the water pump, which had to be manually cleaned during much of the trial.

System Performance: Ammonia Processing

The amount of ammonia processing to be expected from various filter media materials under different conditions is the subject of voluminous literature, which is not reviewed here. Rather, the systems are assessed in terms of the summary of expected processing capacities graciously provided by Kevin Hopkins of the University of Hawaii at Hilo (personal communication), which was compiled from original literature and from estimates tabulated by a commercial supplier. Assessments provided here apply generally to warm water situations, but are not adjusted for different temperatures, which were well within the range 20 - 30 ^{o}C on Hawaii Island and similar on Oahu, with possibly greater extremes outdoors there.

Because ammonia processing bacteria occupy thin layers on the surface of filter media, it is reasonable to consider the rate of total ammonia nitrogen (TAN) processed per unit of surface area, when the area can be determined. The summary of capacities shows some variation, but the most common estimate, 0.807 g TAN / m^2 / day, is sufficient for this discussion. Commercial materials may be sold in volume quantities (cubic feet or meters), and catalogued or packaged with an indication of the surface area provided by each unit of volume, that is, the effective surface area as m^2/m^3.

Because production of TAN in a culture system depends mainly on the rate of input of nitrogen in the protein fraction of the feed, the loading of a biofiltration system is most directly expressed as g TAN/day for the system. This input rate might derive from a variety of combinations of biomass, feeding rate, and protein content of feed. Other important estimates of culture system capacity (e.g., fish stocking density in terms of numbers or biomass) are best interpreted as consequences of the loading rate that can be processed by the filter. For present purposes, we will use a conservative estimate that about one third of the nitrogen content of the feed eaten by fish will appear as TAN, a soluble excretion product, the remainder being eliminated as solid waste or incorporated into biomass.

The *Outdoor Green Water Biofilters* were packed with 0.028 m^3 (1 ft^3) of plastic ribbon (Bio Fill) as noted above. This amount of the material (1 package at about $37 before shipping) has an effective surface rating of 820 m^2/m^3, and thus an expected ammonia processing capacity of 820 x 0.807 x 0.028 = 18.5 g TAN/day (Table 3), which Asano et al. (2003) noted was more than sufficient for the loading rates used in the trials. The maximum feeding rate was 125 g/day of feed with 45% protein content. Nitrogen content is usually estimated as 1/6.5 = 0.154 of the weight of protein. TAN loading rate can thus be estimated as 125 x 0.45 x 0.154 x 0.333 = 2.9 g TAN/day. This suggests that the biofilters could have handled six times the actual loading rate, which came from a final fish biomass density of 4.6 kg/ m^3. If biomass density were increased substantially under these conditions, it is likely, as we have seen elsewhere, that factors such as solids, dissolved oxygen, and pH would become problematic before TAN loading. Table 3 compares the demonstration systems discussed here in terms of estimated TAN processing capacity and loading rates during trials. These calculations neglect the ammonia processing that takes place on the underwater interior surfaces of the culture tanks and biofilter containers. In the case of

Table 3. Performance summary for demonstration biofiltration systems. Capacity estimates use a standard rate of 0.807 g TAN / m^2 / day; observed rates presume 1/3 of nitrogen in feed appears as TAN.

System	Total Water Volume	Filtration Medium			TAN Processing Rate	
	m^3	name	volume m^3	area m^2	g /day capacity	g /day observed
A. Green Water Trickling Filter	2.1	Bio Fill	0.03	23.0	18.5	2.9
B. Green Water Submerged Filter	2.1	Bio Fill	0.03	23.0	18.5	2.9
D. Trash Can	4.7	Bio Fill	0.04	32.8	26.5	15+ *
E. Shelf System	0.75	Bio Fill	0.01	8.2	6.6	0.9
F. Fluidized Bed Sand Biofilter	4.8	#20 sand	0.03	n/a	50	15+

* When trash can replaced sand biofilter at end of trial.

System D, the tank walls add about 7.5 m^2 and the trash can about 1.5 m^2 of substrate for bacterial habitation, a total addition of about 27% to the surface area of the filtration media (Table 3). This capacity may be considered from the first in system design, or left as an engineering buffer. Note that the walls' contribution was already operating during the large water consumption example discussed above.

The only quantitative test of the trash can filter was its replacement of the sand biofilter at the end of the latter's formal trial. Because the trash can was the only source of TAN processing support for 1.5 days including 2 feedings, and because TAN levels dropped to near zero during this period, it must have processed the TAN input. The capacity estimate for the sand biofilter is based on the guideline provided by Carlos Martinez of the University of Florida, that 100 lbs of sand can support 100 lbs of fish fed typical feeds at 5% body weight per day. The 52 kg (114 lb) of fish in our trial were taking only about 2% per day near the end. We have found no estimate for the effective surface area of the sand. The design of the sand biofilter system specified silica sand; only size-graded common sand was readily available on Hawaii Island. Some of the carbonate components of the sand dissolved during the trial, about 14 of 120 lb. The pumped water was effective in keeping the sand in motion; optimal system performance requires a particular volume increase upon fluidization, ideally to 150-200% of still volume, to permit optimal colonization of sand grains by bacteria. We generally had less volume than this, but still attained sufficient TAN processing to support the trial.

Adoption of Systems by Farmers

These designs and strategies are reasonably well known, particularly the bucket and trash can ideas. A locally-built turnkey backyard culture system with biofiltration was available on Maui during the 1970's and 1980's. Commercial uses of informal low cost systems in Hawaii began well before our demonstrations. Since we began these demonstrations and described them in print and in public presentations, more Hawaii aquaculture businesses have adopted recirculating biofiltration technology, some with commercially-purchased systems, some with homemade systems including these approaches, and some with combinations of the two. We appreciate the collaboration we have had with many of these businesses, and the opportunities to learn from and assist them.

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