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ADVANCED INTEGRATED WASTEWATER POND SYSTEMS FOR NITROGEN REMOVAL

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ABSTRACT

Wastewater treatment lagoons are well known for their effectiveness in removing biochemical oxygen demand, suspended solids, and pathogens of sewage origin. Their performance in removing fixed nitrogen is somewhat less recognized and documented.

Advanced Integrated Wastewater Pond Systems (AIWPSs), developed at the University of California, Berkeley's Engineering Field Station and constructed at several locations in California and elsewhere, do permanently remove significant amounts of nitrogen from wastewater streams. A major part of this removal can be attributed to the unique design of AIWPSs. Because the unique characteristics of AIWPSs are not yet widely known and understood in the wastewater treatment field a somewhat detailed description of AIWPSs is in order.

First, the basis for the name *Advanced Integrated Wastewater Pond Systems* will be explained. The term *advanced* is used because the design of AIWPSs represents an advancement over that of conventional waste stabilization ponds. The term *integrated* is used because these systems involve a number of well known and lesser known unit processes brought together in optimal sequence. The term *pond* is used because the individual bioreactors of an AIWPS are primarily constructed of earthwork. The term *systems* is used because the ponds are sequentially arranged and hydraulically controlled to optimize their multiple unit processes. The term *wastewater* is included to distinguish the function of these ponds from other types of water impoundments.

THE SYSTEM

As shown in Figure 1, an AIWPS consists of a minimum of four ponds in series. There are three main reasons for the series of at least four ponds. First, the several unit processes involved require distinct environments which sometimes cannot be overlapped. Secondly, the use of four ponds in series with properly designed transfer structures prevents all conceivable short circuiting of influent to effluent. And thirdly, in arid areas where annual evaporation generally exceeds annual precipitation and where rainfall occurs mainly in winter, it is necessary to divide the ponding area into sectors to maintain sufficient depth, to avoid drying, and thus to insure continuity in the requisite biological and physical unit processes. In many of their unit processes, AIWPSs do not differ greatly from conventional wastewater treatment plants. They both incorporate primary sedimentation, flotation, fermentation, aeration, secondary sedimentation,

KEY TO NUMBERS ON FIGURE BELOW

1. SCREENING & GRIT REMOVAL
2. DISTRIBUTOR
3. FERMENTATION PITS
4. METHANE UTILIZATION
5. ADVANCED FACULTATIVE POND
6. OXYGENATED WATER RETURN
7. MID LEVEL TRANSFER
8. PADDLE WHEEL MIXER
9. HIGH RATE POND
10. HIGH LEVEL TRANSFER
11. ALGAE SUBSIDENCE CHAMBER
12. ALGAE SETTLING PONDS
13. SETTLED ALGAE RETURN
14. ALGAE UTILIZATION
15. HIGH LEVEL TRANSFER
16. MATURATION POND
17. MID LEVEL TRANSFER
18. WATER REUSE
19. SUPPLEMENTARY AERATION

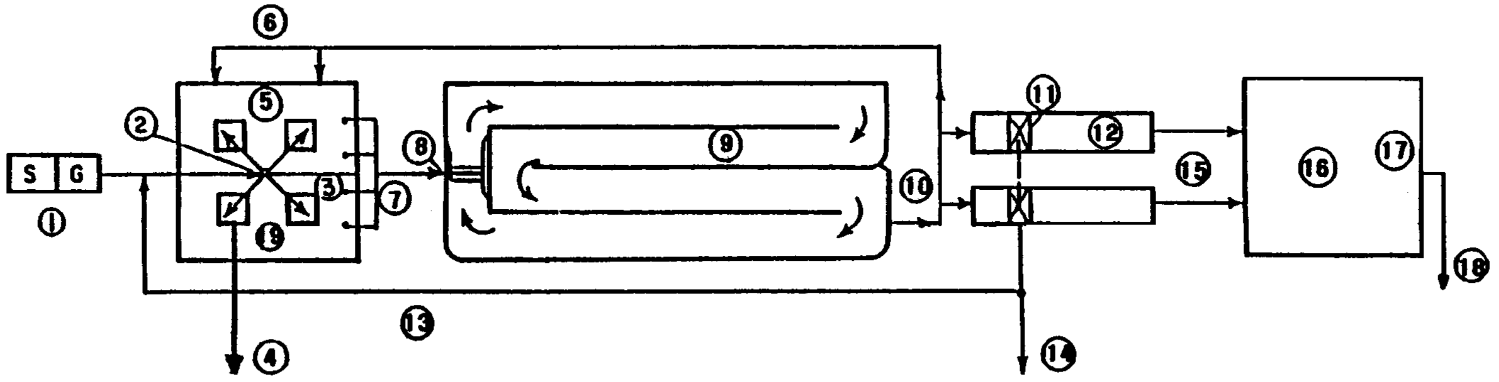


Figure 1. Schematic diagram showing the elements and sequence of treatment in an Advanced Integrated Wastewater Pond System (AIWPS) Type I.

nutrient removal, effluent storage, and final liquid disposal. However, AIWPSs do not require daily sludge management; indeed the time in which sludge residues accumulate to require removal and disposal is on the order of decades. The engineering strategies by which these unit processes are fostered in an AIWPS are described below.

