Emerging Technologies for Mitigation of Environmental Impacts Associated with Shrimp Aquaculture Pond Effluents

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Abstract

The environmental sustainability of aquaculture in general and shrimp farming in particular has received increasing attention in recent years. Discharge of nutrient rich effluent from intensive culture systems can contribute to the eutrophication of receiving waters potentially impacting both natural biota and local culture operations. Technical innovations have focused on reducing effluent volumes and on discharge treatment. A growing volume of scientific research and industry experience confirm that water exchange may be reduced or eliminated. The pond microbial community plays a major role in pond dissolved oxygen dynamics, natural food availability and nutrient recycling rates. Based on an improved understanding of pond microbial ecology, techniques are emerging for community manipulation through supplementation of limiting nutrients, selective habitat expansion, and culture additions. With appropriate aeration rates and optimal pond carbon to nitrogen ratios, bacterial biomass may provide efficient, nontoxic decomposition of waste, reducing total nutrient discharge while improving natural productivity in the pond. Technologies for treatment of effluents include sedimentation and mechanical and biological filtration. Efficiency and cost effectiveness of treatment can be improved through the reduction of exchange volumes and emphasis on drain harvest effluent. Further research along these lines will improve the prospects for more profitable and sustainable production technologies.

Introduction

The growth of the aquaculture industry in recent years has made a significant contribution towards meeting the increasing consumer demand for fish food-products. Aquaculture expansion continues to outpace growth in capture fisheries. From 1990 to 1996 aquaculture's contribution to marine fisheries production nearly doubled from 6 to 11% (New 1999). The high value of marine shrimp, high consumer demand and relatively short production cycle has resulted to an explosive growth in this sector of marine aquaculture. Indeed, between 1985 and 1995 global marine shrimp farming expanded by 430% while capture fisheries increased by only 11%

(New 1997). Rosenberry (1998) estimated that marine shrimp farmers produced over 737,000 metric tons from over 171,000 farms covering an area of over 8,643 square kilometers. The tremendous development of the shrimp farming industry over the past 20 years has not been without problems. A general problem in aquaculture systems is that the target crop utilizes only a small proportion of the feed added to the system. Most farms have relied upon relatively high rates of water exchange to maintain water quality in production systems. This has resulted in the release of waste material from uneaten feed, excess primary productivity and various metabolites, directly into adjacent receiving waters. In some areas where large scale development of shrimp aquaculture is coupled with resource-intensive pond management practices, eutrophication of estuarine waters and/or excessive organic enrichment of the substratum have occurred. This type of environmental degradation reduces farm productivity and increases stress on the target crop often leaving shrimp vulnerable to diseases that have decimated production in many regions (Browdy and Hopkins 1995).

A significant body of current research is devoted to improving the long-term viability of marine shrimp farming. Several areas have been emphasized including proper site selection (Clay 1997), prevention of escapement (Browdy and Holland 1998), control of disease (Lightner et al. 1998), captive breeding of healthy and genetically improved stocks (Browdy 1998), and better system designs and management protocols. The study of shrimp pond ecosystems in relation to surrounding environments suggests opportunities for reducing impacts of farming operations. Optimization of the pond's microbial community for improving in-pond nutrient recycling is an important area of research for the reduction or elimination of water exchange.

The microbial community plays a major role in shrimp production, providing a food source, recycling nutrients, and breaking down organic sludge deposits through a variety of processes. The significance of these beneficial processes depends upon factors such as pond management strategy, shrimp age, and pond production phase. The microbial community may also adversely affect water quality by increasing oxygen demand as a result of consumption of labile organic carbon. Labile organic carbon is released from uneaten feed, algae, and released by sediment bacteria as a result of organic matter digestion (Hansen and Blackburn 1991). Sediment digestive processes also produce potentially toxic compounds such as ammonia and hydrogen sulfide.

The importance of the microbial community on water quality and shrimp production suggests the need for management strategies to promote beneficial processes while controlling adverse processes. Advanced production systems will 1) reduce reliance on water exchange, 2) incorporate technologies to improve production efficiency and recycling of waste material and 3) provide for treatment of effluents. The present contribution provides a brief overview of some research directions and strategies for management of water, feed, microbial community, and waste. These new strategies have the potential to reduce environmental impacts associated with pond effluents.

