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WATER QUALITY MANAGEMENT IN IN-POND RACEWAY SYSTEMS

by

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The US Soybean Export Council has been promoting In-Pond Raceway System (IPRS) technology since 2013. The IPRS is a type of partitioned pond system, the basic concepts of which were developed more than 30 years ago. In conventional ponds, the functions of fish containment, oxygen provision and waste treatment are combined. In partitioned ponds, the fish containment function is separated from oxygen provision and waste treatment functions. The area required for fish containment is far less than the area required to treat the wastes generated by high-density fish culture. Partitioned ponds also require some method to move water between the fish holding area and the waste treatment area. In the IPRS, water is moved with airlift pumps.

For purposes of this white paper, the fundamental rules of IPRS design applies. The basic unit consists of one raceway (22 m long × 5 m wide × 2 m deep) per 10,000 m^3 of system volume. Each raceway includes an airlift pump spanning the width of the raceway and one additional airlift pump in the open pond area for water circulation. A commercial unit would consist of three such raceways in 30,000 m^3 of system volume with three airlift pumps in the open-pond area to effect water circulation.

This white paper will review oxygen supply and raceway carrying capacity, solids capture in quiescent zones and open pond water quality. It must be emphasized that the information on water quality available to support the analysis presented here is rather limited. Where available, field experience with commercial IPRS projects in Latin America and Asia was used to provide examples and indications.

Oxygen Supply and Raceway Carrying Capacity

The heart of the IPRS is the airlift pump, also known as a “whitewater unit” (WWU). At the bottom of the unit is a horizontal grid of lengths of porous diffuser tubing extending across the width of the unit (front-to-back orientation). The diffuser is connected to a PVC pipe manifold that is in turn connected to a 1.5-hp regenerative blower. A curved or angular shield functions to deflect the rising column of bubbles and water and direct water flow horizontally along the water surface.

In operation, the blower creates a flow of air that is forced through the lengths of porous tubing. The bubbles created by this process rise to the surface. Like all airlift pumps, the density of the air-water mixture in the water column above the diffuser grid is lower than the density of water (with no air bubbles) below the diffuser grid. In response to the density gradient, water moves from the high density to low density area, creating water flow. At the water surface, the deflector shield directs the rising vertical column of water in a horizontal direction. The flowing water then enters the raceway and displaces previously pumped water in a downstream direction away from the airlift pump.

There are two aspects of airlift pump performance: water pumping or flow rate (water volume per unit time) and aeration rate (oxygen transfer per unit time). The oxygen supply rate can then be calculated on these measures of airlift performance as water flow rate times dissolved oxygen concentration rate.

Water Pumping Performance

Airlift pumps have been used in many aquaculture applications, particularly in recirculating aquaculture system designs that are operated with low head (<30 cm) water circulation. The design of "Model Trout Farms" in Denmark that recirculate water within trout raceways operated using airlift pump configurations similar to those applied in the IPRS.

Good performance of conventional pipe-based airlift pumps operate with a gas-to-liquid (G/L) ratio of 1. A 1.5-hp Sweetwater-brand regenerative blower produces 100 cfm (2.83 m^3/min) at a water depth of 30 inches. Thus, the expected flow rate using a G/L of 1 is 2.83 m^3/min. However, water flow estimates determined empirically are greater, ranging from 10.6 to13.4 m^3/min (Reinemann and Timmons 1988) and 16.3 m^3/min (Smith 2021).

However, measurements of water velocity collected in IPRS raceways indicate a range of approximately 5-10 cm/sec, equivalent to water flow rates of 30-60 m^3/min. This is 2-3 times greater than the water flow rates generated by individual airlift pumps and far greater than the performance expected from an airlift pump with a G/L ratio of 1. This unexpectedly high water pumping rate associated with operation of airlift pumps should be interpreted with respect to the deployment and operation of all airlift pumps working together. In addition to three airlift pumps – one each at the head of each raceway – there are three or four additional whitewater units that are placed at intervals around the pond perimeter. It is operation of all of these aerators simultaneously that results in water flow rate through each raceway of 30-60 m^3/min. Anecdotally, this characteristic is supported by observation of water flow if operation of airlift pumps cease. In that circumstance, water flow will continue for 1-2 hours until the momentum of moving water dissipates.