Advanced Facultative Ponds

As originally described (Oswald, 1990, 1991), the first of the four ponds series is the Advanced Facultative Pond (AFP) shown schematically in Figure 2. The term facultative implies that waters in the pond are aerobic (oxic) near the surface and anaerobic (anoxic) near the bottom. Our studies have shown that methane fermentation is the principal mechanism for BOD removal in AFPs. A major problem with conventionally designed waste stabilization ponds is that during windy periods vertical mixing carries oxygenated water into the anaerobic zone, thus inhibiting methane fermentation which cannot occur in the presence of dissolved oxygen. In AFPs sedimentation and methane fermentation occur in deep pits specially designed to avoid the intrusion of dissolved oxygen. Raw waste is introduced near the bottom of these pits and, since they are deep and are loaded with low upflow velocities, most of the settleable solids remain within the pits. Overflow velocities are designed to be low enough (less than 2.5 meters/day) to allow most helminth (parasitic worms) ova to settle in the pit. Of course, solids are lifted by the gas bubbles that form on and in them; but, as they rise, the bubbles expand and break away leaving the solids to resettle. The result is that solids with their adhering bacteria rise and fall within the pits creating an anaerobic sludge blanket through which all of the wastewater must flow. As evidenced at St. Helena, California and Hollister, California, sludge fermentation is so complete that day by day sludge handling is eliminated. St. Helena's AIWPS has operated for 27 years without requiring sludge removal, and inspection shows little sludge accumulation. Hollister's system has gone without sludge handling for 17 years. A recent inspection of Hollister's fermentation pits, opened to repair a rock clogged septage inlet, revealed that sludge was evenly distributed in the pit and that the digester had sufficient capacity for at least 10 more years.

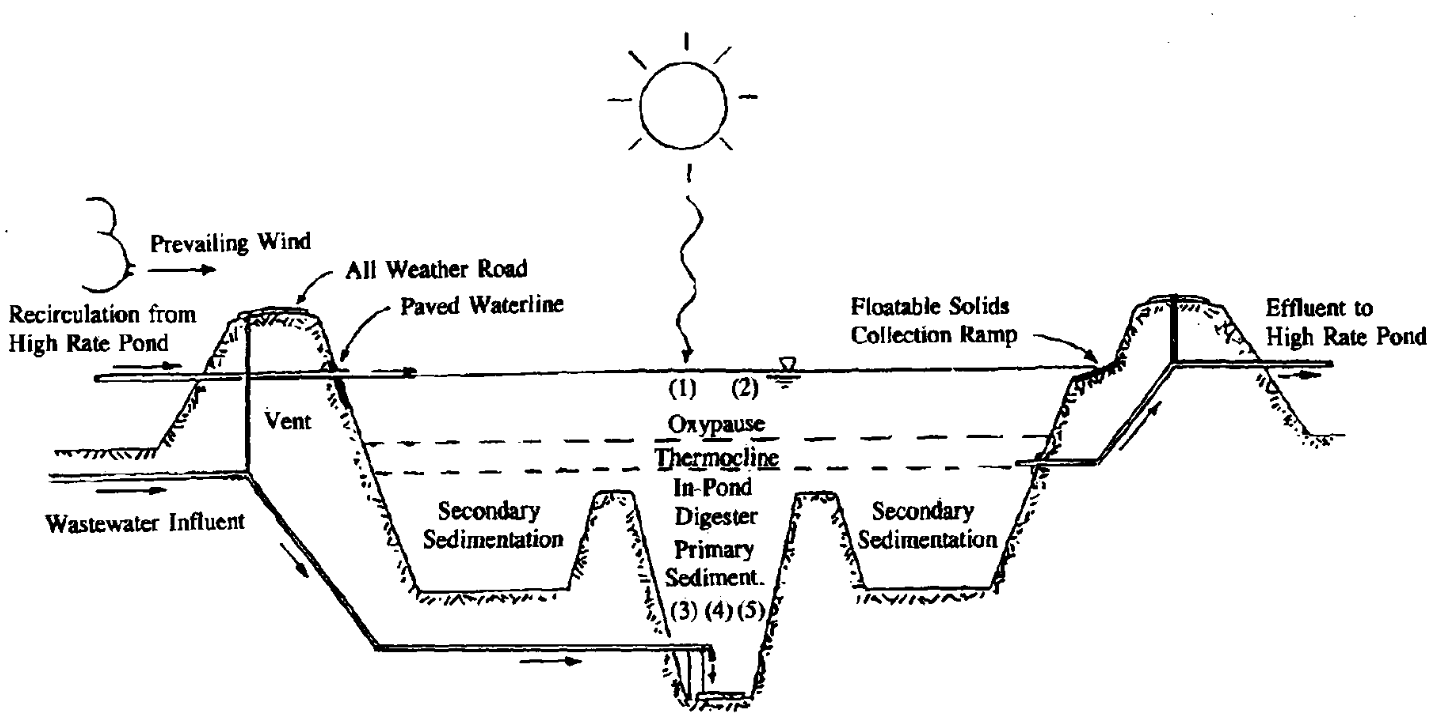
To deal with floatables, AFPs are designed with down-wind concrete "beaches" or scum ramps where floatable trash can be cast up by the wind to dry. These substances are largely inert, light in weight and low in odor. The flotsam can be collected periodically with a loader for burial or disposal as a solid waste. Since AFPs are constant in depth, bank erosion is best controlled with a paved water line. Concrete is the best pavement since asphalt will slowly dissolve in the greases and solvents always present in raw sewage, and plastic liners have a shorter life. A well designed AFP in the sunbelt will remove from 60% to 80% of the influent BOD and virtually all of the original suspended solids.