Water management

On large farms, water exchange is often based on a set schedule with occasional emergency flushes (Macia 1983) rather than on an ongoing response to changing pond conditions. In the water column, ammonia is recycled in the pond through uptake by phytoplankton and bacteria for protein synthesis, and oxidation by nitrifying bacteria. With adequate sunlight and control of phytoplankton densities, oxygen generation by photosynthesis exceeds phytoplankton oxygen consumption by respiration, making this group net producer of oxygen. By maintaining a balanced pond system, the microbial community can positively affect ammonia concentrations and dissolved oxygen levels.

In extensive or semi-intensive systems, little or no water exchange and no aeration is necessary up to a certain level of feed input. Brune and Drapcho (1991) suggest an upper production limit of 1250 kg·ha^{-1} to assure adequate dissolved oxygen in ponds without exchange or aeration. To maximize production in semi-intensive ponds without aeration, oxygen balance must be maintained by controlling phytoplankton populations. Algal densities can be maintained through carefully conceived fertilization regimes and minimal water exchange in response to pond conditions, thereby reducing self shading effects and oxygen depletion on very cloudy days. Water exchange, if necessary, should be determined on a pond-by-pond basis by monitoring algal types and density, diel oxygen and pH fluctuations, secci depth readings and water color (Chien 1992). Minimal proactive water exchange to maintain oxygen balance by controlling phytoplankton densities is more effective and more economical than attempting to increase dissolved oxygen through water intake. When feeding rates are further increased to maintain production levels approaching 2 t·ha^{-1}·crop^{-1}, aeration equipment rather than pumping may be used.

For more intensive systems, aeration is added according to feeding rates to maintain dawn dissolved oxygen levels (Hopkins et al. 1991). At typical intensive commercial production levels, exchange can be significantly reduced (Browdy et al. 1993, Hopkins et al 1993a, Allan and Maguire 1993) or eliminated (Hopkins et al. 1993a, C.P. 1994, Hopkins et al. 1994b, Hopkins et al. 1995b, Hopkins et al. 1996) without affecting growth or survival as long as dawn dissolved oxygen levels are maintained at acceptable levels. Hopkins et al. (1995b) achieved production of 7 t·ha^{-1}·crop^{-1} equivalent in a 0.1 ha pond managed without water exchange. Preliminary estimates suggest elimination of water exchange increases aeration requirements as much as 10%; however, pumping cost savings more than offset operating costs of additional aeration required (Hopkins et al.1995a).

Sandifer and Hopkins (1996) designed an environmentally friendly integrated intensive culture system (EFS) with water recirculating between ponds, no outside water exchange, continuous sludge removal with later use as an organic fertilizer and soil amendment; and a secondary crop (oyster) pond to recoup waste solids and provide a source of exchange water. EFS water was retained at harvest and used to rear successive crops. Shrimp

production in this system was 7 t·ha^{-1}·crop^{-1} and 10 t·ha^{-1}·crop^{-1} in the first and second years, respectively (Hopkins et al. 1997; Holloway et al. 1998). This suggests the potential for eliminating water exchange at harvest without compromising future crops.

Feed management

Recognizing that feed inputs drive the processes that affect pond water quality, improved low pollution and environmentally friendly feed formulations offer opportunities for reducing nutrient release in pond effluents (Lawrence and Beasley 1993). Low pollution diets utilize nutrient dense formulations to achieve very low feed conversion ratios by reducing levels of carbohydrates while increasing highly digestible protein and energy (Chamberlain 1995). Improved feed management also offers very significant opportunities for reducing pollution while decreasing production costs (Jory 1995). The timing and frequency of feed application should be optimized according to the stability of the diet used and shrimp feeding habits (Robertson et al. 1993). In his review of feed management, Jory (1995) provided a detailed summary of shrimp feeding rates and feeding regimes. Excess feed unconsumed by the shrimp directly pollutes the pond system. In addition, overfeeding can result to reduced feed digestibility and significantly increased fecal production. The use of feeding trays to monitor consumption and to adjust feeding rates can improve feeding efficiency and reduce waste (Clifford 1992, Salame 1993, CP 1993). Effective evaluation of consumption allows the grower to gauge the condition of the animals, population biomass, shrimp distributions in the pond, pond bottom conditions, and diurnal feeding trends. Recent reports document successful application of 100% of the daily ration in trays (Viacava 1995). Using this method, feed conversion ratios were reduced to 0.8:1-1.5:1, (mean 1.2:1) with savings of up to 35% in feed. The author suggests that with 2500 hectares in production locally, feed waste has been reduced by more than 3,000 metric tons per year.