Assuming a current velocity of 5-10 cm/sec in raceways (22 × 5 × 2 m) and ideal plug-flow conditions, this results in a hydraulic retention time (HRT) of 3.7-7.3 min, equivalent to 8.2-16.4 volume exchanges per hour. This exchange rate is certainly sufficient to flush wastes generated from feeding from raceways into the open pond and avoid accumulation of any potentially toxic fish metabolites.

Water flow is affected by characteristics of the blower and a host of other factors. Blower characteristics that affect air flow rate include blower model/brand, power (based on raceway width), depth of the diffuser grid, uniformity of diffuser grid depth and blower filter cleanliness. In general, there is an inverse relationship between depth and air flow rate indicated by the performance curve that is characteristic for each model of blower. Bubble size also has some effect on water flow rate, with larger, coarse bubbles better for generating water flow and smaller bubbles better for oxygen transfer. To some extent, the shape or angle of the deflector hood will affect water flow rate, with a sweeping curve providing the most efficient design. Other factors that affect water flow rate include fish species and density, the mesh size and maintenance of fish retention screens, position of the baffle in the open pond, operation of the supplemental air system, pond obstruction such as submerged aquatic plants, the proximity of raceways to pond embankments and the position of knee walls within raceways.

Water flow is also affected by the characteristic of introducing water flow at the water surface at the head end of each raceway. Although most of the flow is unidirectional, resulting in plug flow conditions downstream of water introduction, there is also an area of water flow near the raceway bottom at the head end of the raceway where water is flowing in the opposite direction of the majority of the flow. This so-called "reflux" flow can account for approximately 38% of the total flow introduced to the raceway (Li et al. 2019).

Aeration Performance

The airlift pump is also a type of diffused aerator. Oxygen transfer is effected by diffusion from air trapped inside bubbles to the water across the gas film layer, the liquid film layer and then into the bulk water, known as the two-film theory of gas mass transfer. Compared to other types of aerators, diffused aerators are somewhat less efficient, in part because the retention time of bubbles in the water column is <10 sec. The standard aeration efficiency (SAE) of diffused aerators ranges from 0.7-1.2 kg O_2/hp hr (Boyd et al. 2018). However, in aeration tests of an airlift design similar to those used in the IPRS, using Aero-Tube TM Colorite tubing, the SAE in fresh water is around 2.5 kg O_2/hp hr, which is quite excellent for a diffused aerator. Interestingly, the SAE of this unit increases with salinity.

In general, dissolved oxygen concentrations in raceways are not appreciably different from those measured in ponds. However, average daily dissolved oxygen concentration is slightly but consistently greater in raceways than in the open pond, suggesting a net addition of oxygen to water as it is introduced to raceways. The pattern of daily dissolved oxygen concentration in ponds indicates hypereutrophic conditions, with minimum dissolved oxygen concentration reaching critically low levels in the morning and maximum dissolved oxygen concentration reaching supersaturated conditions in the late afternoon.

Whitewater airlift units operate continuously but the rate of oxygen transfer depends, as it does with all aerators, on the difference between the prevailing dissolved oxygen concentration in the pond and the dissolved oxygen concentration at saturation, which is a function of temperature, salinity and pressure. Whitewater units can add about 2 mg/L when dissolved oxygen concentration is around 0 mg/L and 1 mg/L when dissolved oxygen concentration is around 2 mg/L (Holland 2016). At Demo Farm A in Thailand, a brackish water (up to 9 ppt salinity) IPRS system, whitewater units can add around 0.5 mg/L when dissolved oxygen concentration is about 1.5 mg/L. In general, operation of whitewater units can prevent dissolved oxygen concentration in raceways from reaching less than 2 mg/L.

In the afternoon, when dissolved oxygen concentration in the open pond is at maximum, two processes can affect dissolved oxygen concentration in raceways. In one scenario, operation of whitewater units when open pond water is supersaturated results in off-gassing of dissolved oxygen and dissolved oxygen concentration in raceways can be slightly less than in the open pond. In another scenario, from Demo Farm A Farm in Thailand, dissolved oxygen concentration in the open pond in the afternoon did not exceed saturation and dissolved oxygen concentration in raceways was reduced by about 1.5-2 mg/L by respiration of the fish biomass associated with cumulative feeding.

Raceway Carrying Capacity

Combining information about pumping and aeration performance of whitewater airlift pumps can be used to estimate the carrying capacity of fish raceways. In principal, oxygen supply must match oxygen demand to support the fish crop. Oxygen supply can be calculated as dissolved oxygen concentration times water flow and oxygen demand can be calculated on the basis of published estimates of fish respiration rate.

