

Bulletin 9A
Basic Principles of Biofiltration and System Design

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Introduction

This bulletin is intended to describe the basic principles of biofiltration as they apply to aquaculture, and to discuss some generalized biofilter designs. In addition, examples are given which show some of the uses for biofilters in aquaculture. Throughout this bulletin, the term recirculating system is synonymous with biofilter system, but not water reuse systems which do not necessarily use biofilters.

There is not enough information in this publication to enable a novice to design and construct a money-making biofilter system. However, sufficient information is given so that the reader will be able to talk to knowledgeable individuals about biofilter systems, and to question dealers about the efficiency of commercially manufactured systems. The published literature and our experience have demonstrated that, biologically, aquatic organisms can be successfully reared in water reuse systems. However, independent evaluations of commercially available systems are not available in the literature. Therefore, the economics of rearing aquatic organisms in these systems has not been demonstrated.

Interest in the use of water recirculation for aquaculture began in the early 1960's, when demand for fingerling salmon began to exceed the amount of flowing water available to rear them. At that time, it was also recognized that fish hatcheries were the source of considerable organic pollution in streams and rivers in the northwestern U.S. Therefore, the federal government initiated studies to determine the feasibility of utilizing wastewater treatment technology in fish culture (Burrows and Combs 1968; Liao and Mayo 1972). The concept of water recirculation is basically a modification of wastewater treatment utilizing particulate removal (primary treatment) and nitrification (tertiary treatment). Nitrification is the process by which ammonia, which is toxic to fish at low concentrations, is converted to nitrate, which is relatively non-toxic. The nitrification process will be discussed later.

Advantages of Recirculating systems

There are five major advantages in using recirculating aquaculture systems: low water requirements, low land requirements, the ability to control water temperature, the ability to control water quality, and independence from adverse weather conditions.

Low water Requirements

A properly designed and operated recirculating system requires a minimum daily input of water, just enough to clean particulate waste filters and to replace water lost to evaporation. This permits construction of aquaculture facilities in areas where ground water is limited, and even opens the possibility of an operation being located in an urban area and utilizing de-chlorinated municipal water. The production facility can thus be located close to the market. For example, a recirculating system which produces the same number of pounds of fish as 1000 acres of ponds (about 4.8 million pounds of fish) would require about 4000 gallons of fresh water each day or 1.5 million gallons per year. However, to fill 1000 acres of ponds averaging 5 feet in depth would require 1,6 billion gallons of water,

Low Land Requirements

Since fish in a recirculating system are reared in tanks, with oxygen mechanically supplied and metabolic wastes (ammonia) removed by flowing water, they can be held at extremely high densities. Currently the goal which designers of systems are striving to attain is 1 pound of fish per gallon of water. However, many people consider 0.5 to 0.75 pounds of fish per gallon of water acceptable. In pond aquaculture, the common maximum density is about 0.003 pounds of fish per gallon of water. Therefore, a recirculating system can be located in areas where large amounts of level land are not available. The low land requirement also permits the facility to be located in areas where the soil cannot hold water or, again, in urban areas,

Control of Water Temperature

The low water requirement of recirculating systems opens up the possibility of economically controlling temperature which is one of the greatest benefits of these systems. Control of water temperature allows the aquaculturist to produce species which could not normally be raised in a given geographic area. It also permits the water temperature to be maintained at the optimum level to maximize food conversion and provide optimum growth. Growth can also occur throughout the year, maximizing production and allowing rapid turnover of the product. In theory, marketing of the product is also enhanced, since fish can be supplied each week.

Independence from Weather

By rearing the fish indoors, the culturist is no longer limited by weather conditions. A sudden cold spell can wipe out a year's production by killing the larval fish or disrupting

the normal spawning of the broodfish. In addition,, pond culturists can loose their crop to low oxygen during the summer or winter. Having the fish indoors also permits harvest at times when heavy rain, snow or ice would stop the harvest of pond fish, This is a definite market advantage.

Control of Water Quality

With recirculating systems, the aquaculturist has the opportunity to control water quality, both to the benefit of the fish and to the final product, By maintaining dissolved oxygen at optimum levels, the fish have better food conversion and are less stressed, thus leading to greater disease resistance, In addition, the fish are isolated from potential environmental contaminants such as off-flavor caused by some algal growth and from any potential soil pollution resulting from run-off or residual pesticides. This results in a high quality product,

Some Potential Uses of Biofilter Systems

Because of the advantages fish culture systems incorporating biofiltration have over pond culture, they can be utilized for special applications in addition to intensive food-fish production. Among these are: 1) overwintering warmwater fish or shellfish, 2) training fingerling fish to accept commercial feeds, 3) rearing delicate larvae, 4) combining fish culture with hydroponic vegetable production 5) producing specialty products, and 6) holding aquatic organisms for sale,