The upper limits of production in the no-exchange system may be determined through nutrient input via the feed, especially feed protein nitrogen. In an unreplicated comparison of 20 and 40% protein feeds, there was little difference in shrimp production in intensive, no-exchange ponds. However, suspended solids were lower in the pond receiving 20% protein feed, suggesting the potential for water quality improvements with low protein feeds without compromising shrimp production (Hopkins et al. 1994b).

Microbial community management

Strategies for management of microbial communities can be generally grouped into three categories: nutrient supplementation, habitat expansion, and application of cultured microorganisms. Nutrient supplements in the form of fertilizers are often applied to increase algal and zooplankton biom-

ass. Fertilizer additions may increase microbial community biomass and activity, possibly resulting in increased nutrient cycling and detritus degradation that may affect shrimp growth. Many pond managers use a combination of organic and inorganic fertilizers to stimulate phytoplankton growth (Clifford 1994). Recent studies have suggested the potential for increasing pond bacterial community activity and abundance through the manipulation of carbon/nitrogen ratios (Avnimelech 1999). In tilapia ponds, the addition of carbonaceous substrates increased bacterial uptake of nitrogen for protein synthesis, thereby reducing ammonia levels. Microbial proteins in turn, were taken up by the target crop, hence growth rates increased (Avnimelech et al. 1994). Thus, efficient use of combinations of fertilizers and labile carbon sources may become a crucial component of future pond management strategies. Overall, optimized interactions between algae and various levels of the heterotrophic community have the potential to increase shrimp growth and production while improving feeding efficiency. Further basic research is necessary to improve understanding of these interactions and of the relative contributions of algal, bacterial, and zooplankton components to shrimp growth.

Expansion of specific habitats can promote microbial processes that are beneficial for pond water quality and natural production. This concept can be applied within the pond, or in a specialized compartment through which pond water is recirculated. Microbial community composition and activity is affected by light intensity and penetration, the relative extent of aerobic and anaerobic regions, and surfaces within these regions. Increasing surface area in the aerobic zone may increase nitrification. With sufficient light penetration, aerobic surfaces may also cultivate periphyton communities. In a tank study conducted at the Waddell Mariculture Center (WMC), increases in surface area in the aerobic light zone caused a shift from phytoplankton dominance to periphyton dominance, the latter of which may include both aerobic and anaerobic niches. Under tested conditions, periphyton dominance significantly improved water quality and shrimp production (Bratvold and Browdy 2001). Increasing anaerobic habitats may be desirable to promote denitrification, generally considered to be the primary biological pathway for nitrogen removal from the pond system.

The addition of bacterial and yeast cultures to ponds is being explored as a tool for managing microbial community composition and abundance (Moriarty 1996, Jory 1998). Product advertisements make a variety of claims including: reduction of nitrate, nitrite, ammonia, hydrogen sulfide, blue green algal growth, heavy metals, organic matter, biological oxygen demand (BOD), and sludge buildup; increase of dissolved oxygen, natural food availability, molting and growth; and inhibition of growth of *Vibrio* spp. and other potentially pathogenic bacteria. Many of the advertised benefits lack confirmation by independent researchers in controlled studies.

