Wastewater-Fed Aquaculture

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Advanced Integrated Ponding Systems in Sewage Reuse[1]

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Abstract

There is a great volume of wastewater from sewered communities which could be reused for aquaculture if properly treated. Minimum treatment consists of removal of biochemical oxygen demand (BOD), ammonia, and pathogens from the sewage. Advanced integrated ponding systems (AIPS) are capable of providing this treatment at less than half the cost of comparable mechanical systems. AIPS consist of an advanced facultative pond for solids removal, methane fermentation of solids, and pathogen removal; a high rate pond for rapid production of algae and oxygen, removal of BOD and ammonia, and disinfection; settling ponds for algal removal; and final disinfection and maturation ponds for improved disinfection. Fish may be stocked in the final ponds. Currently there are only two complete AIPS in existence, neither of which is utilized for aquaculture, but it may be possible to combine AIPS with aquaculture.

Introduction

Wastewater reuse, once an idealistic dream, is now becoming a necessity. People in densely populated areas of developing and developed countries alike are facing the reality of a shortage of freshwater for drinking, cooking, irrigation, and other uses. Water use in sewered communities is 40 to 500 l/caput/day (Oswald 1989), so there is a large volume of water which could be reused if properly treated.

Wastewater treatment may be divided into five levels. Primary treatment involves removal of suspended solids. Removal of dissolved biodegradable organic matter is secondary treatment, which diminishes the BOD to a low enough level that the body into which the treated effluent is to flow (the receiving water) will not undergo oxygen depletion. Nitrogen and phosphorus are removed by tertiary treatment in an effort to reduce the stimulation of algae and other aquatic plants in the receiving water. Removal of refractory organic compounds is achieved by quaternary treatment. Finally, quinary treatment removes dissolved inorganic substances such as salts and heavy metals.

The level of wastewater treatment required before water may be reused depends on the manner in which it is to be reused. If the water is to be used for drinking then all levels up through quinary must be performed, since with each pass through the body the level of dissolved solids of water increases by 50 g/caput/day, or 125-500 mg/1 (Oswald 1989). If on the other hand it is used for aquaculture, treatment need not be as rigorous as for drinking. Rather, it is necessary to accomplish three objectives (Montgomery 1985):

1. Removal of BOD to protect the aquacultural ponds from oxygen depletion, which would kill fish;

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[1] Paper not present at the Seminar.

2. Removal of ammonia, which is toxic to fish, especially at high pH where the ammonia is un-ionized;
3. Removal of pathogens, which may be transmitted by the fish to humans or animals consuming them.

Removal of heavy metals may also be required since fish can bioaccumulate these materials. However, it is better to reduce these through source control to prevent their entrance into the waste steam whenever possible.

Advanced Integrated Ponding Systems for Treatment

In conjunction with the World Bank, the World Health Organization, the United Nations Development Programme, the U.S. Agency for International Development, and the Pan American Health Systems, we have been developing Advanced Integrated Ponding Systems (AIPS) at the University of California, Berkeley for over 30 years as an economical method for treating sewage and other liquid wastes. These systems are composed of a series of earthen ponds using algae and bacteria to treat the waste. Wastewater first flows into deep pits in an advanced facultative pond (AFP), where solids are fermented to methane and many pathogens are removed. The water then flows to a high rate pond (HRP) for rapid growth of algae and concurrent production of oxygen, oxidation of organics, ammonia removal, heavy metal removal, and disinfection. Downstream ponds remove algae and provide further disinfection. AIPS have been proven to be simpler to operate and less expensive than mechanical systems. They are particularly well suited for treatment of sewage to be reused in fish culture because algae in the effluent can be consumed by the fish. Also, fish can be stocked in some of the final treatment ponds.