Depth is regulated in an AFP by the level of the invert of the outlet pipe. The inlet of this pipe should be located below the surface to avoid transfer of floatables into the secondary pond. Because sludge removal from the AFP may be required every 10 to 30 years, there should be two units in parallel as shown in Figure 1.

Secondary Facultative Ponds or Algal High Rate Ponds

The secondary unit of a conventional wastewater pond system is typically another facultative pond. However, much greater treatment is attained if the second unit is an algal high rate pond (HRP). Although it is much shallower than a secondary facultative pond, a HRP requires a much shorter retention time and produces much more dissolved oxygen. A well designed HRP that is paddlewheel-mixed will generate daily on the order of 100 to 300 pounds of dissolved oxygen per acre. It will also daily generate on the order of 75 to 200 pounds of algal biomass (ash free dry weight). Microalgae in the effluent from a paddle-wheel-mixed HRP settle readily; from 50% to 80% of the algae will be removed by sedimentation in a settling pond whose hydraulic residence time is one or two days. The settled algae have a low respiration rate and will remain concentrated on the settling pond bottom for many months or even years without releasing significant amounts of nutrients. Ideally, however, the algae should be removed periodically and used to its highest fixed nutrient and protein value.

One of the unique contributions of algae grown in HRPs is their daily elevation of pH in the pond. A pH of 9.2 for 24 hours is known to provide a 100% kill of *E. coli* and presumably most pathogenic bacteria. It is



Biochemical Reactions Located by Number

(1) Photosynthesis: $CO_2 + H_2O \rightarrow CH_2O + O_2$
(2) Aerobic Oxidation: $CH_2O + O_2 \rightarrow CO_2 + H_2O$
(3) Organic Acid Formation: $2CH_2O \rightarrow CH_3COOH$
(4) Methanogenesis: $CH_3COOH \rightarrow CH_4 + CO_2$
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
(5) Heterotrophic Nitrification: Fixed N $\rightarrow NO_x^-$
Denitrification: $2NO_3^- + 3CH_2O \rightarrow N_2 + 3CO_2 + 3H_2O$

Figure 2. **Cross section of an Advanced Facultative Pond showing the dominant biochemical reactions.**

not uncommon to reach pH levels of 9.5 or 10 in HRPs during the day and to provide as a result a high disinfection rate. On the other hand, continuous input of settled sewage and complete flow mixing tends to conceal such high rates of disinfection. Because they usually produce a surplus of dissolved oxygen (usually several times the applied BOD), some HRP effluent is used to overlay the primary AFP with warm oxygen-rich water to absorb any odors of reduced substances coming from the anaerobic bottom or fermentation pits. The recirculation of HRP effluent to the AFP also assures the presence of oxygen-producing algae in the surface waters of the AFP. Effluent from a HRP should be taken from the surface to transfer only the most oxygenated, highest pH water. Programmed withdrawal only during the day will enhance both disinfection and other pH related benefits attained in HRPs.

