

Using the Pond as a Biofilter: Review of Theory and Practice

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ABSTRACT

Intensive aquaculture systems are being used to efficiently produce fish and shrimp. However, an intrinsic problem of these systems is the rapid accumulation of feed residues, organic matter, and toxic inorganic nitrogen species. This cannot be avoided, since fish assimilate only 20-30% of feed nutrients. The rest is excreted and typically accumulates in the water. Often, the culture water is recycled through a series of special devices (mostly biofilters of different types), investing energy and maintenance to degrade the residues. The result is that in addition to the expense of purchasing feed, significant additional expenses are devoted to degrade and remove two-thirds of it.

There is a vital need to change this cycle. One example of an alternative approach is active suspension pond (ASP) systems where the water treatment is based upon developing and controlling heterotrophic bacteria within the culture component. Feed nutrients are recycled, doubling the utilization of protein and raising feed utilization. Other alternatives, mostly based upon the operation of a water treatment / feed recycling component besides the culture unit, are also relevant.

Active suspension ponds are being practiced and their numbers have increased dramatically during the last 10 years, most notably with shrimp culture. The purpose of this paper is to raise discussion on alternative routes to the classical recycling approach.

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INTRODUCTION

There is a natural desire to achieve higher and higher yields. However, getting listed in the *Guinness Book of World Records* is not the goal of an aquaculture business. The justification for intensification stems from specific culture, environmental and economic reasons. Several reasons for intensification, listed here, have different priorities under different conditions.

1. Environmental regulation prohibiting or limiting water use and disposal.
2. Biosecurity concerns limiting water intake.
3. Water scarcity or cost. Conventional aquaculture usually uses 2-10 m³ water to produce 1 kg fish. In Israel, for example, water costs are rising to ~0.4/m³ (US\$), i.e., 0.8-4.0 \$/Kg fish.
4. There is a demand for product quality control and transparency, which are otherwise difficult to achieve in intensive systems.
5. Feed utilization may be higher than in conventional systems.
6. In cases where production occurs close to a major market, space limitations are also of concern.
7. Intensification enables easier temperature control.
8. Intensification and automation may save labor costs.

However, intensification costs money, and is not always the recommended mode of development.

DISCUSSION

Development and Modes of Intensive Aquaculture Systems

The evolution of pond intensification can be better seen in perspective by looking at the whole spectrum of pond intensity, as given in Table 1.

Feed, generally, did not limit fish growth once fed ponds were introduced. The limiting factor in fed ponds was usually early-morning low oxygen conditions. With aeration, though partial and not aerating the whole pond area and volume, there is enough oxygen to support the fish, and it can usually be assumed that oxygen is not a limiting factor. The next limitation is the high rate of organic matter accumulation on the bottom of the pond,

development of anaerobic conditions and production of toxic metabolites (Avnimelech and Ritvo 2003), retarding further intensification. This was overcome by thoroughly mixing the pond and aerating it 24 hours/day, enabling growers to raise yields to levels of up to 100 kg m⁻³.

Fish (and shrimp) can be grown at very high density in aerated – mixed ponds. However, with the increased biomass, water quality becomes the limiting factor due to the accumulation of toxic metabolites, the most notorious of which are ammonia and nitrite. To realize the potential of aerated – mixed ponds, water quality has to be controlled.

Three different approaches can be used to control water quality:

- (a) Replace pond water with fresh water, usually at exchange rates of over five times a day. This option, though, is in conflict with environmental constraints, biosecurity needs, and water-scarcity issues.

Table 1. Levels of pond intensification: Schematic representation.

POND TYPE	HUMAN INTERVENTION	Approximated YIELDS (kg/ha*yr)	LIMITING FACTOR
Minimal feed	Feeding with grain, farm & home residues. Fertilizers	2,000	Limit of primary productivity. Food chain efficiency
Fed Ponds	Feeding by complete diet pellets	4,000	Night time oxygen deficiency
Night time aeration	Night time or emergency aerators ~1-5 hp/ha	10,000	Sludge accumulation. Anaerobic pond bottom
Intensive mixed –aerated ponds	24 h/day aeration (~ >20 hp/ha), constant and full mixing	20,000 – 100,000	Water quality control

- (b) Recycle the water through an external unit (“biofilter”) that treats and purifies the water.
- (c) Treat water quality within a pond system, using algae in partitioned aquaculture ponds, (Brune *et al.* 2003) or bacterial communities (e.g. active suspension ponds, ASP).