Climatological Considerations

Before describing the design of the components of AIPS, it is necessary to discuss limitations imposed by climate. First, sunlight and warm temperatures are required for algal growth. Because artificial illumination and heating of algal cultures is only economical if producing an algal product worth several US$/g (Oswald 1988a), the use of AIPS for sewage treatment is realistically limited to locations where sunlight is plentiful. This includes many temperate, subtropical, and tropical areas. However, certain tropical regions have extended periods of cloud cover which greatly reduce light available for photosynthesis. Since at night algae respire at a rate proportional to temperature, they may consume as much oxygen as they produce during the cloudy daytime. Thus warm continuously cloudy locations are less suitable.

Evaporation can be significant in any ponding system, and it is enhanced in AIPS. Because of the large area of water exposed to the air in the shallow ponds, much water is lost to evaporation in regions in which net evaporation (annual evaporation minus annual precipitation) is high. Furthermore, algal cultures act as near perfect "black bodies," absorbing almost all incident light and reflecting very little. Thus, water temperatures in high rate ponds can rise, thereby increasing evaporation. If relative humidity is very low, evaporation may be so great that salt is concentrated in the pond, requiring a "blow down" much like a cooling tower. On the other hand, if humidity is high then evaporative cooling may be too slight, causing the pond temperature to rise excessively. High temperatures could be lethal to fish in downstream ponds and possible even lethal to the algae. Thus, average humidities less than 50% to 60% are preferable (Oswald 1988a).

Regions with torrential rainfall are not preferred for AIPS because rains can destroy pond dikes and seriously dilute or wash out the algal-bacterial cultures. Overflow spillways are needed in these areas.

Design of Advanced Integrated Ponding Systems

Advanced facultative ponds

Wastewater first flows into a deep fermentation pit in the AFP after passing through screening and grit removal devices, if necessary (Figure 1). The pit is designed to

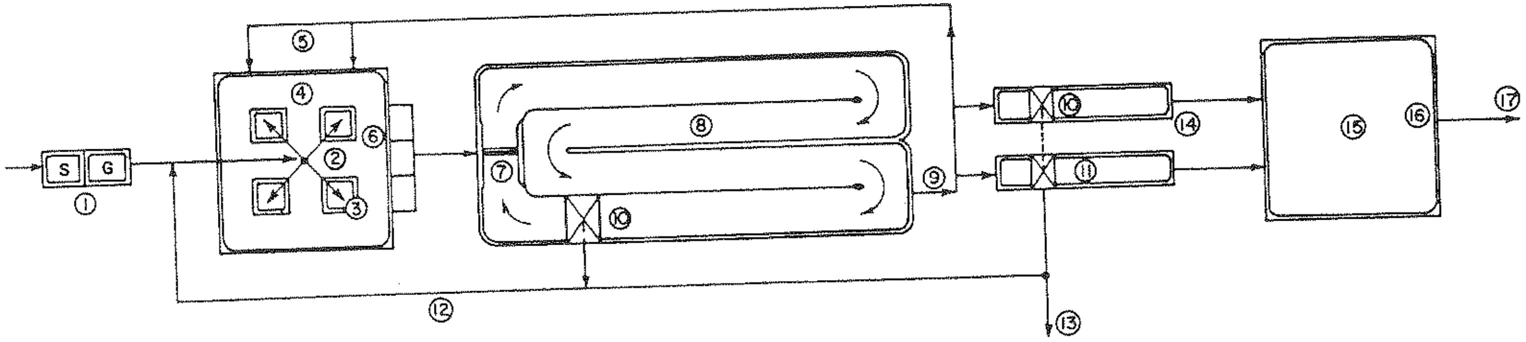

Figure 1. Schematic diagram of an advanced integrated ponding system. 1. Screening and grit removal; 2. Distributor; 3. Fermentation pit; 4. Facultative pond (primary); 5. Oxygenated water return; 6. Low level transfers; 7. Paddle wheel mixer; 8. High rate pond (secondary); 9. High level transfer; 10. Algal subsidence chambers; 11. Algal settling pond; 12. Settled algal return; 13. Algal harvest; 14. Low level transfer; 15. Maturation pond; 16. High level transfer; 17. Water reuse.

maintain the water in a strongly anoxic (reducing) environment for a residence time of 1-2 days. If calculations show that for a depth of 5-6 m the pit must be larger than 0.2 ha, multiple 0.1-0.2 ha pits are recommended. High walls or berms surround the pit to prevent oxygen present in the surface water from entering the pit.