Algae Settling Ponds

As noted above, the HRP should be followed by an Algae Settling Pond (ASP) or some other method of removing algae from the HRP effluent. If the water from the HRP is to be used for crop irrigation, algae need not be removed; settling and storage should be sufficient to achieve an MPN of 10^3/100 ml or less in compliance with the latest agricultural reuse guidelines recommended by the World Health Organization. Higher removals to an MPN of less than 2.2/100 ml and a turbidity standard of 2 NTU may require flotation and/or filtration to remove residual algae and enhance disinfection. UV disinfection of the effluent may be required to meet viral standards when specified.

As markets and internal uses for waste-grown algae become established, techniques for harvesting algae will improve. Harvesting algae by natural sedimentation, of course, implies that at least two settling units in parallel must be provided to allow periodic decantation and removal of the settled algal concentrate. Harvesting is now required to permit effluent discharge to aquatic bodies, although algae may be beneficial to the aquatic ecosystem, wetland or stream, to which the final effluent is discharged. There is no evidence that algae are harmful in moving waters. On the other hand, if they are heavily chlorinated they will die, settle, and release BOD depleting the level of dissolved oxygen in the bottom strata of the receiving water. If AIWPSs are designed properly to avoid short circuiting and to enhance disinfection, chlorination should not be necessary. If, because of regulation or sensitivity of a receiving body, effluents from AIWPSs must be disinfected, final flotation/filtration of the residual algae will improve disinfection efficiency and avoid the BOD exerted by dead and dying algae. Recent studies of UV disinfection by our group indicate that it is less harmful to algae than is chlorine. And UV disinfection has also proven to be more effective against indicator viruses than has chlorine.

Although natural sedimentation of algae from paddlewheel-mixed HRPs is feasible to remove 50 to 80% of the algae, if higher degrees of removal are required, physical harvesting is indicated. Of the available harvesting systems, dissolved air flotation (DAF) is by far the most economical and efficient. Modern DAF systems of the type developed by Krofta Engineering Corporation have achieved 99% algae removal with 20-30 mg/L of alum and a DAF residence time of less than five minutes. If such systems are followed by filtration and UV disinfection, effluent quality suitable for unrestricted reuse can be attained. Even with the addition of DAF, filtration and UV disinfection, AIWPSs will cost much less than mechanical wastewater systems to build and to operate.

Maturation Ponds

If the effluent from an AIWPS having passed through the AFP-HRP-ASP sequence is to be reused for agricultural or landscape irrigation where human contact is expected, storage for a minimum of 10 to 15 days in a deep maturation pond or storage reservoir will provide adequate die away of pathogenic bacteria of human origin. Maturation ponds will be occupied seasonally by wild fowl—ducks, coots, geese, gulls, and many others birds. The *E. coli* they contribute are innocuous but will add to the measured MPN. Discharge of such effluents to constructed wetlands may satisfy concerns regarding human health risks and improve habitat. The risks are actually minimal. Maturation pond effluents meet the bacteriological guidelines recommended by WHO for agricultural reuse.

Returning to our concerns in this paper—the removal of nitrogen in AIWPSs—four mechanisms seem to be responsible. These are anoxic denitrification in the AFP, algal uptake and ammonia stripping in the HRP, cell removal in the ASP, and final particle separation by flotation and filtration.

Anoxic Denitrification

In early studies of conventional anaerobic ponds in Concord, California, Bronson (1963) using special submerged gas collectors, found the intensely anoxic environment to be emitting almost as much nitrogen gas as methane and hydrogen gas. Bronson initially thought that atmospheric nitrogen might be absorbed by the pond water and subsequently stripped out by the rising bubbles of methane and hydrogen gas coming from the anoxic sludges at the pond bottom. To check this hypothesis, he placed some of his collectors upon the bottom sludge and some just below the pond surface. By an ingenious stirring device he was able to dislodge and collect large amounts of gas emitted freshly from the bottom sludge. This gas, containing from 25% to 35% N_2, was often richer in N_2 than the gas collected at the surface. This observation ruled out stripping as the source of N_2 and left little doubt that the source of N_2 was the anoxic sludge. Subsequent studies by Brockett (1976) and by Green (1994) have confirmed Bronson's findings. As shown in Figure 3 biogas collected in the digester of the Richmond AIWPS is approximately 23% nitrogen, while biogas collected at the surface is only 10% nitrogen, leading to the presumption that more than half of the nitrogen gas has been absorbed by the overlying water. In Green's work the water column overlying the active digestion zone is approximately 3.8 m (12.5 ft) providing for absorption of CO_2 and N_2 and enriching the biogas to 88% methane.