Carrying capacity (kg/m^3) = ($DO_{in} \times Q_{in}$) / ($R_f \times V$)

where DO_{in} is the dissolved oxygen concentration of inflowing water in mg/L or g/m^3, Q_{in} is the water flow rate in m^3/hr, R_f is the fish respiration rate (assumed to be around 200 mg O_2/kg fish hr) and V is the raceway volume (220 m^3).

DO (mg/L)	CC @ 5 cm/sec (kg/m^3)	CC @ 10 cm/sec (kg/m^3)
1	41	82
1.5	61	123
2	82	166
2.5	102	205
3	123	246

The table provides an indication of the fish biomass density that can be supported by the oxygen supply at various inflowing dissolved oxygen concentrations. Assuming an inflowing dissolved oxygen concentration of 2 mg/L and a current velocity of 5-10 cm/sec (equivalent to a flow rate of 30-60 m^3/min), the fish biomass density that can be supported is between 82 and 166 kg/m^3. This is consistent with the carrying capacity of raceways between 100 and 150 kg/m^3 based on field experience. Obviously, if the dissolved oxygen concentration of inflowing water is greater than the critical or limiting values indicated in the table, more fish biomass can be supported by the available oxygen supply.

This simple model assumes that all the oxygen supply is available to support the fish biomass, resulting in a dissolved oxygen concentration in water leaving the raceway of 0 mg/L. Clearly this is an erroneous assumption and only a portion of the inflowing oxygen is available to support fish respiration. Dissolved oxygen concentration in water leaving the raceway must be above some specified critical level (e.g., 2 mg/L). The values in the table above should be considered as the excess above the critical threshold that is available to support fish respiration.

Sufficiency of Installed Aeration Capacity

Shrimp producers in Asia using intensive ponds apply a general rule that installed aeration capacity of 1 hp of Asian-style paddlewheel aerators can support 400-500 kg of shrimp. For finfish, this ratio is likely higher, in the range of 600-800 kg/hp. Intensive shrimp ponds in Asia have installed aeration capacity of 20-50 hp/ha. In contrast, the IPRS, with three whitewater airlifts at the head of each raceway and 3-4 additional units in the open pond, have installed aeration capacity of 6-10 hp/ha, resulting in an installed aeration capacity ratio of 800-1000 kg/hp. This indicates either highly efficient use of installed aeration capacity or insufficient aeration for levels of fish production attained. Field experience indicates that ponds can be chronically undersaturated when fully loaded, suggesting that ponds are under-aerated. On the other hand, removal of solids (discussed below) can reduce feed oxygen demand and thereby increase the efficiency of installed aeration capacity. Additional research is needed to evaluate these mechanisms in IPRS.

Installation and Maintenance Issues

Given the importance of the whitewater airlift units in the circulation and aeration of water in the IPRS, proper operation is essential for optimum performance. In terms of installation, whitewater units can be fixed or floating, although floating is preferred to maintain a constant submergence depth of the diffuser grid. With a fixed installation, slight changes in water depth can have a profound effect on air flow rates and hence performance. It is important to place the diffuser grid in such a way that all diffuser tubing is at the same level. If not, more air will be emitted from parts of the grid that are more shallow, where there is less resistance from hydrostatic head pressure. Selection of the type of porous diffuser tubing is important because performance varies by brand.

Over time, fouling of diffuser tubing will occur. Given the nutrient rich aquatic environment, bacteria will grow adjacent to pores of diffuser tubing, eventually leading to clogging. This effect is exacerbated in waters with high hardness levels. Some types of whitewater airlift units have modular diffuser grids that can be easily exchanged once biofouling has occurred. Performance of the whitewater unit should be monitored regularly and diffuser grids replaced as needed. Removed grids can be maintained by hand removal of biofouling, pressure washing, soaking in disinfecting solution and drying.

Solids Capture in Quiescent Zones

Considering the fate of the feed added to ponds, approximately 20-25% of the dry matter of feed is converted to fish that is harvested. Another 35-40% of the dry matter is consumed during respiratory metabolism of the fish. The remaining 30-35% of the dry matter is excreted as fecal solids, which can be partitioned approximately equally between settleable and non-settleable solids. Thus, in general, about 20% of the feed dry matter (200 g/kg feed) is released as settleable solids. These are the solids that are the target to capture and remove from the IPRS.

