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PONDS IN THE TWENTY-FIRST CENTURY

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ABSTRACT

Because they are economical reactors, properly designed ponds for waste management will grow in importance in the 21st Century. They will also be important for water and nutrient recycling and for animal feed production. Paddle wheel mixed algal growth ponds are not only a cost effective choice for wastewater oxidation but also are most efficient in fixing solar energy and in reclaiming water, nutrients, and energy from organic wastes. As the human population increases the amount of arable land will soon be less than one hectare per person and, at current world crop productivities of much less than 0.1 $g/m^2/d$, one hectare of arable land per person will be insufficient to sustain a projected population of more than six billion by the year 2000. Because the amount of land is finite, the apparent solutions are to increase productivity and, ultimately, to attain a constant population. Microalgae in ponds can produce high protein biomass at a rate of 10 to 20 $g/m^2/d$, productivities an order of magnitude greater than land crops. Algae can be combined with grains to produce valuable feed, which through poultry, animals, and fish can improve human nutrition. With improved human nutrition, financial security should increase and birth rates should decline; therefore, algaculture in ponds, together with conventional agriculture, can help reach a stable population and improve the quality of human life.

KEYWORDS

Advanced Integrated Wastewater Pond Systems; agriculture; algaculture; aquaculture; human population; microalgae; nutrient recovery; sanitation; waste stabilization ponds; water reclamation.

INTRODUCTION

One may define ponds as designed reactors constructed through excavation and compaction of earth to create reservoirs capable of holding water or wastewater for predetermined periods of time. Per unit volume, such earthwork reactors will cost at least an order of magnitude less than alternative reactors such as those constructed of steel-reinforced concrete. Ponds are, in fact, by far the most cost-effective reactors available for liquid waste management and for efficient capture of solar energy. A pond system, correctly designed and managed to cultivate anaerobic and aerobic bacteria and green microalgae, can decompose waterborne organic wastes efficiently and synthesize protein- and energy-rich algal biomass from the products of decomposition. Multi-faceted treatment-reclamation processes have attained solar energy conversion efficiency of three to four percent. Because of these efficiencies and other capabilities, I believe that, in this world of exploding population and vanishing resources, ponds must be a continued and increasingly vital part of our liquid waste management, nutrient recycle, and food production systems in the coming century. By use of productive ponds in conjunction with scientific sanitation and aesthetic concerns, we may comfortably buy sufficient time to gain control of the world's human population and restore a reasonable balance between ourselves and the world's biota.

Advanced Integrated Wastewater Pond Systems have been described previously (Oswald, 1991) and are discussed in several papers in this symposium. For this reason, I will not dwell on pond design but rather attempt to address the precarious human predicament with respect to land productivity and sanitation, and how it may be mitigated by using pond technology.

It would be cavalier of me to presume that I can predict all types and uses of ponds in the 21st Century, but given the rapid increase in human population and the deterioration of the environment, it is worthwhile to suggest some plausible alternative solutions to our current apparent paralysis. As a credential to look forward into the 21st Century, I would like first to look backward through a misty 70 years to my first remembered encounter with sanitation or the lack thereof. The reason for this digression is to emphasize how much progress has been made in my lifetime and thus to suggest that dramatic future changes can be made in food and waste sanitation, particularly for developing countries where waste management infrastructure is just beginning to be built. A personal recollection will perhaps illustrate my viewpoint.

In 1923 my folks had bought some property and had to go to the county seat 50 miles away to file the deed in person. Lacking anyone to stay with, I had to go with them. We did not yet own an automobile, so the trip required three days by horse and buggy. We had to stay overnight in an inn when we reached the halfway point. The first evening before we stopped at the inn, mosquitos by the scores joined us, and we went to bed with welts on all exposed parts of our bodies. My introduction to wetlands! The next day we entered the county seat. There cars and horses mingled in the streets leaving the crowns of the streets paved with oil and horse manure. It had rained and I was much intrigued by the wet gutters which were teeming with worms, flies, and maggots. When we went to eat our evening meal in the restaurant, it seemed to me that all of the flies came in with us; black ones, blue ones and green ones. Hundreds were squirming on spirals of sticky paper that hung from the ceiling. Many flies had not yet found the fly paper but preferred to join us in eating. I was most impressed by the fact that the waiter put small pieces of ice in our drinking water. The ice did not look very clean, but it was cold. That night I was unforgettably ill with nausea and diarrhea. My mother and father were also ill but not as violently as I was. My father, who had worked for the United States Public Health Services during the Bubonic Plague epidemic in California circa 1906–1914, said we had "ptomaine poisoning," an archaic term for bacterial food poisoning. My mother thought it was an reaction to bad ice. Retrospectively, my father was no doubt correct. With little or no refrigeration some of the prepared food we ate had evidently grown a large crop of heterotrophic facultative bacteria and we were the recipients of their exo-toxins. Fortunately, their toxins were not lethal; but, having spent the first four years of my life in a clean home, I was vulnerable and fell easy prey to poor urban sanitation.