In temperate regions such as Illinois, certain species of fish and shellfish can grow adequately during the summer, but suffer thermal stress and die during the winter, Included in this group are threadfin shad (*Dorosoma petenense*), tilapia,,and the freshwater prawn (*Macrobrachium*), Threadfin shad, although not a food-fish, has high market potential for sale to pond and lake owners as a source of forage for predatory sport fish (Heidinger et al, 1983), Large numbers of fingerling fish can be held in heated recirculating systems during the winter and then transferred to grow-out ponds when the pond temperature is adequate (or sold directly,, in the case of threadfin shad). Because small individuals are involved and rapid growth is not critical, a relatively small system can be used for this application. It should be noted here that tilapia and freshwater prawns are not on the Illinois approved species list, Therefore, the Illinois Department of Conservation reviews permit requests for these species rigorously to prevent adverse effects to native fauna and flora by escaping organisms.

Certain species of fish such as largemouth bass, walleye, and striped bass do not readily accept commercial feeds. Fingerlings of these species must be concentrated at high densities in tanks and subjected to a training process to get them to accept commercial feed. Greater success (both in percentage of fish trained and in speed of training) is achieved when optimal temperatures and dissolved oxygen concentrations are maintained. Therefore, a recirculating system becomes attractive as a training facility because of the ability to control temperature,

Fish culture systems which use recirculating, biofiltered water also have a definite advantage when rearing the delicate larvae of some fish species, such as walleye, striped bass and the hybrid striped bass, and the pikes. At hatching, larvae of these fish can be as small as 0.25 inches long and incapable of swimming. If stocked into ponds at this time, they can settle to the bottom and suffocate in the mud. They are also very vulnerable to predation from aquatic insects and to sudden cold spells. Therefore recirculating systems have been used to rear these fish.

One of the principal waste products found in biofiltered fish culture systems is nitrate. This byproduct could be utilized for the production of hydroponically grown vegetables. Several studies conducted at the SIUC Fisheries Research Laboratory (SIUC Fisheries and Illinois Aquaculture Center) (Lewis et al, 1978, 1981; Sutton and Lewis 1982) have given positive results, with the fruit grown in biofiltered water from the fish culture system ranking much higher than that grown only with chemical fertilizers. However, in such a system, the optimum conditions for rearing the fish must closely match those of the plants. A balanced system will produce much higher yields of fruit or vegetables than fish.

Because of the tight controls over temperature and water quality available with a recirculating fish culture system, they can be utilized to produce various specialty products such as soft shell crawfish and to rear larval freshwater prawns. Soft-shell crawfish production is occurring in biofiltered systems on a large scale. Pre-molt crawfish are harvested and placed in shallow trays in a system maintained at the optimum temperature, careful monitoring allows the growers to harvest the recently-molted crawfish from the trays at the ideal time.

The low water requirement of recirculating systems also allows producers to rear small quantities of animals in salt water far from the ocean. This makes the culture of freshwater prawns feasible, since the prawns only require salt water during the larval stage. Adult prawn females which are carrying eggs can be transferred to a recirculating salt water system. There, the eggs hatch and the larvae reared until they can tolerate fresh water. They can then be stocked into ponds or a standard fresh-water system. Because of the short time that salt water is required, and the small size of the prawn larvae, this system can be relatively small.

A third special use for recirculating fish culture systems is for the maintenance and off-season spawning of broodfish. The ability to control water temperature and photoperiod in these systems permits the producer to supply larvae and fingerling fish throughout the year.

Biofilter systems also have application for the continuous, but short-term holding of aquatic life. These systems are used by the wholesale and retail bait industry to hold minnows, crayfish, and other bait organisms at high density until they are sold. Biofilter systems are also the primary means of holding fish in the aquarium trade.

Basic Components of Biofilter Systems

There are numerous designs for aquaculture systems utilizing biofiltration, ranging from a simple tank-biofilter to high tech designs with computer control. However, all systems have certain basic components, These components may be separate pieces, or several may be integrated into a single unit. All systems need a water supply, tanks to rear the fish in, a method of removing particulate waste, the biofilter, a method to re-oxygenate the water and a method to move the water, In addition, there are numerous support facilities which must be considered, including; the building to house the facility, the heating or cooling system (heat the water or the room), food storage facilities, quarantine facilities, pre-market holding facilities, transport facilities, and back-up equipment. In a recirculating system, back-up equipment (pumps, air blowers, electric generator) can never be considered as optional,

Water Supply

Although water reuse with biofiltration greatly reduces the quantity of water needed for aquaculture, a certain amount of fresh water is required. The major use of water in recirculating systems is to backwash the particulate filters, Other uses are to replace evaporative loss and biofilter cleaning, When sufficient water is available, some aquaculturists "purge" their fish with cool, fresh water before market to improve flesh quality. Therefore, the amount of water required varies depending on individual need,