One possible explanation for the evolution of nitrogen gas from AFPs is a process known as heterotrophic nitrification. In 1971, Laurent at the Pasteur Institute published a paper on autotrophic nitrification (AN) and heterotrophic nitrification (HN) in aquatic systems. Laurent attributed the phenomenon of HN to bacteria of the genus *Arthrobacter* and assumed that undetectable traces of O_2 permitted nitrification to occur. He excluded hydroxylamine (NH_2OH) as a substrate for nitrification. In 1973, Verstraete and Alexander studied HN and in their search of the literature found that

> "In the process of HN, both inorganic and organic nitrogenous substrates are metabolized and the products known to be excreted in the reaction sequence include hydroxamic acids, oximes, nitrose compounds, nitro compounds, nitrite and nitrate."

Verstraete and Alexander then studied the fate of such compounds *in vitro* and in natural ecosystems. They found that *in vitro* hydroxylamine is apparently nitrified while 1-Nitrosethanol remained. In natural ecosystems, however, both substances were reported to disappear in a few days. They stated that such reactions are favored in alkaline media to pH 9. One could conclude from their data that the nitrogenous substances studied were converted to nitrite or nitrate and thence to N_2.

There has followed a number of papers on HN, each one drawing nearer to, yet avoiding, the idea that nitrification of organic nitrogen and ammonium can occur under intensely anoxic conditions. Bergerova (1975) stated:

> "The existence of HN has long been denied, the results concerning HN being taken to be erroneous. Though the existence of heterotrophic nitrifiers—bacteria, actinomycetes and fungi—is no longer doubted, the biochemistry of the process is not yet clear."

Bergerova listed a number of heterotrophic microorganisms all capable of oxidizing ammonium if grown on a medium with reduced nitrogen forms. Various amino acids and ammonium sulfate served as sources for the formation of hydroxylamine, nitrite and nitrate. R. L. Tate III (1977) studied nitrification in histosols and found that when he blocked AN with an AN inhibiter, the heterotrophic nitrifier *Arthrobacter* sp. produced nitrate whether the soil was amended with sodium acetate and/or ammonium sulfate or not. The histosols studied were, of course, very rich in organic matter. He suggested that the heterotrophic population may be responsible for some of the nitrate produced in histosols. In 1977, Focht and Verstraete summarized the state of knowledge on HN in a table which compared the rates of AN with those of HN pointing out that AN can produce nitrate at rates several orders of magnitude greater than HN. According to this table the fastest heterotrophic nitrifier, an *Arthrobacter* sp. produced 9000 g of nitrite N, 4500 g of

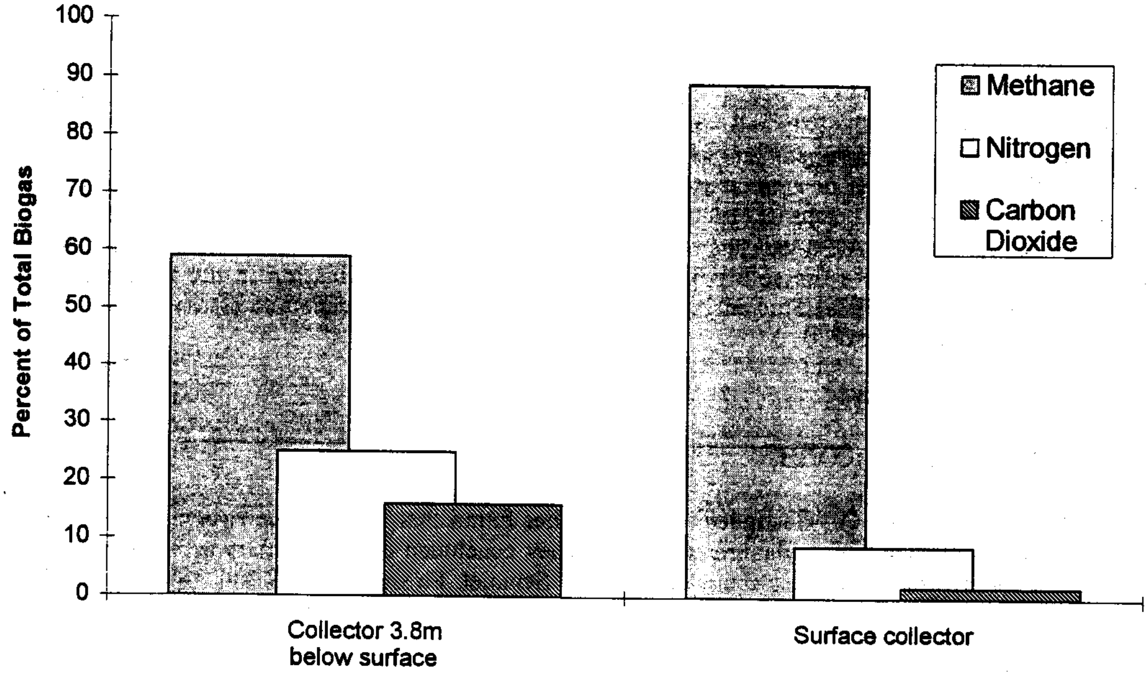


Figure 3. Nitrogen fraction of biogas collected in the fermentation pit and at the surface of the AFP in the Richmond AIWPS.