Solids entering the pond tend to settle easily in the pit because of the quiescent conditions present. Algae at the AFP surface convert light energy to heat. Since this pond is not mechanically mixed, a thermocline is established, so the subsurface water is very still and promotes settling.

In the pit, fermentation by anaerobic bacteria converts organic material in the waste stream to methane and carbon dioxide. Each gram of methane produced decreases the BOD by 4 g. Experience at St. Helena, California has shown that solids in the isolated volume are eventually completely converted to methane and inert solids. The pond has been in operation for over 20 years but the sludge volume has never required removal. Only 30 cm of inert solids have accumulated in twenty years (SOA International 1985). The gas formed by fermentation rises through the mixture in the pit to the pond surface. Much of the carbon dioxide is absorbed by the surface water, which because of photosynthetic uptake of bicarbonate by algae near the surface, has a high pH (up to 10 or 11 in the afternoon). The gas obtained at the surface is thus high in methane but low in carbon dioxide. Nitrogen gas is also present in the digester gas, apparently due to heterotrophic denitrification of organic nitrogen in the waste stream (Verstraete and Alexander 1973). Any hydrogen sulphide in the digester gas leaving the pit is oxidized to sulphate in the oxygen-rich surface water.

The fermentation pit also acts to disinfect the waste. Parasite ova were shown by Zhao (1982, 1983) to settle in Chinese biogas digesters which contain viscous sludge. It is expected that their removal is even better in the pits where the sludge is much less viscous and hence settling is better. Also, the intensely anoxic environment of the pit is lethal to some pathogens. Finally, recent study on anaerobic units has shown that many refractory organic compounds can be biologically destroyed (McCarty 1985; Jewell 1985).

High rate ponds

The liquid stream in AIPS flows from the facultative pond to the high rate pond. The HRP is a shallow, gently mixed, continuous channel pond in which algae grow at high productivity. Bacteria consume oxygen produced by the algae to oxidize the BOD to carbon dioxide and water. The CO_2 is then used by the algae for cell growth. Thus, a symbiotic relationship exists between the algae and bacteria in the HRP.

The algal concentration, amount of BOD to be removed, pond depth, and residence time are all interrelated in the design of a HRP. Generally what is known from the outset is the BOD of the waste stream. Assuming that 50% of the BOD is removed by the AFP, then the remaining 50% must be oxidized by oxygen produced by the algae. Algae produce oxygen in conjunction with production of cell material through a series of reactions which can be summarized by the following idealized equation:

$$CO_2 + 2\,H_2O \xrightarrow{\text{Light}} (CH_2O)_x + O_2 + H_2O, \qquad (1)$$

where $(CH_2O)_x$ represents algal cell materials. Studies have shown that the oxygen formed is derived from the water, not the carbon dioxide, so there is essentially an infinite supply of oxygen for BOD removal.

A more rigorous equation for algal growth (Oswald 1988b) in which algal cell material is represented by the more realistic formula $C_{106}H_{181}O_{45}N_{16}P$, reveals that the ratio of oxygen produced to algae produced on a weight for weight basis is 1.55. This factor is termed q, the oxygen to algae quotient. Field studies have shown that q can vary, depending on cell age and species.

A second parameter, the oxygenation factor O_f, gives the ratio of oxygen produced to oxygen demand (BOD):

$$O_f = qC_{ct}/Y_t, \qquad (2)$$

where C_{ct} is the concentration of algae grown at a given residence time t and Y is the BOD measured for the same period t. Studies have shown that the optimal O_f is about 1.5 (Oswald 1970) . If it is too high, algae tend to excrete organic matter. Also, pH may be too high in cultures with high oxygenation factors.

