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Biological filters in aquaculture: Trends and research directions for freshwater and marine applications

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Abstract

Factors such as limitations in water quality and quantity, cost of land, limitations on water discharges, environmental impacts and diseases, are driving the aquaculture industry toward more intensive practices. This will force producers to adopt environmentally friendlier technologies. Recirculating systems, with a biofilter as the most prominent characteristic, treat internally the water contaminated with dissolved organics and ammonia and reduce the amount of water use and discharge from aquaculture operations. This paper reviews the implications of the changing use of recirculating aquaculture systems (RAS) on biofiltration research for freshwater and marine operations. Demand for cost effective biofilters will increase with the expansion of recirculating systems, both as a complement and replacement of traditional ponds. For freshwater aquaculture, emphasis should be placed in cost competitiveness, low head operations, intensification of ponds with RAS biofiltration and the evaluation of suspended growth systems. In the marine systems, an increase in demand of oligotrophic and ultraoligotrophic systems is expected, particularly in the nursery systems. Sizing and cost efficiency of biofilters for nursery operations should be addressed. Problems in marine biofilter acclimation appear to justify the development of new acclimation procedures. Biosecurity concerns, land cost and storm threats will drive nursery systems inland, where saltwater supply and disposal will force an increased water reuse. Denitrification strategies will need to be redefined and optimized for the marine nursery environment.

Keywords: Aquaculture; Biofilters; Recirculation; Nitrification

1. Introduction

Over the last two decades, aquaculture has gone through major changes, growing from small-scale homestead-level activities to large-scale commercial farming, exceeding landings from capture fisheries in many areas (National Research Council, 1992; NACA/FAO, 2001). While output from capture fisheries grew at annual average rate of 1.2%, output from aquaculture (excluding aquatic plants) grew at a rate of 9.1%. The latter is a faster rate than any other animal food producing systems such as fisheries and terrestrial farmed meat (FAO, 2003). This growth is expected to continue as the population grows and the per capita consumption of seafood increases while

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other protein sources consumption decreases. As an example, fish consumption per capita increased 24% from 1970 to 1998, legumes increased 13% as egg and meat consumption had a net decrease (USDA/ERS, 1999).

The need to increase aquacultural production is driving the industry toward more intensive practices. Some of the factors that influence this trend are: limitations in quality and quantity of water, availability and cost of land, limitations on water discharges and environmental impacts. Recirculating technologies help minimize these issues. A recirculating aquaculture facility reduces water demands and discharges by reconditioning of water (Goldburg et al., 2001). Better food conversions are achievable with a recirculating aquaculture system (RAS) which means less waste is generated by the feed (Lorsordo et al., 1998). In recent years, there has been a growing concern over the impacts of aquaculture operations (Buschmann et al., 1996; Harache, 2002; Naylor et al., 2000; Cranford et al., 2003; Johnson et al., 2004). It is estimated that 85% of phosphorus, 80–88% of carbon, 52–95% of nitrogen (Wu, 1995) and 60% of mass feed input in aquaculture will end up as particulate matter, dissolved chemicals, or gases (Masser et al., 1999). Increasing regulatory pressure focusing on discharges to natural water bodies will force producers to adopt methods that are environmentally friendlier (White et al., 2004). RAS technology can reduce the effluent waste stream by a factor of 500–1000 (Chen et al., 1997; Timmons et al., 2001). Thus, recirculating technologies may allow existing operations to upgrade and expand and comply with future regulations.

Recirculating systems have been identified as one of the two main research areas in aquaculture (NOAA, 2001) and one of the proposed research areas for the European Union (Martin, 2002). The most prominent characteristic of these production systems is the presence of a biofilter, which reflects a commitment to internally treat water contaminated by dissolved organics and ammonia rather than discharge them, as in the case of net-pens and flow-through systems, or to treat them extensively as in the case of pond production. This paper reviews the implications of the changing use of recirculating systems on biofiltration technologies for freshwater and marine systems with the intention of assisting researchers and biotechnologists in selection of research topics.