The ideal water supply would be one with no contaminants, either introduced or natural, Among the common natural contaminants are carbon dioxide, hydrogen sulfide, ammonia, iron, and salt. Moderately hard water with methyl-orange alkalinities above 200 mg/liter will assure adequate buffering for the acids produced in a biofilter. In small to moderate systems, it is feasible to use potable city water. The chlorine can be removed with charcoal filtration, or chemically with sodium thiosulfate. However, this will result in some additional cost. The "ideal" water would also have a temperature near the optimum for the species of fish being reared to reduce the costs of heating or cooling it,

Fish Tanks

The type of tank suited to a particular aquaculture system depends, in part, on the species being reared. Other considerations include the amount of space available and the budget. Common tank shapes include long, narrow raceways or troughs, square or rectangular tanks, and circular tanks. Construction materials include concrete, block and mortar, fiber glass, stainless steel and coated steel,

Raceways are the easiest type of tank to harvest, and they also allow separation of several groups of fish within a tank by screening them into compartments, However, raceways can develop areas of low flow with resultant poor water quality. In addition, fish in the lower end (farthest from the incoming water) are often exposed to consistently poor water quality.

Square or rectangular tanks, although the most space-efficient, tend to develop "dead" areas in the corners. This type of tank is also not suited to some species of fish. Pelagic

fish such as striped bass or hybrid striped bass tend to bump into the corners of this type of tanks in their active swimming.

Circular tanks waste floor space, inasmuch as they require more floor space per gallon of water. This type of tank is also somewhat more difficult to harvest. However, the circular flow produced in them eliminates "dead" areas of no water movement, Also, when larger fish are being reared, these tanks are virtual- ly self-cleaning.

Tank construction materials are usually constrained by budget. However, a definite advantage of fiber glass tanks is that they can be moved if a change in system configuration is necessary.

The size of the rearing tanks depends on the operating plan, Ideally, a tank which holds one "harvest unit" is best, Por exam- ple, if the plan of operation calls for the harvest of 2000 pounds of fish per week, at 1 pound per gallon, a tank holding 2000 gallons is needed. However, this does not imply that fifty- two 2000-gallon tanks are needed (1 tank per week), The number of tanks needed depends on the growth rate of the species being cultured, Smaller fish would be held at greater densities (number of fish per gallon) and only spread to more tanks as they grow,

Primary Clarifier

Solid wastes are produced by the fish and also result from uneaten food. This material should be removed from the water rapidly because it can be a major source of poor water quality and is the source of most biofilter problems. Particulate waste can contain 70% of the nitrogen load in the system (Liao and Mayo 1974). If this material enters the biofilter, it can cause problems in several ways. The particulate waste can clog the biofilter, resulting in low water flow through the filter or causing the nitrifying bacteria to die from lack of oxygen, Particulate waste entering the biofilter can also cause the growth of heterotrophic bacteria which produce ammonia while digesting the wastes. The particulate removal system is the key to a successful recirculating fish culture system.

Numerous means are available to remove particulate waste, However, there is still a search for a more efficient method. An efficient system should remove as much of the waste as possible and concentrate it for easy removal, while using minimal amounts of water and energy,

Early methods of removing particulate waste were by settling basins or sand filtration, Settling basins must be large to be effective, (Davis 1977) recommended a 30 minute retention time to allow the, solids to settle, Thus for a system moving 500 gallons per minute, a settling basin holding 15,000 gallons would be required. Sand filtration, although more compact and more efficient, requires frequent back-washing. Back-washing uses a large amount of water which must be replaced and heated (which costs money).

Several recent designs of filters are currently being tested in recirculating systems, including hydrocyclones, rotating screens, and tubular or plate settlers. Some of these have shown potential. A hydrocyclone is a conical type of filter in which the water spins down, forcing the particles to the side by centrifugal force. Although effective, hydrocyclones waste a lot of water because they continually discharge concentrated waste. Rotating screen filters are used by industry to effectively remove particulate waste from water. When used in aquaculture, they rapidly clog with organic growth. This necessitates frequent back-washing which wastes water,

Recently, improvements have been made to the 'original settling basin. By adding a series of vertical plates or tubes, efficiency has increased, thus allowing significant reductions in size. These filters have been shown to be effective on smaller systems. However, there have been reports that production-sized units did not adequately clarify the water.

Biofilters

The biofilter is the heart of a recirculating aquaculture system. Basically, a biofilter is simply a surface on which bacteria grow. While growing, the bacteria convert toxic ammonia produced by the fish and feed to much-less toxic nitrate.