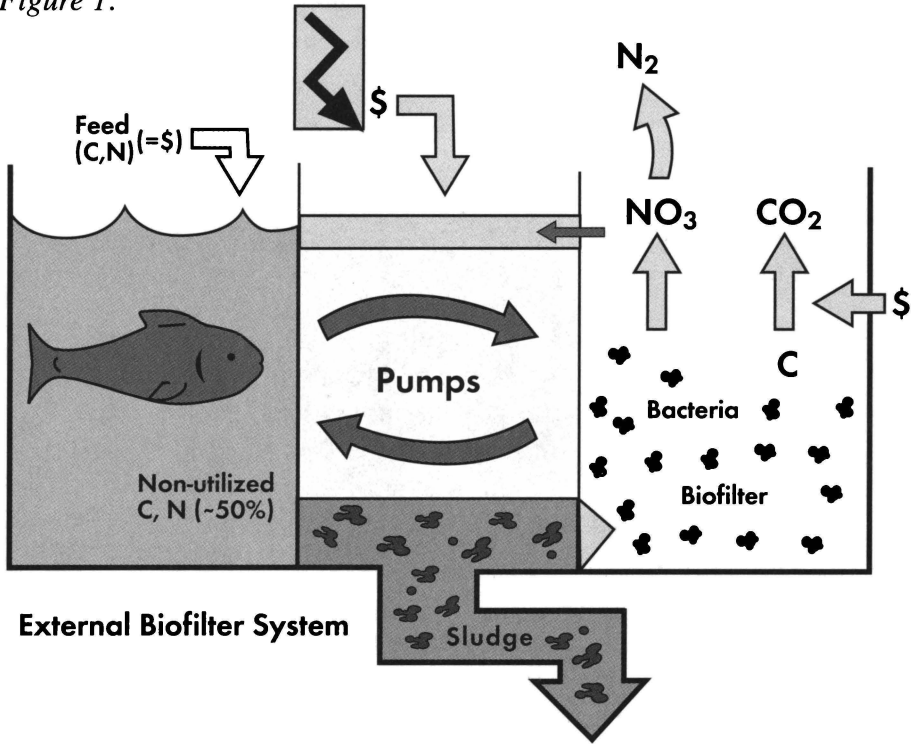
The use of external biofilters (schematically shown in Figure 1) has been practiced for years in hatcheries, nurseries, culturing of ornamental fish, and to some extent, in culturing of commodity fish. These systems are operative, well-tested, proven, and can be obtained commercially. However, they are quite costly, both in investment and in operation. As an example, we can compare wastewater treatment plants’ required biofiltration capacity. Taking an average chemical oxygen demand (COD) in raw municipal wastewater as 600 mg/l and wastewater production of 300 l/capita x day, we get a COD release of 180g/capita x day. A town of 10,000 inhabitants has to treat 1800 kg COD/day. In an equivalent fish farm, about 20kg feed is given per ton of fish each day. About half of it is released to the water, i.e. 10 kg COD/ton x day. A fish farm holding 180 tons of fish emits about the same load as the 10,000-inhabitant town. Moreover, the standards and demands in fish water treatment are generally higher than in wastewater treatment. The latter releases treated water having more than 10 mg total ammonia nitrogen (TAN) per liter, while in fish farming, less than 1mg/l is standard (in Israel).

An additional basic feature of the “biofilter” approach is the rapid removal of feed residues. According to classical biofilter design parameters, one removes unused feed or feed residue as fast as possible, in contrast with the “in pond” method, which strives to recycle the non-utilized feed as much as possible.

Research efforts of the last decades were (and are) directed to lower the cost of biofilter systems, raise the efficiency of water treatment, oxygen introduction, and utilization of energy input. Efforts to maximize feed utilization and recycling have been meager. Yet, feed cost is the biggest component in the cost of producing fish in intensive systems.