Rearrangement of equation (2) shows that the ratio of algal concentration to BOD is simply O_f/q. Since both factors are roughly 1.5, we have the serendipitous result that their ratio is 1. Therefore the concentration of algae to be grown in a HRP should be equal to the amount of BOD to be removed.

Experience has shown that algal concentration in a HRP is related to pond depth by an empirical equation:

$$C_c = 6000/d \text{ to } 9000/d, \qquad (3)$$

where C_c is the concentration in the pond in mg/l and d is the depth in cm. The value of 6000 is better if light transmission is poor, such as in areas with frequent cloudy weather or in water containing large amounts of non-algal suspended matter.

Sufficient residence time must be allowed for the algal concentration to reach the level predicted in equation (3). The residence time may be predicted from an energy balance, equating the energy stored in the algae to the absorbed solar energy with which the algae were formed:

$$hC_c = FS_iA\theta, \qquad (4)$$

where h is the energy content of algae (cal/mg), F is a dimensionless efficiency of solar energy conversion, S_i is the incident solar energy flux (cal/cm^2/day), A is the pond surface area/l (cm^2/l), and θ is the residence time (days). Since

$$A = 1000/d \qquad (5)$$

then the residence time θ may be calculated by a rearrangement of equation (4):

$$\theta = (hdC_c)/(1000FS_i) \qquad (6)$$

Note that if equation (3) is inserted into equation (6) then d and C_c cancel out. Then the value of θ depends on whether the value 6000 or 9000 is chosen in equation (3). This choice is related to the value of F, since both are concerned with efficiency of light absorption and conversion. It must be recalled that equation (3) is merely an empirical observation.

As a numerical example, suppose a waste stream contains 400 mg BOD/l. Since 50% is removed in the AFP, there remains 200 mg/l to be removed in the HRP. Thus, an algal concentration of 200 mg/l is desired. Choosing the value 6000 in equation (3), the required depth (d) is then:

$$d = 6000/200 = 30 \text{ cm}$$

The heat of combustion of algae (h) is about 5.5 cal/mg, and the efficiency of solar energy conversion by algae (F) is about 2.5%. The solar energy flux (S_i) varies from a minimum of 0 to a maximum near 800 cal/cm^2/day, so an average value of 400 cal/cm^2/day may be used. The required residence time (θ) is then:

$$(5.5 \text{x} 30 \text{x} 200)/(1000 \text{x} 0.025 \text{x} 400) = 3.3 \text{ days}$$

The high rate pond is mixed by a paddlewheel, screw pump, or propeller pump. Paddlewheels are preferred because of their high efficiency. Mixing accomplishes several things. First, it prevents thermal stratification. As noted previously, algae in the AFP absorb light and convert it to heat, thereby establishing a thermocline. In our studies at Richmond, California, unmixed ponds were found to have a temperature difference of as much as 8°C over their 30 cm depth (Oswald 1988a). While the thermocline is desirable in the AFP to provide quiescent settling conditions, it is very undesirable in the HRP, where stratification can lead to excessive pH rise and subsequent precipitation of inorganic salts. The precipitation can cause algae to flocculate and settle in the pond, and it blocks light transmission. By maintaining in suspension the faecal pellets of predators, which contain live algae, continuous mixing assures culture continuity in spite of predation. Continuous mixing with paddlewheels also outgasses ammonia, aiding in nitrogen removal. This is very important for water which is to be reused for growing fish because they tend to be very sensitive to ammonia. Paddlewheels enhance absorption of CO_2 from air to water (when the pH is above 8.5), since a paddlewheel exposes many hectares of wet blade area to the air each day. For example, an 8-bladed, 6 m long paddlewheel with blades 30 cm wide turning at 6 rpm will expose nearly 25 ha of wet blade area to the air each day. Paddlewheel mixing also preconditions the cultures so that they agglomerate and settle readily when they are removed from the mixing field.