$\text{NH}_3(\text{ammonia}) \rightarrow \text{NO}_2(\text{nitrite}) \rightarrow \text{NO}_3(\text{nitrate})$

However, in reality, it is a complex system comparable to a living organism. The biofilter must be "fed" and supplied with oxygen in order to remain healthy and function properly. It also releases carbon dioxide and hydrogen ions as a waste products,

As previously stated, the purpose of the biofilter is to convert ammonia to nitrate. Ammonia is the end-product of protein metabolism. Fish and other aquatic organisms generally excrete ammonia in the pure form, while mammals first convert it to less toxic urea. Ammonia in water can be in two forms, molecular (unionized) ammonia (NH_3) and ionic ammonia (NH_4^+). It is the molecular form that is toxic. Concentrations of molecular ammonia as low as 0.01 mg/liter resulted in sublethal toxic effects (clubbed gills, poor growth) in salmonids (Burrows 1964) while channel catfish show these effects at 0.12 mg/liter (Robinette 1973). The temperature and pH (acidity) control the ratio of molecular ammonia to ionized ammonia in water, with pH having the greatest effect (Trussell 1972). As pH increases (less acidity), the percentage of total ammonia in the toxic molecular form increases logarithmically (Table 1). At a temperature of 69°F and a pH of 7.0, about 0.4% of the total ammonia is in the molecular form. At a pH of 8.0, this increases to 3.8%, while at pH 9.0 28.4 percent is molecular. As an example, a measurement of 2 mg/liter of total ammonia in a system at a temperature of 68°F and a pH of 8.0 would result in 0.764 mg/liter of toxic molecular ammonia ($3.82\% = 0.0382$; $0.0382 \times 2\text{mg/liter} = 0.0764\text{mg/liter}$).

Table 1, Percent of total ammonia in the unionized form at various pH and temperatures (after Thurston et al, 1974).

Temperature (F)	pH			
	7.0	7.5	8.0	8.5
50	0.19	0.59	1.83	5.56
59	0.27	0.86	2.67	7.97
68	0.40	0.86	3.82	11.20
77	0.57	1.89	5.75	16.20
86	0.80	3.48	7.46	21.30

Ammonia in the biofilter is oxidized by a group of chemo-trophic bacteria (chemotrophic = chemical eaters), These are common bacteria, found in water and soil, One group of these bacteria (Nitrosomonas) utilizes ammonia (NH₃) and oxidizes it to nitrite (NO₂). However, nitrite is also toxic to fish, Nitrite ties up the oxygen binding sites in the blood hemoglobin, causing the problem which is commonly known as "brown blood disease." Toxic levels of nitrite are in the range of 24 mg/liter (or greater) for channel catfish, but as low as 0.55 mg/liter for salmon (Piper et al.1982). Fortunately, a second group of bacteria (Nitrobacter) utilizes nitrite and subsequently release nitrate (NO₃)' In actuality, nitrite and nitrate are released as nitric and nitrous acids,, resulting in a decrease in pH (more acidity) unless the water is well buffered,

The size of the biofilter needed depends on the amount of ammonia added to the system, Ammonia production is most closely related to the feeding rate and the efficiency of food utilization. Feed utilization, in turn, depends on the size of the fish, the quality of the feed, temperature, activity level of the fish, and the feeding rate. Generally, 1 to 3 pounds of ammonia is produced for each 100 pounds of feed. Thus 10,000 pounds of fish being fed 300 pounds of food per day (3 percent of body weight per day) produce 9 pounds of ammonia per day.

The quantity of bacteria available to oxidize the ammonia is limited by the surface area of the biofilter medium. As a bacterial population develops, it coats the surface upon which it is growing to a limited depth, The efficiency of this bacterial coating is then controlled by: 1) mixing the water to assure that the ammonia comes in contact with the bacteria, 2) dissolved oxygen level, 3) pH, and 4) temperature, In warm-water fish culture systems nitrification occurs at a rate of 200 to 400 mg of ammonia per square meter of biofilter surface area per day (0,00037 to 0,00074 pounds per square yard per day). Thus to oxidize the 9 pounds of ammonia produced in the example above, a biofilter with 24,500 square yards of surface area would be required (15,2 acres), Thus, it is apparent that an important factor in biofilter design is to get the maximum amount of surface area into a given volume. The surface areas of some common fixed media are found in Table 2, It is apparent that the smaller the particle size, the more the surface area per unit volume. However, when the particle size is reduced, the probability of filter clogging increases and the ability to mix the water within the biofilter decreases. The

major engineering problem with biofilters is to develop a method which uses small particles and assures that oxygenated water circulates throughout the filter,

Table, 2, Surface areas of some common biofilter media.

Medium	Surface area/volume		Fish supported(a) (pounds/ft ³)
	M ² /M ³	ft ² /ft ³	
.			
granular carbon(b)	3510	1070	54.1
no. 8 stone(c)	584	178	9.0
3-cm gravel(b)	330	101	5.1
1-cm spheres(d)	323	98	5.0
1,9-cm stone(c)	279	85	4.3
rotating disk(e)	210	64	3.2
Telpak(R) media(f)	130	40	2.0
PVC modules(c)	89	27	1.4

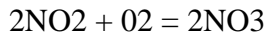
- (a) Based on 3% feeding rate, 0.027 kg NH₃/kg feed and oxidation of ammonia of 200 mg/m²/day.
- (b) From Paller and Lewis (1988)
- (c) From Meade (1974)
- (d) Author's calculations
- (e) Based on 1/8-inch plates spaced 1/4 inches = 32 plates/ft
- (f) From Aquatic Eco-Systems, Inc. (1988)