The main feature used to collect settleable solids in IPRS are quiescent zones (QZ), which are simply extensions of fish raceways that are demarcated by fish retention screens that prevent fish from gaining access to the QZ. In this way, solids can settle without interference from swimming fish. Quiescent zones extend from 1-5 m from the end of the fish raceway and include a weir (knee wall) adjacent to the QZ outlet that encourages further settling. Solids have also been captured in settling cones, but these are not in widespread use.

Once solids have settled, they can be removed from the system. Various mechanical solids collection systems have been used, most using some kind of vacuum system, operated either manually or automatically. There is considerable uncertainty regarding the quantity of solids relative to the feeding rate that are removed using these mechanical solids collection systems. More data needs to be collected to understand the average and range of performance of solids collection systems. One of the keys to success of the IPRS is the capacity to remove solids before their decomposition exerts an oxygen demand in the system.

To determine the size of the smallest particle captured by quiescent zones, a simple equation that relates particle size to water flow rate and quiescent zone area was used.

$$Vsc = Q / A$$

Where Vsc is the critical settling velocity of the particle, Q is the water flow rate and A is the quiescent zone area. Water flow rate was determined on the basis of raceway current speed (5-10 cm/sec), equivalent to 30-60 m^3/min, as discussed previously. The quiescent zone area was calculated on the basis of raceway width (5 m) and depth (2 m) for quiescent zones of lengths ranging from 1 to 5 m. This model assumes ideal settling conditions, an assumption that is likely violated, resulting an overestimation of the particle size captured. Critical settling velocity (Vsc) is also equivalent to the overflow rate, which is the basis for the criteria used to design sedimentation basins.

L of QZ (m)	V_{sc} @ 5 cm/sec (cm/sec)	V_{sc} @ 10 cm/sec (cm/sec)
1	10	20
2	5	10
3	3.3	6.6
4	2.5	5
5	2	4
6	1.7	3.3

The table indicates the expected trend that the size of the largest particle captured by a quiescent zone decreases as the length of the QZ increases and the flow rate decreases. The settling characteristics of fecal solids vary by fish species, size and diet formulation. Species like tilapia release fecal strands that may float, negatively impacting their capacity to settle. The settling velocity of fecal solids from rainbow trout is about 2-5 cm/sec and 90-95% of settleable solids from rainbow trout raceways can be captured in a sedimentation basin with an overflow rate of 4.2 cm/sec. The table indicates that, for a current velocity of 10 cm/sec, this overflow rate requires a QZ length of at least 5 m. Design criteria published by the Western Regional Aquaculture Center (2000) for trout raceways indicates that QZs should have an overflow rate less than 1 cm/sec. Taken together, these results suggest that QZs should be at least 5 m and that solids capture in QZs with lengths less than 5 m is minimal. For all sedimentation basins, there is a minimum overflow rate that results in the capture of a relatively large proportion of total solids (around 4 cm/sec). Reducing the overflow rate by increasing QZ length results in diminishing returns with respect to solids removal efficiency. More research is needed to determine the optimum QZ length that results in good solids removal efficiency and the amount of solids that can be removed from QZs of different lengths.

More information is needed about the settling characteristics of solids in effluents from fish raceways in IPRS. Depending on species, size and feed formulation, solids in effluent from raceways have characteristic settling curves, which are graphical representations of the distribution of solids settling velocity. Using these curves, the overflow rate of sedimentation basins (ultimately the length of QZs) can be determined to capture a specific proportion of solids (e.g. 50%) in the raceway effluent. These solids settling curves can be the basis for selection of an appropriate overflow rate.

Another way to view solids settling performance in QZs is to consider hydraulic retention time (HRT), or the time duration that a parcel of water equivalent to the volume of the QZ remains in the QZ before being replaced by another parcel of the same volume. For QZ lengths between 1 and 5 m, the volume of the settling basin is 10-50 m^3 and the HRT is < 2 min. Based on experience in recirculating aquaculture systems, simple sedimentation basins (clarifiers) operated with a HRT of 20 min can remove all solids greater than 100 µm. A sedimentation basin in an IPRS operated with a HRT of 20 min would require a volume of 600-1200 m^3 depending on flow rate, equivalent to sedimentation basin lengths of 60-120 m. This suggests that the first 100 m or so of the open pond area immediately adjacent downstream of fish raceways function as secondary solids settling areas for finer solids not removed in QZs, which only capture the largest solid particles.

