Wastewater Treatment and Resource Recovery

Report of a workshop on high-rate algae ponds, Singapore, 27-29 February 1980

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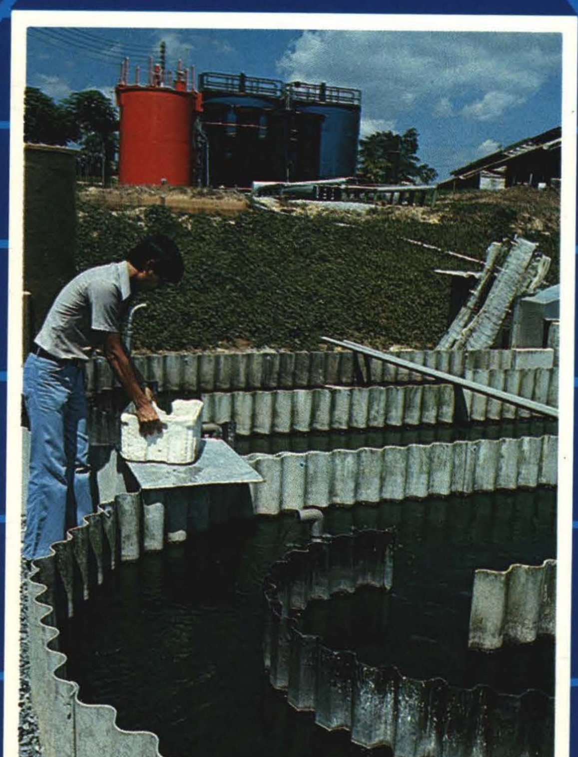

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Wastewater Treatment and Resource Recovery

Report of a workshop on high-rate algae ponds, Singapore, 27-29 February 1980

Sponsored by the International Development Research Centre in collaboration with the Primary Production Department, Ministry of National Development, Republic of Singapore

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Foreword

The 1980s have been declared the Decade for Water Supply and Sanitation. Much attention is being focused on the problem of water quality, giving rise to a search for low-cost methods of wastewater treatment. Domestic sewage, which is 99% water, is extremely dilute and therefore difficult to treat. The Western world has, with few exceptions, chosen to regard such wastes as nonrecoverable and has managed them at considerable cost. There are, however, techniques for treating wastewater and at the same time reclaiming wasted nutrients in the form of reusable by-products.

One of these, the high-rate algae pond, intensifies the natural process of microalgae growth in open ponds. The algae use waste nutrients and solar energy to grow and, when harvested, can be used as a protein-rich component of livestock feeds. The high-rate pond incorporates sewage treatment and feed production and also provides the possibility of reusing the treated water for irrigation or other uses.

Laboratory and pilot-scale trials on wastewater-fed ponds have been successful in Thailand, Australia, the USA, Israel, the Philippines, India, and Singapore. But to develop practical prototype-scale systems, a critical mass of expertise, facilities, and financial support is required. These prototype experiments are now under way in Israel and Singapore where pollution control, water resource development, and the search for local alternatives to imported products are of national importance.

The International Development Research Centre (IDRC) has, for the last 3 years, supported the Primary Production Department of the Republic of Singapore in a project that is demonstrating the functional use of high-rate algae ponds for treating piggery wastes. As the project was about to enter into a second phase to focus on harvesting methods, IDRC, in collaboration with the Primary Production Department, sponsored an international meeting to bring together scientists from nine countries so that there could be a free exchange of ideas. This report has been prepared from their discussions and presentations in an effort to consolidate and disseminate the findings of current efforts aimed at fully developing the high-rate pond process.

In Singapore, the algal biomass is being harvested from the effluent of the demonstration ponds and livestock feeding trials have been initiated. Recent developments there and elsewhere have demonstrated the technical viability and potential of the high-rate algae pond for water reclamation and resource recovery. We look forward to the day when wastewater treatment ceases to be a burden on the economy and becomes a profit-making endeavour.

Michael G. McGarry
Associate Director
Health Sciences Division
International Development Research Centre

The full-scale high-rate algae ponds used to treat domestic wastewater at Elat, Israel (courtesy G. Shelef).

Overview of Wastewater Treatment and Resource Recovery

Lee Boon Yang, Lee Kam Wing,
Michael G. McGarry, and Michael Graham

Introduction

The provision of adequate sanitation and food is a major problem in developing countries. Because of high population growth rates, the situation is likely to worsen. The world population will soon require more than 200 million tonnes of protein a year, and developing countries are searching for alternative protein sources. Wastes, both human and agricultural, are a good source of nutrients and thus potentially a valuable natural resource.