2. Freshwater

The feasibility of raising freshwater species to market size in recirculating systems has been demonstrated (Broussard and Simco, 1976; Buckling et al., 1993). RAS systems have the advantage of temperature control which opens the door for year around production (Lazur and Britt, 1997; Funge-Smith and Phillips, 2001). Recirculation can be an economic alternative when energy costs associated with temperature control and pumping requirements are otherwise high. Buckling et al. (1993) working in an ornamental fish production facility calculated that the average RAS savings in energy for heating and pumping was US$ 0.96 per pound of fish produced. Seasonality of tilapia production from southern ponds was a major factor encouraging the development of RAS tilapia production in the United States. The catfish and eel production facilities found in the Netherlands also exist, in part, because of the heating advantages presented by RAS systems (Bovendeur et al., 1987; Kamstra et al., 1998).

Water use issues are also rapidly becoming a strong factor driving the adoption of recirculating technologies. Varadi (2000) discusses the increasing pressures being placed upon the world's freshwater supplies. Major recirculating developments being undertaken in support of hybrid striped bass production in the deserts of California in the western United States (Carlberg et al., 2003) and similar work in Israel are being driven by underlying water resource issues (Barak and van Rijn, 2000). Additionally, urbanization brings with it increased water use demands. The ornamental fish industry in relatively wet Florida is experiencing severe water use restrictions as a result of the population growth in the Orlando-Tamps area. Asano et al. (2003) describes an even more severe water resource threat to Hawaii's ornamental fish industry which is prompting an examination of RAS technologies. Likewise, water use and the underlying competition with urban areas for this limited resource has driven a major recirculating thrust supporting cold water production in the Northeast regions of the United States (Heinen et al., 1996). Schuster and Stelz (1998) also frame their description of cold water trout recirculation designs in terms of water conservation. Water resource limitations increasingly are becoming a major factor in prompting RAS adoption.

Recirculating aquaculture systems are unable to compete directly with pond or flow-through systems producing freshwater commodity food fish. This is the main obstacle for a wider adoption of RAS technologies (Timmons and Losordo, 1994; Lorsordo and Westeman, 1994; Malone, 2002). The water reconditioning burden borne by the recirculating systems renders them less competitive in the low priced fish market. Lorsordo et al. (1998) reports an investment cost of US$ 0.90 per pound of annual production for pond systems, compared to US$ 1.00–4.00 for recirculating systems. When all costs are considered in the U.S., a native foodfish can be raised in a pond for about two-thirds of the RAS price. Although the cost of recirculation will continue to drop, and while water resource concerns and environmental regulations will continue to threaten flow-through strategies, pond culture will likely remain the most cost effective production mode for commodity food product. RAS systems are, however, proving them a complement to pond culture and are gradually being accepted as a useful tool. A wide variety of successful strategies that have been identified for fingerlings and broodstock (Rakocy and McGinty, 1989) and given the relative higher prices, that can go from US$ 5.00 to 40.00 per pound of fingerlings (Hinshaw et al., 1990; Davis and Lock, 1997; Hinshaw and Thompson, 2000) the time of recovery of a higher capital cost can be reduced.

Recirculating systems play an important role in environmental and biomedical research with the adoption of some aquatic species, like the zebrafish (Streisinger et al., 1981; Driever et al., 1994; Ma et al., 2001; Zon and Peterson, 2005) and medaka (Hutchinson et al., 2003; Sarmaski, 2003) among others, as model animals for research. Areas such as genetics, molecular studies, mutagenesis, teratogens evaluation, transgenics production, endocrine disruption and vertebrate development require a reliable supply of these organisms in optimal condition. The high level of population control in closed systems minimizes the introduction of uncontrolled diseases and unknown effects.