Boyd et al. (1984) compared replicate channel catfish ponds treated with a commercial bacterial suspension to control ponds with no bacterial addition. The commercial product was advertised to reduce ammonia, nitrate, and nitrite. No significant differences were found in water quality

parameters including inorganic nitrogen and BOD, and bacterial and algal levels. Using a different product, similar findings resulted from a study in laboratory and pond systems (Chiayvareesajja and Boyd 1993). Hawthorne (1995) tested seven different products in a microcosm system and found no enhancement of removal of total ammonia nitrogen or facilitation of conversion to nitrite or nitrate. Queiroz and Boyd (1998) report a test with a commercial product applied three times per week. Some differences in growth and survival were reported although the mechanism by which the inoculum may have influenced catfish growth could not be explained from the water quality data collected in the study. Unpublished data from a tank study conducted at the WMC suggests that replicate tanks receiving a weekly application of a bacterial product yielded a small, but significant increase in shrimp production and had significantly lower ammonia levels.

Bacterial cultures have also been employed for potential probiotic effects. Applications of non-pathogenic *Vibrio* spp. to shrimp larval cultures have been suggested to control disease, increase production, reduce hatchery down time, and reduce the need for antibiotics (Garriques and Aravalo 1995; Griffith 1995). In theory, the addition of appropriate types of bacteria under the proper conditions (i.e, sufficient amounts, frequency of addition, etc.) may affect species composition through mechanisms such as competitive exclusion. Moriarty (1998) suggests that pond treatment with 10^4 to 10^5 *Bacillus*/ml reduced luminescent *Vibrio* spp. and improved shrimp survival and production. Although control ponds in this study were at a different farm, presumably increasing variability in management protocols, both farms used the same water source. While this study lacks rigorous control, it does suggest potential probiotic effects of the *Bacillus* strains used.

Reproducible and controlled manipulation of pond microbial communities will likely depend upon several basic requirements. First, the pond manager will need the ability to monitor and understand basic ecological processes in the pond. Second, the segment of the microbial community to be manipulated will need to be well defined, along with environmental conditions that promote and restrict the desired processes. Finally, management methods for achieving the desired environmental conditions need development. The eventual success of products and technologies for treating aquaculture systems will likely depend upon an improved understanding of basic pond microbial ecology, the nature of the products used, and the technical skill of the end user.

Waste management

The pond system has a finite capacity to process organic material from plant matter or unconsumed feed. Pond bottom conditions deteriorate over time as organic material builds up. Some evidence indicate that a certain level of anaerobic decomposition on the pond bottom may be tolerated by shrimp because healthy individuals can be found in sludge deposits (Hopkins et al 1994a), and very little hydrogen sulfide has been found free

in the water column (Ray and Chien 1992). On the other hand, significant sludge buildups may negatively affect cultured shrimp populations by increasing BOD, releasing toxic compounds to the sediment and water column, reducing usable habitat, and decreasing availability of natural prey organisms (Boyd and Musig 1992, Chien 1992). Poor growth, disease and mortality have been observed in ponds with relatively good water quality, possibly suggesting that pond bottom condition can be a severe limitation to semi-intensive and intensive shrimp production (Boyd 1991). In some areas it is necessary to remove solids from ponds and supply; if incoming water has high, suspended soil particle concentrations. However, soil analyses suggest that sediment in intensive Thai shrimp ponds was made up of largely mineral soil. In this case, no valid reason for removal of sediment from ponds between crops was found (Boyd et al. 1994). These authors suggest that sediment removal was in fact an environmental hazard and that pond bottoms would be better managed by spreading and drying sediment between crops to oxidize the organic material.

Culture methods have been designed with the goal of removing sludge during the growing season through strategically placed drain ports (Shigueno 1975, Wyban and Sweeney 1991, Clifford 1992, Hopkins 1994, Chien and Liao 1995). Proper removal of sludge during the growout period can extract primarily organic material, entraining little of the initial bottom matter. Water quality effects of sludge removal and options for disposal of waste material have been the subject of recent research (Hopkins et al. 1994a, Hopkins et al. 1997, Holloway et al. 1998). In the study of Hopkins et al (1994a), removal of sludge from a pond appeared to reduce ammonia-nitrogen, orthophosphate and phytoplankton densities while increasing pond dissolved oxygen. In the pond with sludge removed, 67% of the nitrogen added as feed was harvested thereby reducing the impact of drain harvest effluent on the receiving stream.