Early HRP studies in the Philippines (Oswald *et al.* 1978) showed that a linear velocity of only 5 cm/sec was required to maintain algae in suspension. However in wide, shallow ponds it is difficult to maintain a constant velocity, especially when the channel is folded. Therefore a minimum linear velocity of 15 cm/sec is recommended. Operation at a velocity much higher than this becomes expensive since the power requirement increases rapidly with velocity.

The power required to mix the pond depends on the velocity of mixing and the head loss around the channel, which in turn depends on the length of the channel and the surface roughness. Manning's equation is an empirical relationship between velocity, head loss, and roughness:

$$V = (1/n)\, R^{2/3} S^{1/2} \qquad (7)$$

where V is velocity (m/sec), n is the Manning friction factor, R is hydraulic radius of the channel (m), and S is the dimensionless loss of head (potential energy) per unit length of channel. The head loss, caused by friction between the water and the pond lining, is the difference in water level between the downstream (high energy) and upstream (low energy) sides of the paddle-wheel. Since this head loss Δd is lost over the length L of the channel, S is equal to $\Delta d/L$. Equation (7) can be used to calculate Δd as a function of L, since the velocity is known (15 cm/sec). The value of n depends on the surface of the pond, varying from 0.008 for smooth plastic on smooth concrete to 0.03 for rough earth lining (Oswald 1988a). Then the power required to overcome Δd and mix the pond is given by:

$$P = Qpg\, \Delta d/e \qquad (8)$$

where P is the power (W), Q is the volumetric flow rate of the water (m^3/sec), p is the density of the water (kg/m^3), g is the gravitational acceleration (m/sec^2), Δd is the change of depth across the pond (m), and e is a dimensionless efficiency of the paddlewheel motor. Q is the product of the velocity and the width and depth of the channel.

The HRP has other benefits in waste treatment besides BOD removal. As algae consume CO_2 during daylight hours, pH rises. The high pH combined with the supersaturated oxygen produced photosynthetically is very effective in pathogen removal. Also, the high pH tends to cause heavy metals to precipitate, thereby removing them from the liquid stream.

Algal separation

Effluent from a HRP contains so much algae that if one small downstream fish pond were to receive the effluent, the pond would become eutrophic and the fish would die (Oswald 1987). This is because of nocturnal algal respiration which consumes 5-7% of the algal dry weight of oxygen each night. During the daylight hours the algae do not produce oxygen at the rate at which they produced it in the HRP, so there is a net oxygen loss. A sewage HRP produces enough algae to meet the food needs of 5 to 10 naturally oxygenated fishponds of equal volume. However, it is best to remove the algae from the liquid stream and readd it for food as necessary, in order to maintain control over the system.

As noted previously, paddlewheel mixing selects for larger species of algae which tend to settle easily when removed from the mixing field. Smaller species are grazed to extinction by predators, which are kept in suspension by the mixing. Consequently, a downstream pond or channel with a residence time of a few hours is normally sufficient to remove the algae (Nurdogan 1985). A subsidence pit should be installed in the pond into which the algae can collect and can be periodically removed. The algae can be used as a high-protein feed supplement for livestock or can be used in other fishponds.

Disinfection and maturation ponds

Disinfection in a completely mixed facultative pond can be described by the formula of Marais (1974):

$$N_t = N_o/(Kt+1) \qquad (9)$$

where N_t is the Most Probable Number (MPN) of bacteria after time t, N_o is the initial MPN, t is the pond residence time (days), and K is the bacterial death rate (1/day). Marais (1974) developed a useful expression for estimating K:

$$K = 2.9(1.19)^{T-20} \qquad (10)$$

where T is the water temperature (°C). For a ponding system such as AIPS in which each pond has a different residence time, the drop in MPN can be calculated for each pond using equations (9) and (10). The Marais expressions are very conservative since they are based on data from conventional lagoons (Slanetz et al. 1970) and consequently do not include any specific correction for pH effects. In high rate ponds, high pH levels significantly increase the indicated K values in equation (10). A pH in excess of 9.3 for 24 hours is lethal to all *Escherichia coli* (*E. coli*) (Parhad 1970). Such levels occur daily in HRPs.