RAS biofilter technologies can be divided in two main categories: fixed film (attached growth) in which a media is provided for the microorganisms to attach and grow, and suspended growth in which the microorganisms are maintained in suspension. Most of the biofiltration on recirculating systems has been focused on aerobic, fixed film filters (Wortman and Wheaton, 1991; DeLosReyes and Lawson, 1996; Westerman et al., 1996; Greiner and Timmons, 1998; Singh et al., 1999; Malone and Beecher, 2000; Lekang and Kleppe, 2000; Sandu et al., 2002) in which a substrate is provided for the growth of a biofilm that utilizes oxygen to convert ammonia and nitrites to nitrates, and oxidize organic matter. Recently, interest in other biofiltration alternatives, such as the suspended growth systems (Avnimelech, 1988; Van Wyk et al., 1999) has increased. These systems are used extensively in wastewater treatment, but the higher level of management needed for their operation has slowed their incorporation in aquaculture. Suspended growth systems have been considered unstable and associated with poor water quality by the general aquaculture community. The inability of fixed film systems to meet the economic expectations will, however, force revalidation of these conclusions particularly as they apply to commodity production of hardy species.

A second way in which demands of economics are being manifested is in the intensification of pond culture. As engineers work to increasingly partition pond operations (Drapcho and Brune, 2000) as a means of increasing production the distinction between pond and RAS culture will begin to blur. The increased use of unit processes including biofilters in direct support of ponds can be expected to continue (Van Rijn and Rivera, 1990; Tilley et al., 2000). This work will demand that biofilters of large scale must be designed to treat large quantities of water with extremely low headloss and energy consumption. Filters with these characteristics will also be in demand to support commodity fish production in areas where the use of genetically altered organisms, water resource and land limitations or environmental concerns force the pond like systems indoors (Lutz, 1997).

Finally, although the freshwater RAS biofilter industry must now be considered reasonably mature, the introduction of biofiltration technologies from the much larger water and wastewater industry can be expected to continue. This was recently evidenced by fairly rapid dissemination of moving bed reactors into the RAS industry, a technology whose development was largely supported by the water and wastewater industry (Odegaard et al., 1994; Zhu and Chen, 1999). It is only a matter of time, until approaches such as the Biological aerated filters or BAF (Mann et al., 1998) and airlift reactors (Garrido et al., 1997; Seo et al., 2001) experience a similar pattern of introduction. These continued introductions will have to be evaluated and compared against currently popular biofiltration options.

3. Marine

Concurrent with the technological evolution of recirculating systems, the aquaculture industry is in a state of transition. The world fisheries harvest has reached a plateau and future increases in seafood demand must be supplied by aquatic farming. Marine fish and shellfish dominate the world fisheries landings (FAO, 2003) so we can expect a dramatic increase in the farm production of marine species.

The applicability of RAS technologies to production of marine species has been amply demonstrated (Manthe et al., 1985, 1988; Davis and Arnold, 1998) but the commercial production has been limited by a number of factors (Mozes et al., 2003). Lisac and Muir (2000) report a production cost 19% lower for offshore facilities compared with land based extensive operations. This basic observation would appear to drive RAS systems into a support role for ponds and net-pens operations (Funge-Smith and Phillips, 2001).

In the saltwater arena, it appears that recirculating systems will play an important role in the production of healthy, properly sized fingerlings for stock out in net-pens or ponds (Fielder and Allan, 1997). Recirculating systems are very compatible with the complex nature of reproduction in marine species and the broodstock fecundity of most marine species diminishes the impact of waste processing costs. The high values associated with fingerlings and marine ornamentals will also promote adoption of recirculating technologies (Howerton, 2001; Kholer, 2004; Palmtag and Holt, 2001). Reliable supply of fingerlings is a bottleneck for the commercial production of marine species, as sea bass, sea bream, flatfish and cobia among others (Watanabe et al., 1998; Schwarz et al., 2004). The higher market prices of marine fishes make this an attractive niche for recirculating systems.