Intrinsic features of intensive ponds are high aeration rate and thorough mixing. These features, obtained as existing features of the pond, are the ones that we find in almost all biotechnological industries as features maximizing the activity of microorganisms. An additional characteristic that encourages microbial dominance in intensive ponds is the

Figure 1.

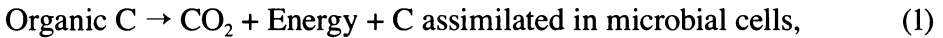


accumulation of organic substrates in zero or limited exchange ponds. The organic residues mixed in the water serve as a growth substrate for bacteria, leading to a transition of the pond to a more and more heterotrophic system. Achieving high heterotrophic biomass and providing optimal conditions toward their activity is an intrinsic trait of intensive ponds.

The Nitrogen Syndrome

An intrinsic problem in intensive ponds is the nitrogen syndrome. Inorganic nitrogen accumulates in the pond due to several reasons. Fish metabolize proteins as an energy source (Hepher 1988), leading to the excretion of ammonia that accumulates in the pond. Moreover, while organic carbon in the pond is metabolized to CO₂ that leaves the pond to the atmosphere, the transformation of inorganic nitrogen is not effective in getting the nitrogen out of the system (unless intensive nitrification and subsequent denitrification take place). As a result, the C/N ratio continually narrows with intensification and time, with the result that toxic ammonia and nitrite levels may endanger fish growth and health.

The nitrogen syndrome can be controlled by utilizing the microbial system that exists in intensive ponds. A straightforward solution is to raise the C/N ratio, counteracting the nitrogen deterioration trend. Adding carbon-rich and nitrogen-poor feed, the following processes take place (Avnimelech 1998):



where the ratio of C assimilated to the organic carbon metabolized is defined as the microbial efficiency (E).

For the creation of new proteinaceous cell material, microorganisms need to take up inorganic nitrogen (preferably ammonium). Adding carbonaceous material (CH) leads to the immobilization of inorganic nitrogen into the microbial protein pool (Equations 2 and 3).

$$\Delta C_{\text{mic}} = \Delta \text{CH} \times \% \text{C} \times E \quad (2)$$

$$\Delta \text{N} = \Delta C_{\text{mic}} / [\text{C/N}]_{\text{mic}} = \Delta \text{CH} \times \% \text{C} \times E / [\text{C/N}]_{\text{mic}} \quad (3)$$

where ΔCH is the amount of carbohydrate fed into the pond, ΔC_{mic} is the amount of carbon assimilated in microbial cells, $\% \text{C}$ is the percentage of carbon in the added feed, and $[\text{C/N}]_{\text{mic}}$ is C/N ratio in the microbial cells.

The amount of carbonaceous feed needed to remove one unit of inorganic nitrogen, ΔN , following Equation 3 (using approximate values of $\% \text{C}$, E, and $[\text{C/N}]_{\text{mic}}$ as 0.5, 0.4 and 4, respectively) is:

$$\Delta \text{CH} = \Delta \text{N} / (0.5 \times 0.4 / 4) = \Delta \text{N} / 0.05 \quad (4)$$

The equations given here, as well as others defining microbial kinetics and input-output data were used to model nitrogen transformation in active suspension ponds (Kochba *et al.* 1994). Nitrogen control using carbon addition is predictable and controllable. A more comprehensive modeling effort has been initiated by Bergeron *et al.* (2004), a model covering both carbon and nitrogen fluxes in ASP. Inorganic nitrogen in intensive ponds, through the manipulation of C/N ratio, is easily controlled, predictable, and inexpensive as cheap carbohydrates can be used.