Looking back at conditions then, I wonder who before 1920 could have imagined the progress that has been made in sanitation, in communication, and in travel. Who then could imagine traveling 50 miles (80 km) on freeways or 500 miles (800 km) in the air in much less than an hour, walking on streets free of horse manure, eating fast food in a restaurant where there are no flies, getting pure ice and ice water out of a spigot on the side of a refrigerator, or communicating by fax and e-mail? All these activities are so commonplace today that we take them for granted. Certainly no one then could have accurately imagined our life today, nor can anyone today accurately imagine life 70 years from now, in 2063.

Perhaps life will not change greatly in developed countries, but it must change in developing countries, hopefully for the better. Regrettably, there are still many places in the world today where sanitation is worse than I encountered in the county seat 70 years ago. Homeless and starving people in the developing and developed world give testimony that vanishing resources are creating great disparities in wealth among individuals and in the quality of life and great lapses in the practice of sanitation in spite of our sophisticated knowledge. For example, food poisoning is a continuing commonplace occurrence which affects millions each year and all too often leads to disability or death in sensitive individuals. We know that disparity can never end but perhaps by knowing and analyzing its causes some improvement can be made in the average quality of human life. In the last analysis, I am sure that the quality of life must depend on population control, political stability, the available surface area that can be exposed to the sun, the efficiency with which we convert solar energy into food, the sanitary management of our environment, and the will to do better. In the following we will examine these factors in more detail, and suggest how such lowly devices as ponds may play an important role in the quality of life in the next century.

POPULATION GROWTH

In 1923, the population of the world was probably less than 1.5 billion, and the numbers were still held in check by the four horsemen — Famine, Plague, Pestilence and Death. The industrial revolution, improved sanitation and health care, and the Green Revolution all have reduced the chance of the first three and delayed the fourth. Consequently, world population has now grown to between 5 and 6 billion persons. According to most authorities, it will reach beyond 6 billion by 2000 A.D. and exceed 10 billion by 2020. Some countries still have an excess of births over deaths of nearly 2% per year. At this rate, assuming that the 1993 population is 5.5 billion, the population in 2063 would be 22 billion. Even with a 1% increment — our best hope — the population in 2063 will be 11 billion. A future with this many more people is indeed hard to imagine. Can our lives continue to improve under this pressure, as it has during my lifetime, or must our standard of living decline? Probably it will decline unless we find new resources and/or improved ways to conserve and recycle existing resources to produce more food and energy.

Neglecting a few million people now in near starvation, how can 5.5 billion people be supported currently when famine often ruled after World War I when the world's population was a fourth or fifth of what it is now? In answer, as we have noted above, many things have happened since 1918. In the developed world, horses, mules, and oxen have been replaced by tractors; worldwide agricultural productivity has more than tripled; distribution of food worldwide is almost complete; efficient refrigeration, canning, drying, and other processes preserve more food indefinitely, so less is wasted; and through dam and canal construction, new areas have been brought under cultivation. Each of these and more have had an incremental effect on the magnitude of the sustainable population. There is, however, a limit to both the amount of arable land and the efficiency with which we can use land for food production and waste disposal. Land becomes depleted of nutrients, particularly where wastewater is discharged to the sea. In irrigated agriculture salt accumulation robs plants of their efficiency, and wind and water erosion are inexorably thinning our top soil. Crops under stress fall prey to blight and insects, and drought is always present somewhere.