RAS adoption for larvae, fry and fingerling production is also driven by biosecurity issues (Turk et al., 1997; Otoshi et al., 2003; Pruder, 2004). Water recirculation dramatically reduces the possibility of pathogen introduction (Davis, 1990; Goldburg et al., 2001). As an example, the shrimp culture production requires separate installations for the maturation and breeding, with shallow tanks, low density (5–7 shrimp/m^2), and fatty, high protein food. High biosecurity is critical to prevent introduction of diseases that have plagued the shrimp industry in recent years, as the WSSP, YHV, VP, IHHNV REO and TSV viruses. Infectious disease is currently the single most devastating problem in shrimp culture and presents ongoing threats to other aquaculture sectors (FAO, 2003). The larvae of the shrimp have three distinctive stages of growth (nauplius, zoea and mysis), with further subdivisions, all of them requiring different feeding regimes and very high quality water, as they are very sensitive to suspended solids, and bacterial infections. Temperature control is critical at this stage as a few degrees variation can delay or impede the development of the larvae and ultimately cause their mortality. At these stages, the food supplied to the organisms is commonly cultured in the same facilities, and consists of microalgae and zooplankton. The culture of these feeds have different requirements, but with the same high biosecurity of the larvae culture. At the post-larvae and juvenile phases the shrimp can be placed in ponds for the grow-out phase.

First feeding in marine species can be a critical stage (Sahin, 2001). The early depletion of the yolk sac, small size and immature digestive system of these larvae, make them more vulnerable to environmental factors. In this stage, the right prey to mouth size ratio and the composition of the food should be carefully monitored. Many marine fish need live feeds to trigger the eating response. A slight retardation on the first food ingestion can impair the larval development (Mercier et al., 2004).

The use of RAS for marine hatchery operations has significant implications for biofiltration. This expanding niche will demand operations under oligotrophic regimens (Malone and de los Reyes, 1997) which are rarely demanded by freshwater applications. A biofilter's nitrification capacity is proportional to the TAN (or nitrite-N) concentration below 1.0 mg/l (Zhu and Chen, 2001). Marine larval systems can demand TAN and nitrite-N levels below 0.1 mg/l well below the maximum set for the oligotrophic category (0.3 mg N/l) used for freshwater and fingerlings in the freshwater industry (Malone and Beecher, 2000). The change in water quality objectives can demand a three- or fourfold increase in the sizing criteria for the biofilter, a change that clearly justifies the establishment of a new ‘‘ultraoligotrophic’’ category. Research focused on the evaluation and redesign of biofilters to serve this ultraoligotrophic market needs to be expanded.

A number of factors are pressuring these nursery systems further inshore away from the coasts. In the more developed sectors of the world, coastal lands are simply becoming too expensive for hatchery operations. Movement inland reduces the potential for introduction of non-indigenous species and assures to a large extent assures the containment of genetically modified organisms. The increasing interest in genetically modified organisms for research (Jagadeeswaran et al., 1997) and production of biochemical products (Rodgers et al., 2001; Schultz and Dawson, 2003) has generated concern over the impact of such organisms on the environment. Calls for effective physical containment (Alestrom, 1996; Schuur, 2003) have resulted. The movement inland also prevents the accidental introduction of marine parasites that may detrimentally impact natural fisheries (Castilla et al., 2005; Cohen, 2002; Cohen et al., 2001; Peterson et al., 2005). And finally, the capital intensive nurseries are more secure from storm damage when placed inland.

The movement of the nursery systems inland creates a secondary problem with saltwater supply and disposal which pressures the recirculating system to extend water reuse. Hydraulic residence time (HRT) increases are normally easily accommodated; however, declines in alkalinity and increases in the color and nitrate content of the RAS waters must be recognized. Color buildups are largely tolerated, but, can be easily dealt with by changes in feed and application of moderated doses of ozone (Christensen et al., 2000), but the costs of handling the alkalinity exhaustion and nitrate accumulation in a system that is operated strictly in an aerobic mode are significant. The most effective way of dealing with this problem is denitrification, a process that removes the nitrogen from the system while replenishing the alkalinity lost in the aerobic nitrification process (Van Rijn and Rivera, 1990; Shnel et al., 2002).

In some marine and freshwater organisms, lethal and sub-lethal effects of high concentrations of nitrates have been documented. An amount of 50 mg N/l is a generally accepted safe limit for nitrate nitrogen in fish culture, but this concentration varies widely for different species and development stages. The effects of excess nitrates can mean slower growth, susceptibility to diseases, retardation in development, low fertility and poor survival. The reported LC50 for freshwater organisms ranges from 5 to 2107 mg N/l of nitrate, with amphibians and invertebrates as the most sensitive groups. In marine species the ranges are 2.2–5050 mg N/l of nitrate with larvae and broodstock as the most sensitive stages (Environment Canada, 2003).