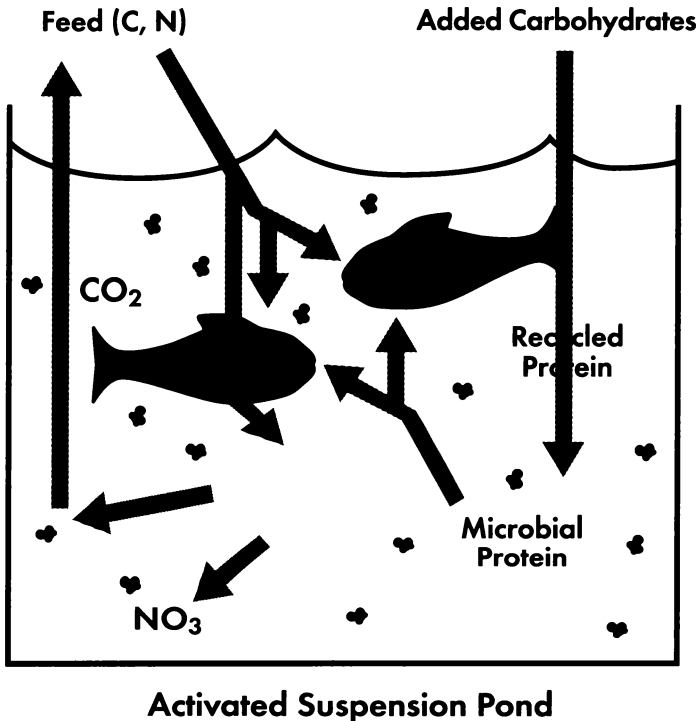
In addition to controlling inorganic nitrogen concentrations in the pond, the uptake of nitrogen by bacteria is in essence a process that enables the recycling of protein. The ammonium excreted as a waste material of the fed protein is reclaimed as microbial protein. The microbial biomass, when aggregated as microbial flocs, is a good source of protein for tilapia and

shrimp. Both McIntosh (2001) and Avnimelech *et al.* (1994) found that the utilization of protein, conventionally around 25% (Boyd and Tucker 1998), increases to about 45% in both shrimp and tilapia ASP ponds.

These findings were further elaborated by studying floc formation and characteristics in very detailed works published by Tacon and co-workers (Decamp *et al.* 2003, Tacon *et al.* 2002). It was found that there is more than 30% protein in the flocs, containing essential amino acids in sufficient quantities. In addition, it was demonstrated that the microbial flocs contain vitamins and trace metals, enabling emission from the feed, saving a significant fraction of the feed cost.

An important contribution to our understanding of ASP systems was made by the works of Burford and co-workers (2003) based on detailed studies of ponds in Belize. The uptake and utilization of microbial flocs by shrimp was evaluated using N^{15} -tagged flocs (Burford *et al.* 2004). The proportion of daily nitrogen uptake of the shrimp contributed by the natural biota was calculated to be 18-29%. Similar, though qualitative, results were found by Avnimelech *et al.* (1989), derived from the evaluation of the C^{13}/C^{12} ratios in feed and tilapia muscle samples.

Figure 2.



The utilization of microbial flocs as a source of feed protein leads to a lower expenditure on feed. Avnimelech reported that feed cost for tilapia production was reduced from \$0.84/kg of fish in conventional ponds to \$0.58 in ASP. McIntosh (2001) reported that feed cost using the reduced protein diet in Belize ponds is about 50% as compared to conventional shrimp farming.

Protein is an expensive feed component. Generally, it is at least partially made of fish meal, a component that is becoming increasingly scarce as concerns increase over environmental damage and overharvesting in the oceans. The fact that protein utilization rises from 15-25% in conventional ponds to 45% in ASP is very important economically and environmentally.

The transition from algal-controlled conventional ponds to ponds with heterotrophic bacterial control has many implications. Algal activity is sensitive to environmental conditions, firstly to fluctuating light intensity. Heterotrophic bacteria are less dependent on environmental variability in ponds (Avnimelech 2003). The transition toward heterotrophic systems enables better control of the pond and is in essence a transition toward the change of aquaculture to a biotechnological industry. As an industry, it should follow a clear set of design parameters. Detailed ones have not been developed yet, but there are clear principles that should guide design of ASP ponds. Oxygen should not be a limiting factor. Aeration capacity on the order of 30 hp/ha is commonly used in shrimp ponds (ca 1 hp per 500 kg shrimp biomass), and higher aeration (more than 100 hp/ha) for more intensive tilapia ponds. In southern California, it was found that using pure oxygen may be more economical than using aerators (Dean Farrel, Seagreen Assoc., personal communication); however, this can be different in places where pure oxygen is more expensive. Ponds should be perfectly mixed, avoiding any stagnant zones where organic sludge might accumulate. Presently, the best aeration/mixing devices are paddle wheel aerators, placed radially in the pond, at a distance from the dikes of about one third the pond width. Aspirator-type aerators (or air lifts in small ponds) should augment the paddlewheels, in such a way that sludge settling near the center of the pond is resuspended. However, there is a need for aerators that are better designed and adjusted to ASP demands. Aerator placement and pond design should be made to prevent the formation of sites in the pond where sludge accumulates. However, it is difficult and not desired to resuspend the full amount of sludge generated. There is a need to concentrate the excessive sludge at a point in the pond and to drain it out. The common way to do it is by constructing