Open Pond Water Quality

Like other types of partitioned pond systems, the open pond component of the IPRS represents the overwhelming majority of the surface area and volume of the system. It is the area responsible for producing nearly all of the dissolved oxygen used by the fish crop and for decomposing organic matter not collected and removed from QZs, and for controlling ammonia concentration. Although there are other important biogeochemical processes that occur in the open pond area, these three aspects are discussed here.

The key to maximizing the rate of oxygen production and waste treatment processes is maintaining good water circulation in the open pond area. The design rules for IPRS call for additional whitewater airlift units to be placed at intervals around the open pond to assist with water circulation. These airlift units work together in such a way that water flow generated by one airlift unit is picked up by the next, downstream unit. The collective operation of these airlift pump units generates the observed flow pattern.

Assume a 30,000-m^3 pond with three whitewater units, one at the head of each of three raceways, can generate a collective flow of 180 m3/min (60 m^3/min x 3 whitewater units @ 10 cm/sec current velocity). Three addition whitewater airlift units are also required to maintain this flow rate. Further assume that the pond operates in plug flow conditions. Thus, the turnover time is 30,000 m^3 / 180 m^3/min = 167 min = 2.8 hrs. The assumption of plug flow conditions in the open pond is not realistic but the calculation gives some indication of the potentially rapid turnover of pond water.

Dissolved Oxygen

Water quality depth profiles indicate well-mixed conditions. At Demo Farm A in Thailand, there was < 0.5 C difference between temperature at 1 m and 2 m pond depth, indicating no thermal stratification. However, there was a consistent difference in dissolved oxygen concentration between 1 m and 2 m depth, indicating a slight chemical stratification that suggests some light limitation of photosynthesis by phytoplankton at 2 m depth due to algal self-shading.

There are two aspects of oxygen requirements in all aquaculture ponds, including the IPRS. First is ensuring that there is a sufficient supply, not only to support the respiratory requirements of the fish crop at maximum density, but also to support the waste treatment functions of the pond. In hypereutrophic ponds like the IPRS the requirement for oxygen by the fish crop is far less than the respiratory demand by the large algal standing crop and by bacteria in the water column and at the sediment surface. A sufficient supply of oxygen will maximize the waste treatment function of the pond. The second aspect is maintaining a minimum concentration of dissolved oxygen above a threshold that varies depending on fish species and size. Under hypereutrophic conditions, dissolved oxygen concentrations vary between undersaturated and supersaturated states. The dissolved oxygen supply must be sufficient to avoid excessive exposure to low dissolved oxygen concentrations, which will negatively affect fish growth, survival and feed conversion efficiency.

One of the main drivers of oxygen dynamics in the IPRS is feed loading. The feed oxygen demand (FOD) is the amount of oxygen required to oxidize the organic carbon (FOD_C) and nitrogen (FOD_N) in feed that is not converted to harvested fish. The FOD is sensitive to feed conversion ratio but generally ranges from 1.0-1.2 kg O_2/kg feed. The FOD can be partitioned into various components: FOD_C from respiration by fish (250-350 g O_2/kg feed), FOD_C from oxygen demand for decomposition of organic matter (500-600 g O_2/kg feed), and FOD_N from nitrification of ammonia (120-160 g O_2/kg feed). This partitioning indicates the magnitude of the various processes that contribute to FOD and indicates the importance of FOD_C from oxygen demand for decomposition of organic matter. This further suggests that removal of the organic solids generated from feeding is key to reducing FOD and sparing available oxygen for fish respiration.

Experience at Demo Farm A in Thailand illustrates how oxygen is a limiting factor for fish production, particularly in brackishwater systems. When fish biomass was about 16 t/ha, early morning dissolved oxygen concentration reached 3 mg/L. When fish biomass increased to about 30 t/ha, early morning dissolved oxygen concentration was about 2 mg/L. This information suggests that the carrying capacity of the IPRS lies between these two levels, consistent with reported carrying capacity between 20-25 t/ha.

Organic Matter Decomposition

Nutrient budgets can be used to trace the gains and losses of organic carbon in the IPRS. Feed is a major source of organic carbon but algal photosynthesis produces about three times as much (Brown et al. 2012, 2015). About half of the total organic carbon gains is lost from respiration by algae and bacteria in the water column. Organic carbon is used as an energy source for fish respiration (~25%) and is removed in fish harvest (~10%).