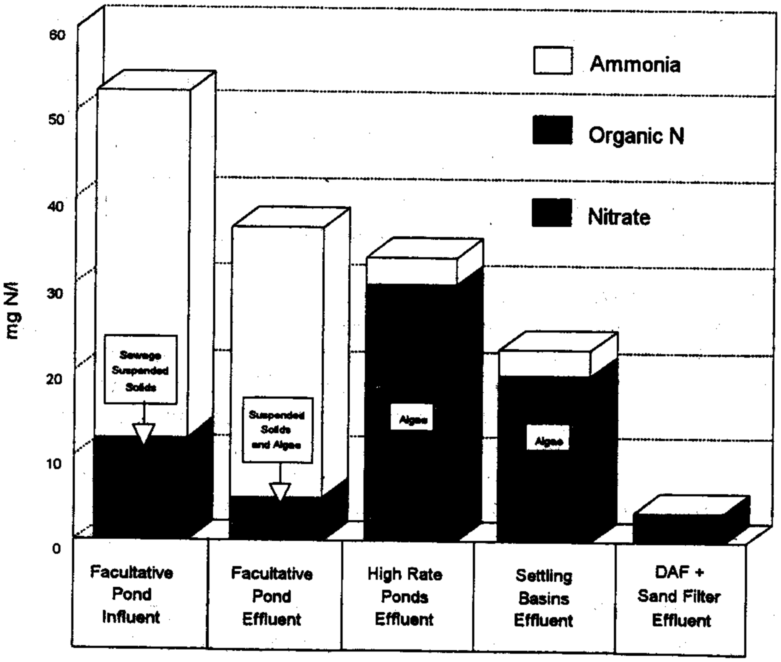
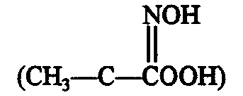


Figure 4. Nitrogen removal by a 132 m^3/d (35,000 GPD) Advanced Integrated Wastewater Pond System at the University of California's Engineering Field Station in Richmond, California May 25-September 13, 1992. DAF & Sand Unit treatment based on studies at Richmond AIWPS using Settling Basin effluent.

hydroxylamine, 650 g of nitrate, 600 g of hydroxamic acid, and 300 g of 1-Nitrosoethanol, all per day per tonne of dry cells. These rates were compared with the AN organisms *Nitrobacter* and *Nitrosomonas* which can produce 1,000,000 to 30,000,000 g of nitrite.. and 5,000,000 to 70,000,000 g of nitrate per day per tonne of dry cells. Witzel and Overbeck (1979) studied HN by *Arthrobacter* sp. (Strain 9006) as influenced by culture conditions, growth state, and acetate metabolism. This organism accumulated nitrite up to 15 mg/l using yeast extract, acetate, and ammonium. The release of nitrite paralleled growth, and magnesium was essential for nitrification of ammonium. Glyoxylate cycle enzymes influenced nitrification patterns during growth *in vitro*. R. L. Tate III (1980) in further studies of what he termed "Pahokee muck" heated the muck in such a way that AN organisms were inactivated and HN organisms survived. His data indicated that the HN organisms were the sole population responsible for nitrification in the Pahokee muck. Castignetti and Hollocher (1984) studied 12 denitrifying bacteria from six genera to determine their ability to nitrify both pyruvic oxime (PO):



$$(CH_3\text{—}C\text{—}\overset{\overset{NOH}{\|}}{C}OOH)$$

and hydroxylamine (NH_2OH). Castignetti and Hollocher found that eight of the twelve bacteria in the resting state could oxidize hydroxylamine to nitrite. They concluded that denitrifiers active in the nitrification of PO and hydroxylamine are abundant in soils. Schimel, Firestone, and Killham (1984) identified HD in a Sierran Forest Soil. They used acetylene to block AN of ammonium and chlorate to block oxidation of nitrite to nitrate. The rate of nitrate production was much greater than that of nitrite and was not significantly affected by acetylene or chlorate. The use of radiolabeled ammonium with ^{15}N demonstrated that nitrate was not coming from ammonium. They concluded that in the forest soils studied the potential for HN was much greater than for AN.