Re-oxygenation Since the fish utilize oxygen dissolved in the water and release carbon dioxide and since the biofilter also utilizes oxygen, a recirculating system requires a method to aerate or oxygenate the water. Maintaining high levels of dissolved oxygen (DO) in the water is critical to the success of the system. With low DO the growth rate of the fish is lower and food conversion decreases,

The amount of oxygen consumed by the fish is a function of fish size, feeding rate, activity level of the fish, and temperature, Meade (1974) determined that the oxygen consumption of salmon being reared at 57F was 0,004 pounds of oxygen per pound of fish per day, Lewis et al, (1981) determined that striped bass raised at 77F consumed 0.012 to 0.020 pounds per day, Consumption of oxygen by the biofilter bacteria is most closely related to the amount of ammonia entering the filter. Meade (1974), using the formulae of several authors, determined that a biofilter utilizes 4,0 to 4,6 pounds of oxygen for every pound of ammonia oxidized. The basic equations are:



for the conversion of ammonia to nitrite, and:



for the conversion of nitrite to nitrate, However, due to the presence of other bacteria in the system, we recommend that a ratio of 6 pounds of oxygen to 1 pound of ammonia be considered.

In the above example (10,000 pounds of fish, 9 pounds of ammonia) the oxygen requirement is:

$$10,000 \times 0.012 + 9 \times 6 = 174 \text{ pounds of oxygen per day,}$$

Not all of this 174 pounds of oxygen would have to added either through mechanical aeration or through direct oxygenation, since some aeration occurs naturally with the movement of the water.

Several methods are available for aerating water (adding air; 20 percent oxygen). Among these are the aspirators of Burrows and Combs (1968), mechanical agitators, and air blowers, Although effective, aspirators require pressurizing the water, which adds to the pumping costs. Care must also be taken with these systems to prevent nitrogen supersaturation, which is harmful to fish, Agitators are only suitable for relatively small systems, since a separate unit is required for each culture tank, Low-pressure, high-volume air blowers are probably the most effective method of aeration for medium to large systems, However, they are also the most expensive to purchase,

As the size of a system increases, the use of pure oxygen becomes more economical, Pure oxygen is available in either gaseous or liquid form, For use in a moderate-sized fish culture system, liquid oxygen is recommended for both economic reasons and practical storage, A large tank of compressed oxygen only contains 20.2 pounds of oxygen, while the standard 160 L liquid oxygen tank contains 403 pounds of oxygen. Thus a large number of tanks of compressed oxygen would have to be stored and changed frequently, Liquid oxygen is also less expensive than the compressed form, Recently, oxygen concentrators have been introduced for use in fish culture, These units take compressed air and extract the oxygen by passing the gas through a semi-permeable membrane, The 20% of air that is oxygen is stored for use while the 80% off-gas (mainly nitrogen) is left in another tank or purged outside, However, several problems exist with these units. Their initial cost is high, and their operation requires the use of a large high volume air compressor. In addition, a larger backup generator plant is required to run the units during line power outages, Therefore, unless a use for the high volume of pressurized off-gas is initially designed into the system, the cost of operation is also high.

The cost effectiveness of an oxygen system is limited by the efficiency with which the gas is dissolved into the water, The efficient transfer of oxygen depends on bubble size, pressure of the water and gas, temperature, contact time, and initial level of oxygen in the water,

One of the most efficient devices for introducing oxygen in the water is the U-tube, This device is simple (no moving parts) and takes advantage of pressure differentials to increase the gas transfer without requiring a highpressure pump, However, with a U-tube it is only practical to introduce the oxygen at one central point, Thus it is advisable to have an alternative oxygen delivery system to each fish culture tank for use when there is no water flow (power outage and generator failure, and main pump failure), During normal operation, the main water supply would be oxygenated using a U-tube contactor. However, if water flow is disrupted, oxygen would be diverted to diffusers in the individual fish culture tanks, U-tube oxygenators should not be used with compressed air, since supersaturation of nitrogen gas can occur. Supersaturation of nitrogen produces an often-lethal condition known as "gas bubble disease," where bubbles form in the arteries and block flow of blood.

Another form of oxygenator is the cone oxygenator (Figure). Water flows downward through a widening cone while bubbles of oxygen, which were introduced at the bottom, rise. At some point in the cone, as the water velocity slows with the larger "pipe diameter", the speed in which the bubbles rise will equal the speed of the down-flowing water. The bubble of oxygen will remain in this area until absorbed.