In the sediment, about 10% is lost in respiration and about 10% accumulates. Removal rates are affected by temperature and DO in the water column and at the bottom of the open pond. Organic matter accumulation in sediment will depend on availability of oxygen to support organic matter decomposition, although relative to the supply during a production cycle, accumulation is modest (10%).

At Demo Farm A in Thailand, five sampling stations were established at intervals downstream from the raceways around the open pond and sediment cores collected at intervals during a production cycle. Oxygenated, deoxygenated and original clay layers were distinguished. Oxygenated layers were identified at all stations and all sample dates. Over time, at the first station, the depth of the oxygenated layer decreased until the deoxygenated layer extended to the sediment surface. These observations are consistent with a point made previously that the open pond area downstream and immediately adjacent to raceways functions as a secondary settling area.

Ammonia

Nitrogen waste loading to the IPRS can be calculated as the difference between the nitrogen in added feed and harvested fish, as follows:

$$N_{waste} = [(FCR)(N_{feed}) - N_{fish}] \times 10^3 \text{ (kg/t)}$$

For a feed conversion of 1.7, the nitrogen waste loading is about 55 kg/t of fish. Given the low new water exchange rates of IPRS, internal processes are responsible for processing and removing this load.

At feeding rates < 300 kg/ha per day, algal activity is the major factor controlling water quality. Algal uptake of ammonia is the main removal mechanism. IPRS ponds are hypereutrophic, indicated by a high magnitude of DO and pH fluctuation. In such ponds, due to the high density of phytoplankton, water transparency reduces the availability of solar radiation for photosynthesis in the water column. Limiting the photic zone reduces the capacity of algae to photosynthesize and take up inorganic nitrogen.

In conventional static ponds, carbon fixation rates range from 1-3 g C/m^3 per day, equivalent to ammonia uptake of 0.18-0.53 mg/L per day. It is possible to increase carbon fixation rates by 3-4 times by improving pond mixing to reduce light limitation. For carbon fixation rates of 6-12 g C/m3 per day, this is equivalent to 1.1-2.1 mg/L per day. Feeding rates between 400 and 600 kg/ha per day result in ammonia loading to the IPRS of 1.3-1.9 mg/L per day. Unfortunately, measurements of primary productivity and respiration in IPRS are needed to confirm mechanisms.

At some point of nutrient loading, the system begins to transition from green water to brown water. The mechanism for ammonia control shifts from dominance by algal uptake by algae to chemical oxidation by nitrifying bacteria. In biofloc systems without solids removal, the transition occurs at feeding rates between 200-300 kg/ha per day. At this point, there is a large increase in water respiration rate, requiring a substantial increase in aeration power to maintain oxygen concentration. Between 300-400 kg/ha per day, photosynthesis and water column respiration are the same and net photosynthesis is 0. The levels reported here are likely greater in the IPRS, depending on the effectiveness of solid removal.

Nutrient budgets for the IPRS indicate that denitrification was responsible for ~40% of the added nitrogen. The full process is coupled nitrification-denitrification, mediated by a consortium of bacteria. Nitrification is the oxidation of ammonia to nitrate in aerobic conditions and denitrification is the reduction of nitrate to nitrogen gas in anoxic conditions. In the sediment, nitrification occurs in the surface oxic layer and the nitrate produced in this reaction diffuses into the anoxic sediment layer, where it is denitrified. These reactions can also occur within particles, flocs and aggregates suspended in the water.

The extent of suspended-growth nitrification in the water column of the open pond area of the IPRS is unknown. Alkalinity declines have been measured in some ponds, suggesting active nitrification, a process that produces acid and consumes alkalinity.

Loading Limits

For purposes of this white paper, loading limits refer to the maximum daily feeding rate that can be applied to the IPRS without causing a deterioration of water quality to the point where production performance is reduced. The factors that affect loading limit include 1) effects of temperature on pond metabolism and water quality, 2) oxygen supply and minimum concentration, 3) fish water quality tolerance limits, 4) elimination and decomposition of organic matter, and 5) elimination of nutrients by biological and chemical processes. In brief, loading limits are a function of the interaction among fish biology, climate, and ecological characteristics of the pond.

Temperature has a profound effect on loading limits. It is the principal factor that affects fish metabolism, determining feed consumption, growth rate and fish production. Furthermore, extreme temperatures act as a stressor. Temperature also has pronounced effects on water quality, affecting the kinetics of chemical reactions, nutrient uptake by algae, microbial growth and activity, and dissolved oxygen concentration at dawn. The waste assimilation capacity of the IPRS is largely a function of temperature. Seasonal variation of maximum feed loading has been observed in IPRS projects in China, Mexico and Thailand. Feed loading rate must be adjusted according to temperature tolerances of fish.