LAND AVAILABILITY

We can estimate agricultural land area availability in the future by making a few rational assumptions. Of the earth's total surface area about 70.8% is permanently covered by water, and a significant amount of the remainder is steep mountains, deserts, tundra, parks, cities, protected forest, etc., or permanently frozen. Only about 2/3 of the remaining land can ever be used for agricultural purposes, and of this, perhaps 25% is lost in canals, roads, hedge rows, homes, out buildings and fallow land. Only a little more than six billion hectares are available for crop production. These areal estimates are shown in Table 1. Beginning with 6 billion persons at the turn of the century, in Table 2, we project future populations assuming 1%, 1.5% and 2% per year increases. Many developing countries are increasing at even greater rates, but many of these growth rates are beginning to decline. A dramatic fact evident from Table 2 is that the human population is approaching a point where there soon will be less than 1 hectare of agricultural land per capita to grow our food and treat our wastes. By 2063, 70 years hence, the area for food production will almost surely be less than 1/2 hectare per capita! At the close of the next century, depending on the excess of births over deaths, the availability of arable land will be from 0.4 to 0.15 hectares per capita. Both food production and wastewater disposal will then be major problems particularly if we continue our current practices for food production and waste management.

Table 1. Earth areas; original data from *Handbook of Chemistry & Physics* (1954)

Item	ha*
Area of the Earth	51,010,100,000
Land Area	14,884,700,000
Useful Land Area[1]	8,512,429,700
Agricultural Potential[1]	6,384,322,200

[1] Estimates by author
* 1 ha = 2.471 acres = 0.01 km^2

Table 2. Finite land use for increasing population

Annual rate of population increase:	1.0%		1.5%		2.0%	
Year	Population (billion)	ha/cap*	Population (billion)	ha/cap*	Population (billion)	ha/cap*
2000	6.0	1.06	6.0	1.06	6.0	1.06
2025	7.7	0.83	8.7	0.73	9.8	0.64
2050	9.9	0.64	12.6	0.50	16.1	0.39
2075	12.6	0.50	18.3	0.35	26.4	0.24
2100	16.2	0.39	26.4	0.24	43.2	0.15

* 1 ha = 2.471 acres = 0.01 km^2; cap = capita.

FOOD AND WATER

Thomas Malthus (1798) made two postulates: one, that food is necessary to the existence of man; and two, that the passion between the sexes is necessary and will remain nearly in its present state. He then drew the conclusion, that "The power of population is indefinitely greater than the power of the earth to produce subsistence for man."

Following generally the concepts of Malthus, Dr. Paul R. Ehrlich (1968) predicted uncontrolled population expansion would be accompanied by failing per capita food production in the 1990s. He has been proved correct by the famines in Somalia, Ethiopia, and other parts of north-central Africa that are becoming part of the Sahara-Sudan Desert complex. He predicted that U.N. surplus supplies of food would be used to feed these starving people. He did not predict how these shortages would reveal another dimension of food. The withholding of food and water has become a political force, a potent weapon that can bring entire populations to their knees. Indeed the cruel forces of politics are the cause of most starvation today.

The Green Revolution of the 1970s somewhat postponed Ehrlich's prophesies and, with improved transport, has made the Philippines and India virtually free of grain shortages. The Green Revolution is mainly based on new, more productive strains of wheat and rice that, alas, require more fertilizer, more water, and more pest control than previous agricultural crops. According to Holmes (1993), improvements in rice yields are continuing, but the amount of useable land per person inexorably declines.

The main grain in the human diet is wheat, not rice; but, data for rice production are more available. Productivity of rice can be as high as 6,000 kg per hectare per year, but according to Holmes (1993), Japan's

1991 rice yield was 4,500 kg/ha — about 1.25 $g/m^2/d$. At 1 $g/m^2/d$ of rice production, one would produce 10,000 g/ha/d. At 4,500 cal/g, a hectare of rice will have an energy value of 45,000,000 cal/d. A human requires at least 2,000,000 cal/d for healthful body cell replacement, movement, respiration, and blood circulation. More is required when performing work. So 1 hectare producing 1 $g/m^2/d$ would produce sufficient grain to sustain 22 persons. With this yield, 6 billion hectares could support 132 billion persons. So why are some people starving when there are less then 6 billion to feed? I have mentioned politics but another reason is that the world's average agricultural yield is much less than 1 $g/m^2/d$, in fact it is probably less than 1/20 $g/m^2/d$. To produce 1 g/m^2, each square meter would require at least 2,500 g of water, 500 mg of carbon, 80 mg of nitrogen, 10 mg of phosphorus, about 10 mg of potassium, and 3,000,000 calories of solar energy. A basic problem is that not every hectare shown in Table 1 can provide the necessities to yield 1 $g/m^2/d$ or even 0.1 $g/m^2/d$.