Cone Oxygenator

Water pumps

The method by which water is moved in a recirculating system will depend significantly on the system configuration, Systems which raise water to overhead biofilters or utilize an aspirator for aeration requires pumps which can deliver adequate water at 20 feet of head.(10 psi), Low-head systems can be operated with high volume, low pressure pumps, or with air-lift pumps. An air- lift pumping system appears to be promising with small to moderate systems due to the large volume of water which can be moved at a relatively low horse-power, and due to its ability to aerate the water. The disadvantage of an air-lift system is the requirement that all parts of the system be essentially at the same elevation, thus requiring more floor space and making harvesting and draining the tanks difficult,

Whichever pump system is utilized, it is advisable to divide the pump load among two or three pumps. In the event of failure of one unit, the system can continue limited operation to prevent loss of fish until a replacement unit is installed.

Types of Biofilter Systems

There are four basic types of biofilter designs: submerged- bed, trickier rotating disk, and fluidized bed. In addition, the submerged bed type of biofilter can be divided into downflow, upflow, and lateral flow sub-categories.

Submerged-bed biofilters

Submerged-bed biofilters are characterized by having a fixed (non-moving) medium that is constantly under water. The biofilter medium (attachment surface for the bacteria) used in these filters is highly diverse. Some of the materials which are used include gravel, oyster shell, solid plastic beads, extruded or molded high-surface-area plastic rings, and plastic screening.

Submerged bed biofilters are classified into three groups, depending on the direction of water movement. In downflow biofilters (Figure 1), water from the clarifier enters the top of the filter by gravity and flows through the filter to a sump. From there the water is pumped to a head tank, oxygenated, and flows by gravity to the fish culture tanks. Downflow filters are subject to frequent clogging and must be backwashed often. However, they are the simplest and least expensive to construct. Some success has also been achieved by using large volumes of air to dislodge particulate matter during backwashing.

Figure 1. Submerged-bed biofilter.

Upflow filters are similar to the downflow type in that they are operated by gravity. The advantage of upflow over downflow filters is that a settling basin can be incorporated below the medium in an upflow filter. Generally a light weight, buoyant medium is required. However, when the settling basin is located below the biofilter, it becomes difficult to determine when to clean the basin. Heterotrophic bacteria in the settling basins can also use most of the dissolved oxygen, thus reducing the efficiency of the biofilter. Without supplemental in-filter oxygenation, the maximum depth of upflow and downflow filters is limited to about 40 inches.

In lateral-flow biofilters, water enters the biofilter and flows laterally through the medium. One commercially marketed design of this type of system utilizes a small chamber as well as part of the medium for particulate waste removal. In addition, an air-lift is installed in the biofilter to move water from the filter back to the fish rearing tank. The applicability of this system type to large-scale production has yet to be tested.

Trickling filters

Trickling filters are similar to submerged downflow filters in that water enters the top and flows downward through the medium. However, the trickling filter is elevated (Figure 2) and has an open bottom. This configuration allows the medium to be exposed to the air, thus assuring adequate oxygen for the bacteria. In a properly designed trickling filter the water cascades over the medium in a thin film. Packed column aeration/degasification systems work on the same principle as a trickling filter.

One problem encountered with trickling filters is the sloughing of the bacteria. At times, enough bacteria will be lost to significantly reduce the nitrifying capacity of the filter,

Davis (1977) needed to use a secondary (post biofilter) clarifier on a trickling filter to remove particulate material created in the filter,

Figure 2, Trickling biofilter,

Rotating Disk

The rotating disk biofilter (also called rotating biological contactor or rotating biocontactor) has recently gained popularity. In this system (Figure 3) the substrate for the nitrifying bacteria consists of a series of parallel circular plates which are mounted on a shaft with a small (0.25- to 0.5-inch) gap between them. The disks are partially submerged and rotated on the shaft, using either a low-speed gear motor or a paddlewheel driven by the water flow. Usually several of these units are placed in series.

The advantages of the rotating disk biofilter include its tendency to be self-cleaning, its low head requirements, and its ability to maintain high levels of dissolved oxygen (Lewis and Buynak (1976). Because of the rotation, a thin film of water is constantly being exposed to the air, assuring adequate oxygen to the bacteria. Because of this, the nitrification process is consistent. With other systems partial clogging, variations in dissolved oxygen, and variations in water flow can result in fluctuations in nitrifying capacity.

Rotating Disk

Figure 3. Rotating-disk biofilter (rotating biological contactor)

Among the problems associated with rotating disk biofilters are their limited surface area, the additional costs to operate them, and a tendency for them to cool the water through evaporation. With a 0.25-inch spacing between the plates, rotating disk biofilters have only 62 ft²/ft³ of surface area (Table 2). Thus, a large area is required for placement of this filter system since biofilter size is a function of the amount of surface to which the nitrifying bacteria can attach. Because most rotating disk biofilters are operated by an additional motor, the cost of running that motor and the additional maintenance involved must be considered. The third problem with rotating disk biofilters, evaporation, will only affect systems which have a high air exchange rate. The rotation of the disk constantly exposes a thin film of water to the air, which is the same process used in many home humidifiers. Since evaporation causes cooling, this drop in temperature in the culture tanks must be taken into account. Generally it is recommended that systems incorporating a rotating disk biofilter be located in a tightly closed, insulated building. In addition, because of the tendency for a rotating disk biofilter to be self-cleaning, a secondary clarifier is required.