From the preceding literature it is clear that although HN is a widely recognized phenomenon among microbiologists, there is little evidence to explain the production of N_2 in the fermentation pits of AIWPSs. The intermediate steps through which organic nitrogen is converted to nitrate and thence N_2 seem clear, but most of the above specialists seem to imply that HD occurs only in the presence of minute amounts of free molecular oxygen. This simply cannot be the case in our fermentation pits where the redox potential is less than -0.4 volts and yet molecular nitrogen is being evolved. Obviously any nitrate formed would be quickly denitrified under such anaerobic conditions; but, the real puzzle is, if nitrite and nitrate are in this case intermediates between organic nitrogen and nitrogen gas, how may nitrite and nitrate be formed by heterotrophs under completely anoxic conditions where there is intense competition for any source of oxygen.

From a treatment standpoint, the removal of total nitrogen in anaerobic ponds and in fermentation pits is well documented. In addition to the work of Bronson cited above, Meron's (1970) studies of the then new St. Helena system (see Table 1), and Green's (1994) studies indicate that from 30% to 50% of the total nitrogen entering the Richmond AIWPS is removed in the primary AFP. The evidence is that this removal is effected by conversion of organic nitrogen and ammonium to N_2 in the anoxic zones (see Figure 4). According to this figure taken from studies by Green (1994), the forms of nitrogen removed in the primary pond of an AIWPS are indeed organic nitrogen and ammonium. Also according to the data shown in Figure 4, some nitrate was also removed. Nitrate was present in the wastewater and its reduction in the anoxic fermentation pit would be expected. It should be pointed out here that all of our evidence indicates that

Table 1. Nitrogen Removal in St. Helena's AIWPS (from Meron, 1970). Units are in mg/L total nitrogen. DAF & Sand Unit treatment based on studies at Richmond AIWPS using Settling Basin effluent.

	Sewage Influent	Facultative Pond Effluent	High Rate Pond Effluent	Settling Pond Effluent	Maturation Pond Effluent	DAF & Sand Filter Effluent
Winter	35.4	11.5	9.5	6.6	5.0	1.0
Summer	44.9	20.8	17.4	7.3	2.8	1.0

nitrate is formed to a very limited extent, if at all, in AIWPSs. Only if mechanical supplementary aeration is applied over long periods do we begin to see significant nitrate formation.

Algal Uptake

Rapidly growing algae in High Rate Ponds (HRPs) are generally high in nitrogen, and the major source of nitrogen for the rapidly growing algae is ammonium. As shown in Figure 4, 28.4 mg/l of ammonium were removed, and 24.2 mg/l of organic nitrogen were gained in the Richmond HRPs. Of course, it has long been established that fast growing microalgae prefer ammonium to nitrate as a source of nitrogen. A typical formula for rapidly growing, ash free, microalgae in HRP is $C_{106}H_{181}O_{45}N_{16}P$. According to this formula, the molecular weight of this algae is 2,429. The nitrogen portion has a weight of 224 and the percent nitrogen is thus (16x14)/2,429 x 100 = 9.22% ash-free dry weight. If algal ash is included in the calculation, the percentage of nitrogen is usually about 8% of the dry weight. Obviously the only way that one can use algal uptake as a method for nitrogen removal is to remove the algae after they have grown. In AIWPSs, from 30% to 70% of the algae can be removed by natural sedimentation; the higher removals occur in ASPs following paddlewheel-mixed HRPs receiving wastewater high in magnesium and calcium (Nurdogan, 1988). When an effluent low in nitrogen is required, additional algal separation methods should be applied.

The removal of nitrogen-rich algae should be effected first in settling ponds without the addition of chemicals because this algae is potentially a valuable commodity. Since it is about 50% protein when dried, algae can be combined with barley in pelleting machines to produce a 12% to 15% protein feed for fish, chicken, cattle, or swine. Algal grain mixtures attain temperatures above 80°C during pelletization and temperatures of 50°C to 60°C endure for several hours when the pellets are stored in bins or sacks. Concerns about disease transmission through pelletized waste-grown algae are thus largely unfounded. Concerning heavy metals, analyses of settled dry algae from both the St. Helena AIWPS and the Richmond AIWPS indicate levels which are below existing standards. This lack of algal contamination by sewage-borne metals may be attributed to the fact that most heavy metals combine with sulfides and precipitate in the fermentation pits of the AFP, becoming immobilized in the retained sludges, and hence never reach the HRP. Recirculated algae from the HRP to the AFP tend to settle in the AFP and probably adsorb any additional metals that may escape the fermentation pits. Since most of these algae settle before they reach the HRP, further retention of metals in the AFPs is to be expected. Concerning toxic organic compounds that may be found in sewage, although specific data are lacking, it seems likely that most toxic organics will be degraded under the intensely anoxic conditions in the fermentation pits of an AFP.