For example, water, the *sine qua non* of agricultural production, although a renewable resource, is often in the wrong place at the wrong time. According to Skinner (1969), "The problems of water are not only to do with abundance but also with distribution and rates of supply. Some areas are well supplied, others water poor. More than any other factor, availability of water determines the ultimate population capacity of a geographic province." Often where there is much water there is little sunlight and vice versa. To bring water to the sun was the basis of the California Water Plan; its major success is often concealed by "dog in manger" politics.

Returning to world concerns, grain storage is another major problem. Most grains including rice are produced during a four month growing season. These must then be stored for use until the next harvest. For rice in the tropics, more than one crop per year is possible, but yields are often far less than 1 $g/m^2/d$ due mainly to lack of either fertilizer or water. During storage, rats, mice, weevils, and fungus take their toll often leaving less then half of the original product. Grain used to feed animals further reduces net yield to, perhaps, less than 1/50 $g/m^2/d$. Unless food productivity is increased well beyond this level, we may expect millions more to suffer depravation and starvation.

Billions now suffer some degree of protein malnutrition. Protein malnutrition is, in fact, a major world problem, not only because of human misery, but because it impairs intelligence and ambition in adults and brain development in infants. Unfortunately, if grain or rice is their only food, large amounts are needed to satisfy the protein needs of a person. Since wheat and rice are only 10–12% protein, an adult must daily consume at least 1 kg of either to obtain the 12–15 g of protein nitrogen required daily. Another disadvantage of grains is that individual grain species are deficient in certain essential amino acids, so some fish or animal-derived protein is a vital necessity.

Is ocean fishing or aquaculture as it is practiced today an answer? NO! The products of commercial fishing or aquaculture are now far too expensive to improve nutrition in developing countries because the price of a kg of fish or shrimp is today greater than the average daily family income in most developing countries. This economic reality explains why those near the poverty level are forced to live on low protein vegetables and grains with very small amounts of animal or fish protein or none at all.

The productivity of various grains as well as their fertilizer, water, and storage requirements should be compared to those of algae grown in ponds. The average yield of primary biomass in algal cultures is 15 $g/m^2/d$ with peak yields as high as 40 $g/m^2/d$ compared to about 1 $g/m^2/d$ for rice. An algal productivity of 15 g dry weight per m^2/d is attainable year round in most areas where solar energy is abundant. Another advantage of microalgae is that they can be grown in either fresh or brackish waters, or sea water. They also grow vigorously on nutrients from decomposing plant, human, and animal wastes diluted in water, thereby relieving the need for commercial fertilizers. Algae may be produced year around reducing the need for long term storage, and their rich protein content permits them to be mixed with low-cost carbohydrates such as corn and barley or molasses enriched fiber.

Beyond nutrition, there is another incentive for growing algae. In spite of its importance as a component of protein, nitrogen can be an environmental problem. The production and uncontrolled discharge of nitrogenous wastes, particularly in the form of nitrate, has created havoc in some ground waters and in natural lakes and streams. Mechanized processes have been developed to convert organic nitrogen to nitrate and then nitrogen gas, but these processes result in the wasting of fixed nitrogen and require two or three kilowatt-hours for each kg of N_2 released. If instead of converting fixed waste nitrogen to N_2, we convert this nitrogen to microalgal protein, we have produced a valuable animal feed. By growing algae in advanced-design ponds, we can recycle 1 to 2 g dry weight of protein nitrogen per m^2/d, and the energy required to accomplish this is less than 1/10 of that required for N_2 release. Advanced ponds may produce their own energy in addition to conserving the energy used for wastewater treatment. Much of the energy content of the treated waste may be recovered through methane fermentation in internal digesters of advanced facultative ponds. In some communities, a supply of methane could reduce the need for firewood harvest. Water, after growing algae, can still be used to produce a crop of grain or forage.