Marine white spot disease has been linked to nitrate concentrations above 30 mg N/l (Burgess, 1995). A nitrate concentration of 100 mg N/l was clearly lethal to medaka fish (*Oryzias latipes*) when they were exposed to nitrate in both adult and growing phases. A nitrate concentration of 75 mg N/l reduced the fertilization rate, delayed hatching time, reduced the hatching rate of the eggs and decreased the growth rate of juveniles. In addition, nitrate accumulations as low as 50 mg N/l remarkably retarded spawning and lowered the number of eggs laid by fish exposed in the juvenile phase.

The denitrification process is a traditional tool used to reduce nitrogen pollution in agricultural, domestic, and industrial wastewater streams that threaten eutrophication of surface waters. Bacterial denitrification is a form of respiration in which bacteria uses nitrogen oxides as a source for oxygen. Most of the bacteria that perform this process are heterotrophs, and usually facultative anaerobes, that can use oxides when free oxygen is not present. It is through this process, which requires different enzymes and cytochromes not present during aerobic respiration, that the nitrogen oxides can be reduced to a final N_2 form (Barak and van Rijn, 2000).

The application of denitrification to aquaculture has been demonstrated (Balderston and Sieburth, 1976; Kaiser and Schmitz, 1988; Whitson et al., 1993; Lee et al., 1995; Schuster and Stelz, 1998), although the efforts to control this phase of the process have not been as strong as the ones directed to nitrification or solids removal, due to the capacity of many of the freshwater cultured species to tolerate high nitrate concentrations (Van Rijn and Barak, 1998). With the increase in the culture of marine species and the focus on larvae and broodstock, the anaerobic component of the biofiltration will take a more prominent position to increase water retention times, allowing a higher HRT in sensitive species and stages.

The acclimation of biofilters, particularly in marine environments, will require additional research, particularly in bacterial identification and population dynamics. Previous studies have shown that an acclimation period is necessary before a biofilter begins to operate properly (Manthe and Malone, 1987). The acclimation can be achieved by initial light loading with organism or ammonia and nitrite addition. Normal acclimation times can be expected to be of the order of 2–3 weeks for freshwater systems (Masser et al., 1999). However marine systems frequently seem to stop the nitrification in the ‘‘nitrobacter’’ or ammonia oxidizing stage of acclimation. It is not uncommon to see systems with persistent nitrite accumulations for periods as long as 3–4 months (Manthe and Malone, 1987). The cause for these problems remains unknown, and has been attributed to a number of factors, such as high organic loadings (Van den Akker et al., 2003), or changes in salt concentration and operational parameters (Lee et al., 2002; Svobodova et al., 2005). The authors suspect that they are being controlled either by the lack of proper genetic seed or by unrecognized factors influencing the establishment of marine nitrifying populations.

4. Observations

(1) Demand for cost effective biofilters will grow with expanded use of RAS. Freshwater RAS systems will continue to grow in use both as a complement and as replacement of traditional ponds:
   (a) Research should define the cost competitiveness of growout facilities.
   (b) Research should focus on filters of scale capable of low head and low energy use operation in support of large scale facilities.
   (c) Suspended growth systems should be reevaluated and refined as a biofiltration option supporting commodity fish growout.
   (d) Research into the intensification of ponds should be supported by the RAS biofiltration community.
(2) There will be an increase demand for oligotrophic and ultraoligotrophic RAS technologies for marine nurseries:
   (a) Increased emphasis needs to be placed on the sizing criteria, and cost efficiency of biofilters supporting nursery operations.
   (b) Problems with biofilter acclimation in marine biofilters acclimation appear to justify the development of new acclimation procedures.
(3) Biosecurity concerns, land costs, and storm threats will force nursery systems inland where saltwater supply and disposal concerns will force increased water reuse:
   (a) Existing strategies for denitrification need to be defined and optimized to serve the marine nursery environment.

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