Experience has shown that due to short-circuiting at least four ponds in series are needed to adequately disinfect sewage. It is important that transfer structures be designed to prevent short-circuiting of the liquid stream. The schematic of AIPS in Figure 1 shows a low level transfer (LLT) from the AFP, a high level transfer (HLT) from the HRP, another LLT from the algal settling ponds, and another HLT from the maturation pond. The maturation ponds, needed to reduce MPN to an acceptable level for reuse, should be 4-5 m deep.

The disinfection and maturation ponds are ideal for aquaculture. Residual algae that escape removal in the settling pond are available as fish food, and supplemental algae from the subsidence chamber can be added. There are enough algae to maintain a dissolved oxygen level acceptable to the fish without consuming too much oxygen at night.

Costs

It is difficult to compare the cost of AIPS in developing countries with costs of mechanical wastewater treatment systems. Only a few AIPS currently exist, and they are in California where conditions are different from most developing countries: labour costs are extremely high, and temperatures vary widely with season. However, a comparison made between two AIPS systems in California and mechanical secondary treatment systems of equal size is shown in Table 1 (Oswald 1987). In each case the capital cost of AIPS is half that of the mechanical system, due in large part to the use of inexpensive earthen ponds instead of concrete reactors. It is estimated that on an equal volume basis, a pond costs less than 1% of a reinforced concrete reactor. In most cases the savings more than make up for the added cost of land needed for AIPS.

Even greater savings are made in operation and maintenance (O&M) costs which are only 30-40% as high in AIPS as in mechanical systems (Table 1). Savings are largely due to energy costs; mechanical systems must compress air or pump large volumes of water to provide oxygen for BOD removal, consuming about 1 kW hr/kg of oxygen transferred into the water. AIPS use solar energy to produce oxygen. The amount of energy required to turn the HRP paddlewheel is only about 0.1 kW hr/kg of oxygen produced. Energy savings are thus substantial, important for developing countries which must spend much of their limited foreign exchange capital on energy imports. In the event that a third or fourth stage of waste treatment is required, even greater savings result from using AIPS.

Table 1. Comparison of costs for secondary mechanical plants and advanced integrated ponding systems for achieving secondary treatment. Source: Oswald 1987.

Plant Description		Estimated Cost, US$/m^3 (1987)[1]			Reference
m^3/day	Type	Capital	Operation & maintenance	Total	
2000	Mechanical	0.303	0.367	0.670	EPA 1978
2000	AIPS[2]	0.153	0.158	0.311	Personal data
7500	Mechanical	0.270	0.203	0.473	EPA 1978
7500	AIPS[3]	0.124	0.058	0.182	Personal data

1. costs updated according to Engineering News Record index;
2. AIPS plant at St. Helena, California, USA, operational for 22 years
3. AIPS plant at Hollister, California, USA, operational for 9 years.

Use of AIPS for Aquaculture

While cost savings in construction, O & M, and energy are the major attractions of AIPS, their potential value for aquaculture remains to be determined. Only two complete systems are in existence today and these are in the USA where interest in wastewater-fed aquaculture is currently limited. However, studies in Israel demonstrated that sewage-grown algal meal has potential as a protein source for feeds for warmwater fish (Sandbank and Hepher 1980). At Mèze, France, ornamental fish are fed algae grown in a stabilization pond system treating municipal waste, and mussels, oysters, and shrimp are grown in the receiving water nearby (D. Bondon, personal communication). A HRP has been tested at Mèze for possible incorporation into the system. Studies at the Oceanic Institute in Hawaii are underway on the use of animal wastes in HRPs to produce *Spirulina* for shrimp and lobster food (E. Duerr, personal communication). Thus, while AIPS have not yet been combined with aquacultural ponds for sewage reclamation and reuse, the above studies combined with the data presented in this paper on the low costs of construction and operation show that AIPS have potential for this application.

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