A SOLUTION

We thus come to the potential of producing 5–10 g of algal protein per m^2/d, feeding it to livestock or fish, and thereby producing high grade protein in the form of meat, milk, eggs, and fish for human consumption. Algae can be grown year round in the tropics where most malnutrition prevails today, and because this can be done while we are treating wastewater, the economics are much more favorable than they are with commercial aquaculture today. This fact should be a major incentive for waste collection and, as noted above, algae production can be accomplished in brackish or even sea water fertilized by human, animal, or vegetable wastes. Edwards (1992) has shown how such wastewater aquaculture can be done on a highly decentralized, village-level basis. Huge centralized plants are also possible depending on the extent of waste collection, but the decentralized concept is probably most attainable and economical in view of the high cost of large, long sewers, and the availability of large blocks of land. The land area required for an algal based animal protein production is not great. Only one hectare of land is required to treat and reclaim the waste of 500 to 1,000 persons, less than 1% of the land now used to produce our food. Further developments in the technology are required, but algal- based, village-level aquaculture can support many more people, more healthfully than land-based agriculture (Edwards, 1992). Certainly the two used together skillfully and hygienically can and should improve human nutrition and the quality of life.

How can developing communities begin to adopt this integrated approach? It will not be easy because most developing countries do not have waste collection sewers in smaller towns and villages. On the other hand many do have, or could easily establish, night soil and organic garbage collection systems. This material is well suited to initiate units involving algae, fish and livestock production. But more than technical problems persist. Societies in underdeveloped nations often lack the knowledge, resources, or political stability to undertake novel or costly projects. There is seldom enough money for infrastructure development. Clearly investment capital or subsidy and technical assistance will be needed.

On the more positive side, many developing societies have practiced basic, although inefficient nutrient and energy recovery from wastes for several thousand years (Edwards, 1992). For example, crops are fertilized with night soil or raw sewage, and methane is produced in digesters in many countries. Regrettably, the primitive methods used often lead to infestation with parasites and bacterial or viral diseases, causing severe long range health problems. More advanced, effective, and hygienically sound nutrient recovery systems are needed and should be introduced worldwide in the coming decades.

The best approach to encourage pond-aided communities is probably to construct and operate several advanced waste-fertilized aquaculture systems in selected communities in each country, and provide for town or village leaders to visit and study the facilities. The success of this effort will be a first step in attracting local and international attention to the concept of integrated pond-aided economies as opposed to more conventional aquaculture-based economies. Pond-aided economies will be based on the symbiosis of humans, animals, terrestrial agriculture, and aquaculture sustained by water, nutrients, and energy reclaimed hygienically from wastes. The net result should be improved nutrition, decreased disease and child mortality, increased ambition and wealth, and thus a more stable and sustainable society. This concept has been advocated for years, and technical methods to carry it out were set forth by us some years ago (Oswald and Golueke, 1967, 1968, 1973). Regrettably, advanced ponding has been accepted in only a few places so far. I believe, however, that once advanced ponds are built for hygienic waste treatment and water recovery, other options such as food, fertilizer, and energy production will become obvious and should be slowly accepted. Whether the use of ponds will be sufficient to prevent Ehrlich's population disaster only time will tell.

At a minimum, we must change our wasteful methods of liquid waste management. Most treatment technologies practiced today are based on the use of large amounts of energy for dispersal of nutrients and disposal of water. Such extravagance will eventually bankrupt us. We cannot afford the ruinous competitions of the 20th Century. In the 21st Century our infrastructures must be integrated in every way possible. Certainly wastewater systems must reclaim water, nutrients and energy. They must be integrated with our communities and used to improve aesthetics, sanitation and productivity. In short, advanced pond technology will be required to meet human needs and essential to improve the quality of future human life.

SUMMARY

Sanitation problems of the past resulted from lack of knowledge and environmental control, but such problems now recur not due to lack of knowledge but because diminishing per capita resources raise prices above the capability of some persons or communities to pay for environmental control necessities and precipitate political exploitation of the impoverished. Ponds will be a continuing vital necessity in the 21st Century because they are the most cost effective reactors available for capture of solar energy, for waste degradation, and for recycle of water, nutrients, and energy. Because ponds can be designed to utilize solar energy efficiently for nutrient recycling, they should aid in decreasing the amount of money spent on waste management and improve the availability of nutrients. Inasmuch as there are about 6 billion hectares of arable land in the world and the earth's human population is rapidly approaching 6 billion people, there will soon be less than 1 hectare per capita available, and greater efficiency in food production will be needed. Microalgae can synthesize high protein biomass at productivities an order of magnitude greater than is possible with land crops today. It therefore should be possible to utilize microalgae as animal feed to improve the production and lower the relative cost of meat, milk, eggs, and fish. This, in turn, may permit the stabilization of the human population and eliminate the ruinous competition now evident through hunger and disease in developing countries and the poverty and homelessness in the United States and other developed countries.

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