Early morning minimum dissolved oxygen concentration is also a major factor affecting maximum feed loading rate. At Demo Farm A in Thailand, early morning dissolved oxygen concentration was less than 1 mg/L when average daily feeding rate exceeded 500 kg/ha per day, suggesting that this value is near the pond loading limit.

In heavily loaded IPRS, ammonia can accumulate to concentrations that potentially affect fish growth and feed conversion efficiency. At Demo Farm B in Mexico, a freshwater IPRS system, ponds loaded at 800 kg/ha per day had total ammonia-nitrogen concentrations of ~6 mg/L. At the prevailing pH at Demo Farm B, the level of toxic ammonia was about 0.12 mg/L, sufficient to affect feed consumption but below levels that are acutely toxic.

Based on the available information, the following provisional loading limits are provided. In ponds without good solid removal, loading limits should be limited to 400 kg/ha per day. With good solids removal, feeding rates of 400-500 kg/ha per day can be maintained indefinitely. Loading rates of 500-600 kg/ha per day can be maintained for 1-2 weeks and rates of around 800 kg/ha per day can be maintained for less than one week.

Recommendations

The point must be emphasized that water quality dynamics in IPRS are poorly understood. More systematic study of water quality in the IPRS is needed to better understand and manage the system.

Oxygen Supply

Efforts should be made to attempt to maintain higher minimum dissolved oxygen concentration in water supplied to fish raceways. Early morning dissolved oxygen concentrations in these hypereutrophic ponds are often chronically low when the system is fully loaded. It would be beneficial in terms of better growth and more efficient feed conversion if dissolved oxygen concentration is removed as a stress factor.

There are a number of ways to increase oxygen supply. Some producers using IPRS place paddlewheel aerators in the approach zone ahead of fish raceways to increase the dissolved oxygen concentration of water supplied to raceways. Another possibility is to provide pure oxygen from compressed gas cylinders or a pressure-swing absorption (PSA) unit directly to water inside fish raceways. A technology that is on the horizon, but already finding use among shrimp producers using intensive systems in Asia, are generators that produce nanobubbles that can remain suspended in the water column for weeks, theoretically providing a mechanism to maintain good oxygen conditions throughout the pond.

Solids Capture and Removal

More information is needed about solids capture and removal of quiescent zones of various lengths in relation to feed loading rate. Based on the current IPRS configuration, better solids capture can be achieved with a larger settling area or slower flow. The first ~100 m of the open pond downstream of raceways should be considered a secondary settling area for fine solids.

One shrimp recirculating pond design includes a 4-m deep sludge pit immediately following the intensive pond component. Organic matter will accumulate there and can be removed periodically. The sludge pond is also the zone where oxygen concentrations are low or absent, conditions that favor microbial denitrification. Asian shrimp farmers also use circular flow and central cones for sludge collection. These examples may not apply directly to the IPRS but suggests further formalization of the solids capture component could be beneficial for water quality and fish productivity.

Open Pond Water Quality

Open pond water quality dynamics in the IPRS are not well understood. It is primarily a hypereutrophic algal-based system. As currently managed in commercial projects, ponds are operated at nitrogen loading rates beyond the capacity of algae to take up. Nutrient uptake by algae depends on the rate of photosynthesis integrated through the water column. Algal blooms in hypereutrophic ponds are controlled by the limited availability of solar radiation in the water column (photic zone). Field experience with IPRS suggests some light limitation of photosynthesis with depth. (The design rules for IPRS specify the ratio of one raceway per 10,000 m^3, a unit of volume. However, light limitation of algal photosynthesis is a surface area effect.) Light limitation can be overcome with good pond mixing, as provided by the IPRS. Studies of the hydrodynamics of water currents inside the open pond would be useful to understand how well mixed each part of the pond is. Flow is described as a "river" suggesting there are turbulent areas and stagnant areas within the open pond.

When ponds are loaded at feeding rates that exceed the capacity of algal uptake to control, suspended-growth nitrification in the water column becomes more important. In this case, the goal should be to develop a light, autotrophic floc to control ammonia. Water column nitrification is coupled with sediment denitrification to remove excess nitrogen from the system and restore alkalinity lost during nitrification. Confirmation of these mechanisms at high feed loading rates is needed.