Fluidized Bed

Fluidized beds are a relatively new concept in biofiltration. In a fluidized bed, water enters the bottom of a cylinder with sufficient velocity to expand the medium (Figure 4). This permits the use of extremely fine materials for the bacterial substrate. Graded sand is one of the more common substrates used in fluidized bed filters; however, because of its density, a considerable amount of water is required to make it expand. Paller and Lewis (1988) examined the use of bone charcoal granules as a substrate in these filters. They found that a flow of 11 gpm per square foot of dimensional surface was sufficient to expand a filter bed 24 inches deep.

Two major benefits of fluidized beds are apparent. The most obvious is the amount (ft²) of bacterial substrate which can be fitted into a small filter (Table 2). The second is their tendency not to clog. The suspended particles will coat with bacterial growth, but the constant churning prevents excessive growth and adhesion of the particles.

The major problem associated with this filter type is the need for a relatively high pressure pumping system to suspend the substrate. This results in higher pumping costs than some lower pressure systems. A post-biofilter clarifier may be required with fluidized beds because of the self-cleaning of the particles.

Figure 4. Fluidized (liquefied) bed biofilter.

Biofilter Conditioning

The development of Nitrosomas populations in a biofilter bed is favored by high ammonia concentrations. Nitrobacter, however, is inhibited by high ammonia levels, thus requiring the oxidation of much of the ammonia to nitrite prior to the development of Nitrobacter populations (Lees 1952). This is most evident in new systems stocked with a moderate load of fish. Ammonia levels will increase due to the presence of fish and then decline as Nitrosomas populations develop and oxidize the ammonia to nitrite (Figure 5). Only after much of the ammonia is converted will Nitrobacter populations develop and begin oxidizing the nitrite to nitrate. Therefore, unless the system is pre-conditioned, a large mass of fish cannot be stocked. This phenomenon can occur in operating systems as well. A surge of ammonia resulting from over feeding or improper tank cleaning can inhibit Nitrobacter. Nitrate resulting from oxidation of some of the ammonia can cause loss of fish, while ammonia levels remain below the lethal limit.

Figure 5. Typical response of nitrifying bacteria in a new culture System with 2% makeup flush.

Pre-activation of a biofilter system involves seeding the filter bed with bacteria and feeding them with ammonia. Nitrifying bacteria are abundant in rich garden soils, so many people use a small amount of this as a bacterial seed. Commercially concentrated bacteria cultures are also available. Once the filter has been seeded, sufficient ammonia is

added to maintain about 3 mg/liter of ammonia. A good source of ammonia for this purpose is household ammonia without added detergent, although ammonium-nitrate and ammonium-phosphate fertilizers have been used. Ammonium-nitrate is not the best choice because the presence of nitrate is a good measure of the activation process.

Initial additions of ammonia disappear rapidly by being incorporated into the bacteria. After the first week of pre-activation, it is necessary to add ammonia daily. After several weeks, nitrite and nitrate occur in appreciable levels. Once biofilter conditioning occurs, nitrite levels should have risen to 5 to 10 mg/liter and then stabilized below 1 mg/liter, and nitrate levels should be steadily increasing. This process can take as long as 4 to 6 weeks.

As an alternative to pre-activation, a staggered stocking regime can be used. The biofilter is seeded as above and then the system is stocked with a small load of fish. When the biofilter bacteria populations grow to meet this ammonia load, additional fish are stocked. When this technique is used, a sufficient water supply for emergency flushing should be available,

System Monitoring

Once a water reuse system is activated and operating, certain water quality parameters should be monitored regularly. Among these are dissolved oxygen, total ammonia, nitrite-nitrogen, temperature, pH and alkalinity. In addition, nitrate-nitrogen is useful as a measure of how the system is functioning. Dissolved oxygen should be measured in the influent and effluent of the biofilter and in each rearing tank daily. Oxygenation or aeration rates can then be adjusted such that the biofilter effluent maintains at least 5 mg/liter of oxygen to ensure that the nitrifying bacteria are sufficiently supplied. Biofilter influent concentrations may therefore need to be as high as 12 to 15 mg/liter of dissolved oxygen. If a biofilter becomes anoxic for even a brief time the bacteria can be killed, resulting in a rapid build-up of ammonia to lethal levels. For this reason it is best to allow the biofilters to drain during periods of no water flow such as during power outages. It is wise to have some aeration to the biofilters during these periods. In large water reuse systems monitoring of dissolved oxygen is best done with a meter, instead of a test kit. An oxygen meter is a relatively expensive piece of equipment but will save time. Small systems with only one or two rearing tanks can be adequately monitored with oxygen test kits.