The environmentally friendly system (EFS) of Hopkins et al. (1997) and Holloway et al (1998) included intensive shrimp culture with water recirculating between three primary and one secondary crop pond, no outside water exchange, and continuous sludge removal. Sludge from this system provided a tertiary crop through its use as an organic fertilizer and soil amendment. Preliminary nonquantitative observations suggest that sludge used as a soil treatment increased biomass and condition of rye grass (Hopkins et al. 1994a). Studies on the practical value of biosolids removed from the EFS suggested potential for use in production of bell peppers in a field situation (Dufault et al. 1998, Dufault and Korkmaz 2000). Water quality, shrimp growth and survival in the EFS were similar in the triplicate control ponds without sludge removal and minimal water exchange. Water quality parameters were also similar suggesting that at the densities tested, a pond with secondary crops and sludge removal may offer little advantage under the tested conditions beyond crop diversification. In theory, as stocking densities and feed inputs are increased past the carrying capacity of the system, waste solid removal may allow further increases in production rates without water exchange (Hopkins et al. 1994a).

Sedimentation ponds could provide another means of reducing the impact of effluents from shrimp ponds. The effectiveness of settling ponds depends upon the particulate size and density of the solids in the effluent, the design and surface area of the settling pond, and the flow or retention time of the effluent. Increasing the length to a width ratio greater than 4, encouraging laminar flow, reducing turbulence, and installing baffles can improve settling efficiency (Pillay 1992). Preliminary results for a prototype commercial scale solids removal system have recently been reported (Woiwode and Rossello 1995). Sludge collected in settling ponds must be removed periodically and disposed in an appropriate manner. Significant amounts of solid and nutrient release at harvest result from physical disturbance of sediments. Thus settlement ponds could be particularly effective when ponds are drained for harvest. At harvest, discharge water laden with suspended particles of soil and organic matter could be clarified through retention (Boyd 1991). Recent research suggests that within 6 hours, 88% of total suspended solids, 71% of volatile solids, 63% of BOD, 31% of total nitrogen and 55% of total phosphorus had been sedimented from the final 20 cm of effluent (Teichert-Coddington et al. 1999). Shrimp pond discharge, particularly at moderate stocking densities, is often dominated by algal solids. (Brune and Drapcho 1991). Algal biomass can have a much slower settling velocity than fecal solids, limiting the effectiveness of settling ponds. Although addition of flocculants has been suggested for fresh water systems, in marine systems excessive levels of metal salts are required (Brune and Hopkins 1990).

Wetland ecosystems have the ability to remove aquatic pollutants through a variety of physical, chemical and biological processes. Constructed wetlands have been shown to have broad applicability as wastewater treatment systems (Hammer 1989). Schwartz and Boyd (1995) evaluated constructed wetlands for treatment of channel catfish pond effluents. Suggested advantages of such wetlands include low cost of construction and operation, elimination of chemical wastewater treatment, stabilization of local hydrologic processes and contribution of excellent wildlife habitat. In addition, the constructed wetlands were shown to efficiently remove potential pollutants from pond water provided that the wetland is large enough for a 2 to 4 day retention time. Organic matter must be removed from the system to achieve mass conservation. This is accomplished simply by cutting off and removing vascular vegetation. The system must be designed in such a way that vegetation cutting equipment can access the site. The area required in constructing a wetland for channel catfish ponds was calculated by Scwartz and Boyd (1995). These authors conclude that the disadvantage in using constructed wetlands for treating aquaculture pond wastes is the large amount of space necessary. However, there may be some potential in using constructed wetlands to treat effluents from low exchange production systems or effluents high in potential pollutants associated with the final stages of pond drain harvests.