Loading Limits

Field experience with IPRS suggests that producers aim for a maximum sustainable feeding rate of 400-500 kg/ha per day. Feed loading rates are limited by oxygen supply to support organic matter decomposition and nitrification. About 50% of the feed oxygen demand is related to decomposition of waste solids. The degree to which these solids can be removed will reduce oxygen demand and thereby the aeration requirement. To account for seasonality, maximum sustainable feeding rates should be adjusted according to prevailing water temperatures and the thermal tolerance of the species farmed.

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John Hargreaves is an aquaculture expert with more than 40 years of experience in research, teaching, training and development. For the last 15 years, he has been a freelance consultant on commercial aquaculture and development projects, with expertise in water quality management, Best Management Practices, aquaculture carrying capacity, engineering design assessments, and certification systems. He has worked with intensive ponds, bio floc systems, partitioned and recirculating ponds, net pens, raceways, recirculating systems and hatchery and nursery systems. He has broad international experience in Latin America, Africa, Asia and the Middle East. He has worked with many commercially important finfish, crustaceans and molluscs in freshwater and marine systems. He is also the Editor-in-Chief of World Aquaculture magazine, a quarterly publication of the World Aquaculture Society (WAS).

Soy In Aquaculture Program

This technical paper was created through the USSEC Soy In Aquaculture (SIA) program and the USSEC Southeast Asian Regional Program. USSEC works with target audiences in Southeast Asia and globally to show the utility and benefits of using United States soybean products in aquaculture diets.

The SIA program replaces the Managed Aquaculture Marketing and Research Program (the AquaSoy Initiative, funded and supported by the United Soybean Board and American Soybean Association) which was designed to remove the barrier to soybean meal use in diets fed to aquaculture species.

The objective of the SIA is to optimize soy product use in aquaculture diets and to create a preference for U.S. soy products in particular, including but not limited to U.S. soybean meal, soybean oil, soybean lecithin, and "advanced soy proteins" such as fermented soy and soybean protein concentrate.

This paper follows the tradition of USSEC to provide useful technical materials to target audiences in the aquaculture industry.

For more information on soybean use in aquaculture and to view additional technical papers, please visit the Soy-In-Aquaculture website at www.soyaqua.org.

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Addendum to Technical Bulletin (communication between John Hargreaves and Lukas Manomaitis, January 2021):

Lukas: When discussing kg/ha per day, is this surface area? Or per cubic hectare of water? For example, a pond with 15,000m2 of surface area at 2m deep is 1.5 ha surface area, but 3 cubic hectares of water. This could be an important difference.

John: Regarding your comment about area versus volume, this is something I pondered a lot. In considering the continuum between a static, stratified system and a completely-mixed system, the IPRS falls somewhere between, probably closer to completely mixed than to static. I know that Jesse and others often talk about the system operating with processes that occur throughout the water column. To some extent that is no doubt true, but to me it remains somewhat unknown (another research topic) as to the actual extent. My reasoning on expressing feed loading rates as a function of pond surface area is that the main process controlling water quality in the IPRS is algal photosynthesis. Although photosynthesis is depth integrated, the amount of light available to support photosynthesis is a surface area effect. And although this is not the major reason, feed loading rates to pond systems like the IPRS are typically reported in terms of surface area, not volume. Finally, I made my feed loading recommendations using the term "provisional," meaning that they are subject to refinement and change. I reported them as ranges and presumably this will account for variation in the depth of various systems that are in operation. I agree that volume is important for processes like water-column nitrification, but until we have information about the importance and rates of that process, especially when ponds are fully loaded, it's difficult to say that volume is more important than area with respect to water quality control. Happy to discuss this further. If you want to go ahead and make a comment in that section of the bulletin, feel free to do so. The more input on this, the better it will be and more valuable to IPRS producers.

Lukas: This paper will be reviewed and commented on internally, including Zhou and Jesse. This may lead to a potential for research in future to refine this more, is that something that you might be interested in?

John: As far as being involved in future research on IPRS water quality, as you know, I am a freelance consultant and do not have the backing and infrastructure of a research institution to be able to conduct research on my own. Certainly I could help formulate and guide research projects, but they would have to be implemented by your USSEC technical teams in the field. I could definitely see that the information coming out of such research projects adding to enhancements to the technical bulletin. In writing the bulletin, I made a point to suggest various topics that merit consideration for additional research. There's a lot we don't know!