Regardless of the efficiency of natural algal sedimentation, complete algae removal will always require additional steps such as dissolved air flotation (DAF) and sand filtration. One can control the concentration of algae in HRPs to achieve a significant degree of nitrogen removal in addition to that obtained in AFPs. A fairly reproducible relationship between pond depth and algal concentration is given by the empirical expression:

$$C_c = 6000/d, \qquad (1)$$

in which C_c represents the algal concentration in mg/l, d represents the HRP depth in cm and the constant 6000 has been determined experimentally in our work. From Equation 1 and the fact that fast growing algae are about 8% nitrogen, it follows that complete algae removal will be accompanied by proportional nitrogen removal in the form of a potentially valuable commodity. One of the tragedies of modern mechanical nitrification and denitrification is that a great deal of energy is expended to convert fixed nitrogen into a useless gas. Is it not strange that our agricultural industry spends billions of dollars to fix nitrogen while our waste management industry spends billions to unfix it? In an AIWPS at least half of the fixed nitrogen can be captured in the form of microalgae and that which settles naturally can be produced at a very low cost. Much more work should be done to introduce this natural product as a valuable, safe commodity for the animal feed and fertilizer industries.

Ammonia Stripping

If one regards the fixed nitrogen in sewage as a valuable commodity, ammonia stripping is an undesirable method of removing nitrogen from wastewater. Nevertheless, ammonia stripping occurs in HRPs. As has been pointed out by Konig et al. (1987) at a pH of 9, approximately 40% of ammoniacal nitrogen in the water is in the form of NH_3, and at a pH of 10 almost 80% is in the form of NH_3. Ammonia in amounts exceeding its solubility in water will be lost to the atmosphere if an exchange mechanism is provided. Since ammonia like all gases is more soluble in water at low temperatures, its loss to the atmosphere is more likely to occur during warmer periods. In this regard, paddlewheel mixing in HRPs tends to maintain a pH less than 9 most of the time but provides an exchange surface. Our evidence indicates that during warm weather the huge surfaces exposed to the atmosphere by the blades of rotating paddlewheels blades release significant amounts of ammonia even when the pH is less than 9.

Particulates

Even after natural sedimentation and dissolved air flotation of HRP effluents, some turbidity remains. This residual turbidity can be removed by sand filtration. Either slow sand, rapid sand, or continuous backwashed sand filtration following DAF will remove residual particulate nitrogen. There is also some evidence that at very low ammonium concentrations some ammonium ions tend to adsorb to and be removed as the particulates are removed. While effluents with turbidity levels of less than 2 NTU have been attained after DAF and sand filtration, one should question the value of the added cost to attain such clear water.

SUMMARY AND CONCLUSIONS

As may be seen in Table 1, the 2-year-old St. Helena AIWPS removed up to 85% of the fixed nitrogen from the wastewater without special sedimentation and filtration. Recent studies of the St. Helena AIWPS have shown poor nitrogen removal. There are two explanations. Because of increased loadings, supplemental surface aeration is being used in the AFPs and is blocking HD. And since the St. Helena AIWPS has only one algae settling pond from which settled algae is difficult to remove, nitrogen is being released from algae that have remained in the single algae settling pond for many years. The very soft water at Richmond (see Figure 4) permits just slightly over 50% nitrogen removal by denitrification and settling. However with dissolved air flotation and filtration, total nitrogen removal exceeded 90% and reached levels approaching 1 mg/l in final effluents. Such high removals of nitrogen result from the vigorous methane fermentation and denitrification occurring in deep fermentation pits of AFPs and from the assimilation of residual nitrogen by microalgae in HRPs producing a harvestable and nitrogen-rich commodity. Although AIWPS are mistakenly thought to provide only secondary treatment, they in fact provide tertiary treatment with little or no additional costs. An AIWPS, like any waste pond system, will age and diminish in performance if there is no provision for the removal of sludge residues from the AFP and if there is no provision for algae removal from the ASPs. The latter is much more important because the removal of sludge residues may not be required for several decades. But in order to avoid nutrient and BOD recycle the removal of algal biomass should be accomplished every few months. For unrestricted reuse of treated wastewater in the United States, AIWPSs can produce a settled effluent amenable to DAF, filtration, and UV disinfection. The entire system, including land cost, is less expensive to construct and requires less energy and maintenance than any mechanical system that can attain comparable treatment performance.

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