Total ammonia, nitrite-nitrogen, and pH should also be monitored daily in the biofilter effluents and influents. In addition, under certain rearing conditions total ammonia should be monitored daily in the rearing tanks. These situations include any rearing regime where a large amount of feed is offered to the fish (such as rearing larval fish or training fingerlings), or where water flow is insufficient to flush the rearing tanks rapidly.

A definite decrease in total ammonia as the water passes through the biofilter is a good indication of the condition of the system. Water in the biofilter effluent should have an ammonia concentration well below the maximum level allowed in the rearing tanks.

Any decrease in the nitrification rate (influent concentration of ammonia minus the effluent concentration) usually means that a problem exists. Either the biofilter is clogging with heterotrophic bacteria that produce ammonia or the nitrifying bacteria are not getting adequate amounts of oxygen. This problem requires immediate action.

Nitrite, the intermediate step in the nitrification process, should also be monitored daily. An increase in nitrite indicates that Nitrobacter populations are not functioning well. Common causes of increased nitrite are low oxygen in the biofilter and a surge of high ammonia. As mentioned earlier, Nitrobacter is inhibited by high ammonia levels. Therefore, a surge of ammonia produced by fish tank or raceway cleaning can potentially shut down this set of bacteria and result in high ammonia. We have also observed temporary peaks in nitrite following the initiation of biofilter oxygenation. However, the high nitrite levels subside after several days of oxygenation.

The end product of the nitrification process, nitrate, need not be regularly monitored due to its low toxicity (greater than 200 mg/liter). However, nitrate levels serve as an indicator of the efficiency of the biofilter and water use, since its concentration is only reduced through dilution with fresh water.

It is also important to measure pH regularly for two reasons; the pH is needed to calculate the amount of toxic molecular ammonia in the water, and very low pH (high acidity) has both lethal and sublethal effects on fish. The nitrifying bacteria in water reuse systems tend to produce acidic conditions because the nitrite and nitrate are released as nitrous and nitric acids. Therefore, the system pH can drop with time. Low pH reduces the ability of the nitrifying bacteria to work properly and has direct effects on the fish. Poor feeding response and vulnerability to disease are some of the sublethal effects of low pH. When the pH drops below 5.0, the effects become lethal.

To prevent declining pH, the water must be well buffered with a carbonate source. The buffering capacity of the water is best measured as methyl-orange alkalinity (MOA). Thus MOA should also be monitored at least 5-day intervals.

Test kits which allow the measurement of ammonia, nitrite, nitrate, pH, and alkalinity are available from several manufacturers. These kits are a necessary investment for water reuse aquaculture.

It is also important to closely monitor the fish in a water reuse system. Frequent observation can detect changes in behavior which indicate approaching problems. Poor feeding response can be the first signs of disease, deteriorating water quality, or bad feed (insufficient vitamins, etc.). Other behaviors such as scratching (flashing), sluggishness, or color change can also be signs of disease or poor water quality. Therefore, "getting to know" the organism being cultured can reduce the chance of catastrophe in a water reuse system.

Disease Treatment

When working with recirculating aquaculture systems, caution must be taken when using some of the therapeutic chemicals available to fish culturists because some chemicals can destroy the biofilter bacteria. Antibiotics have this potential, although they are generally administered in the feed. Formalin-F, a commonly used chemical for the control of protozoan and trematode infections does not destroy the bacteria. However, this chemical increases the ammonia in the system by killing fungus and other organisms in the filter (Lewis et al. 1981). Breakdown of these organisms results in the release of ammonia. Formalin-F also complicates the analysis of ammonia in the fish culture system because it registers as ammonia in many of the water quality test kits.

Disadvantages of Biofiltration Systems

As stated earlier, there are five major advantages in using recirculating fish culture systems incorporating biofiltration; low water and land requirements, control of water temperature and water quality, and independence from the effects of weather. However, there are also certain disadvantages of these systems, and most of these start with a \$ sign,

The initial set-up costs of a biofiltered fish culture system are formidable. Along with costs of the tanks, biofilters, pumps and plumbing, the costs of the building and insulation must also be considered. Other important initial costs include feed storage facilities and back-up and emergency power equipment. If it is necessary to borrow money for these, the interest on this capital must be considered in the operating costs.

Operating costs of a recirculating system are also substantial. The costs of producing fish should include the cost of feed, the cost of energy to heat and pump water, the cost of that water, whether it comes from a well or municipal source, the cost of treating or otherwise disposing of effluents (particularly back-wash from clarifiers), the cost of labor and the cost of transporting the fish to the market. In addition, the costs of insurance and maintenance of the equipment should also be considered, as well as the cost of the fingerlings, whether they are purchased or raised on-site,

All these costs must be carefully and accurately determined so that they can be included in a production plan. That plan should show how many fish of a particular size can be produced, at what size, and what will be the cost to produce them. From this, the price per pound of finished product can be determined. Then one needs to determine if anyone is willing to pay that price.

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