a sludge disposal pit in the center of the pond and periodically draining it. Sludge is drained daily (Avnimelech 1999), or even more frequently, in tilapia ponds and about weekly in shrimp ponds (Burford *et al.* 2003).

Size of intensive ponds varies from few dozen square meters to almost 2 ha. It is more difficult to control large ponds, yet, as demonstrated by Belize Aquaculture, it is possible to properly manage 1.6 ha ponds.

Anticipated Future Developments

How will ASP look in another 10 years? According to what we know of present plans to construct such ponds worldwide, it seems that in another 10 years, we will have many such ponds and vast practical information will be collected.

On initiating and developing ASP systems, the overall microbial activity has been considered, but very little is known as to the details of the relevant microbes and microbial ecology. Work done by Burford *et al.* (2004) and by Tacon *et al.* (2002) initiated efforts to better understand and control the microbial processes. McIntosh (2001) started with the selection of bacteria that form flocs. It is anticipated that with interest in ASP more studies will be made and more insight will be obtained. Specifically, it is anticipated that more control of floc formation will be obtained, in line with similar work done in water treatment technology.

Feeds and feeding of ASP systems are in their beginnings. We need specially formulated feeds with lower protein. Panjaitan (2004) recently demonstrated that the feed requirement in ASP shrimp systems is just about 70% of that needed in open systems where feed is not recycled and the non-eaten portion is wasted. Better and more accurate feeding schemes will be obtained. Adjusting the C/N ratios in feed has been done either empirically or based on approximated assumptions. Protein use efficiency was raised from 25% in conventional ponds to about 45% in ASP. Yet, obtaining more accurate data and modeling of pond dynamics will probably further raise protein utilization efficiency. The lower feed quantity required and lower cost of feed due to lower protein requirements and avoidance of vitamin and mineral inclusion in the feed will raise profitability when using ASP systems.

ASP systems are turbid. Turbidity can be controlled by mixing and through drainage of excess suspended matter. Presently, we do not know the optimal level of suspended matter in the water. This may well be

different for different species grown. It is rather easy to automatically control total suspended solids (TSS), probably using turbidity as a signal. Ponds can be drained so as to maintain roughly constant turbidity. Efficient resuspension, mixing, and draining of ponds call for use of efficient aerators – ones that will be better adapted as compared to ones we have presently – and to pond structures that assist efficient mixing and drainability.

A problem common to intensive and other ponds is the need to properly dispose or utilize the washed-out sludge. Until recently, many fish and shrimp farmers disposed of sludge in estuaries, the ocean, or in mangroves. However, this is no longer accepted, both due to environmental considerations and aquaculture disease prevention. We have learned to recycle the water from ponds. There is an urgent need to either recycle or properly dispose of the sludge. Among possible options is its reuse as an organic-rich amendment to ponds or agricultural soils, as a base material for composting or as a material for construction, either as such or following sanitation and stabilization processes (Eaton 2004, Evanylo *et al.* 2004, Marsh *et al.* 2004).

With the rise in number of ASP systems, there is a need to develop means to commercially construct ponds. Presently, each farm has its special design, materials and operation protocol. Clearer methods will have to be developed in order to support a mass of such ponds. Possibly, companies that plan, produce components and construct such ponds will rise. Presently, operating ASP demands a thorough understanding of the system and a long learning process by the operators. Modeling efforts, building on what was presented initially by Bergeron *et al.* (2004), will enable a more user-friendly routine to operate such ponds.

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