The culture of bivalves in conjunction with shrimp could also have several potential advantages. Bivalves are able to remove algae and fine sus-

pended solids from the water column for deposition in oyster biomass or settleable feces and pseudofeces. The bivalves may also provide a valuable secondary crop while sharing many of the production inputs including feed, water, energy and ponds (Wang 1990, Wang and Jakob 1991). Biological feasibility and potential water quality advantages of such polyculture have been reported by a number of investigators (Shpigel and Fridman 1990, Shpigel and Blaylock 1991, Hopkins et al. 1993b, Jakob et al. 1993, Enander and Hasselstrom 1994). However, the economic feasibility of large-scale implementation of mollusk/shrimp biculture has not yet been demonstrated. Furthermore, issues related to shellfish sanitation and the acquisition of permits for the sale of bivalves reared in pond effluents must be resolved.

Other bio-filtration systems have been proposed for reducing dissolved ammonia and nitrate in aquaculture effluents. Seaweed culture has been shown to be an efficient means of removing high concentrations of nutrients in the environment (Pillay 1992). The potential of the seaweeds *Ulva lactuca* and *Gracilaria* sp. as a biofilter for effluents of intensive aquaculture ponds has also been demonstrated (Cohen and Neori 1991, Neori et al. 1991, Enander and Hasselstrom 1994). Promising preliminary results have also been reported for a biofiltration media system integrated into a canal adjacent to a one-hectare shrimp pond (Woiwode and Rossello 1995).

Interest in the testing and implementation of closed and semi-closed system designs is increasing (Fast and Menasveta 1998). A model system has been designed and tested for an integrated fish, bivalve and seaweed culture system in Israel (Shpigel et al. 1993). In this model system, particulate and dissolved metabolites from marine fish culture are removed by biofilters of bivalves and seaweeds. In the model, fish yield accounts for 26% of the nitrogen introduced in the feed; bivalve yield, 14.5%; seaweed yield, 22.4%; settled feces, 32.8%; and suspended and dissolved discharge back to the sea, only 4.25%. A similar wastewater treatment system has been described for a shrimp farm in Malaysia (Enander and Hasselstrom 1994). After a one-month trial, the authors reported an 83% reduction in phosphate; 61% in total phosphorus; 81% in ammonium; 19% in nitrite; and 72% in total nitrogen in the effluent. In some areas environmental deterioration and associated disease problems have led to the suspension of previously successful shrimp production. To overcome these problems, large-scale water recycle systems have been implemented (C.P. 1994). In this system, all seawater is chemically disinfected before use. Growing area was reduced and allocated to water treatment ponds with approximately one ha of water treatment for each ha of grow out area. Water treatment during culture is accomplished with sedimentation ponds, herbivorous and omnivorous fish ponds, and aeration ponds. If phytoplankton concentrations become excessive, water is treated with benzalkonium chloride at 1 to 2 ppm to reduce densities. Zoothamnium is controlled using formalin at 15 to 20 ppm. Ammonia concentrations do not become limiting when the system is operating correctly.

Conclusion

A combination of factors has accelerated the commercial application of improved water management regimes. Environmental groups have targeted marine shrimp farming putting increasing pressure on the industry to adopt more sustainable production practices (Goldberg and Triplett 1997, D' Abramo and Hargreaves 1997). Problems with viral diseases have forced growers to limit water inputs to prevent introduction and spread of pathogens (Flegel et al. 1997). Large scale application of zero exchange and recirculation technologies on existing farms have increased producer confidence in and awareness of the potential for reducing or eliminating routine water exchange through most or all of the growing season.

Environmentally and socially sustainable shrimp farming need not impose an insurmountable burden on growers and may in the long-term be the economic interest of shrimp producers. Moderating stocking densities can significantly reduce financial risks while improving long-term crop health and farm conditions. Reduced water exchange results in cost savings in terms of pumping and energy costs. Efficient use of feeds and cost effective formulations for high quality feeds with lower animal protein content reduces overall feed costs. Improving efficiency of pond microbial communities can result in better growth and improved recycling of waste material within the pond system. Development of eco-labeling and potential price advantages for products produced in progressively managed, environmentally friendly systems will reinforce these trends. Thus, the continued development and application of progressive proactive management strategies in an overall framework of good basic husbandry practices will offer new opportunities for improving environmental sustainability of shrimp production while providing opportunities for maintaining or improving overall profitability.

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