Treatment of wastes by conventional techniques, such as activated sludge plants and aerated lagoons, without reclamation of nutrients and reuse of the treated water is both expensive and wasteful. One way to treat and recycle wastewater is by the use of algae. The protein content of algae is 50%, and annual yields of algae on a kilogram of protein per hectare basis are far higher than yields of conventional crops such as rice, corn, or soybean.

Algae play an important role in the photosynthetic process of facultative stabilization ponds treating wastewaters. Algal systems can be highly productive with biomass yields of 20–40 g of dry matter per square metre per day. Most of the early experimental work with algal systems involved algae growth on media fertilized with inorganic chemicals; however, it is more economical to grow algae on wastes. The addition of costly fertilizers is not required, as municipal and agricultural wastes contain all or most macro- and micronutrients required to maintain peak algal growth.

Stabilization ponds that are 20–40 cm deep maximize algae production because sunlight can penetrate throughout. The conversion of nutrients to algae is extremely rapid under these conditions, taking only 3–4 days. This growth/treatment pond is usually referred to as a *high-rate algae pond.*

The possibility of high protein yields through algae production in ponds has long attracted the attention of researchers. Human excreta-fed ponds in which algae proliferate have been used as fish culture ponds in Asia for centuries.

Although several species of fish are capable of harvesting algae, they require long residence times and do not utilize all the algae available. Direct algae harvesting in water fed with chemical fertilizers began in the Carnegie Institute in the early fifties. It was Dr W. Oswald, at the University of California, Berkeley, who first conceived the idea of the wastewater-fed high-rate algae pond. The concept capitalized on the nutrients naturally available in wastewaters, fine-tuning the established oxidation pond method of sewage treatment and maximizing production of proteinaceous algae for purposes of acquiring a salable by-product. His large-scale pond was operating by 1961 and was followed by centrifugal harvesting at the pilot-plant scale (8). This work was succeeded by outdoor sewage-fed cultures in Australia (20) and the use of night soil-fed ponds in Thailand (19).

Seawater-enriched sewage was used in Woods Hole, Massachusetts (7). In Australia, the focus was on mechanical filtration of algae (5) — a process now being refined in an IDRC-supported project in Singapore. One of the most comprehensive research programs on sewage-fed algae ponds, initiated in 1976 in Israel (29), has recently incorporated work on livestock wastes (26). In Florida, algae are being recovered from piggery wastes (14, 15), and sewage-fed pilot ponds are also operating in India (31) and the Philippines (24).

The Process

In the conventional facultative oxidation pond, algae produce oxygen that is used in bacterial synthesis and biodegradation of organic materials. Conversely, they acquire their needed nutrients, such as ammonia and carbon dioxide, as a by-product of bacterial metabolism. Most of the algae grown in an oxidation pond are capable of synthesizing the essential amino acids — a characteristic not exploited by conventional stabilization ponds, which were designed for minimum maintenance rather than for protein production. The high-rate pond is being developed to provide a maximum yield of algae and a reduction of wastewater organics.

The process (Fig. 1) begins with influent wastewater, which may be domestic or agricultural. Settleable solids are removed from the influent by sedimentation and are treated by anaerobic digestion. The digestion by-product, methane, may be used as an energy source for sterilization and drying of the final algal product.

Clarified influent is added continuously to the pond, which is mixed daily so that settleable solids are kept in suspension. In terms of biochemical oxygen demand (BOD), the pond may be loaded as heavily as 350 kg/ha-day in the tropics. At this loading rate, one may expect the effluent to have a filtered BOD of less than 20 mg/l when treating sewage.

The unicellular microscopic algae must be concentrated before they are removed from the liquid medium. The initial concentration or harvesting step is critical to the technical and economic viability of the pond system and has presented a major obstacle to commercial implementation.

The algae may be harvested by centrifugation, mechanical filtration, chemical flocculation and flotation, or autoflocculation. Centrifugation has been shown to be too expensive. Mechanical harvesting involves filtering the algae out of suspension, whereas chemical flocculation uses alum to flocculate the algae and minute air bubbles to float the algae to the water's surface. The alum can be recovered by acidification of the slurry and then recycled. Self- or autoflocculation has proven successful in testing but requires that specific biological and chemical conditions prevail within the pond. With the exception of centrifugation, the chemical and mechanical harvesting processes show good potential but require further testing and evaluation.

Biomass yields from high-rate ponds may reach 40 g/m^2-day under very favourable climatic conditions. However, in practical terms, biomass productivity of 30 g/m^2-day is more realistic considering occasional unfavourable weather conditions, especially in tropical monsoon regions. Thus, it is possible that biomass yields could average 109 t/ha-year or 49 t/ha-year of protein. This is a 37-fold better yield of protein per unit area than the peak yield attained by soybean in the United States.

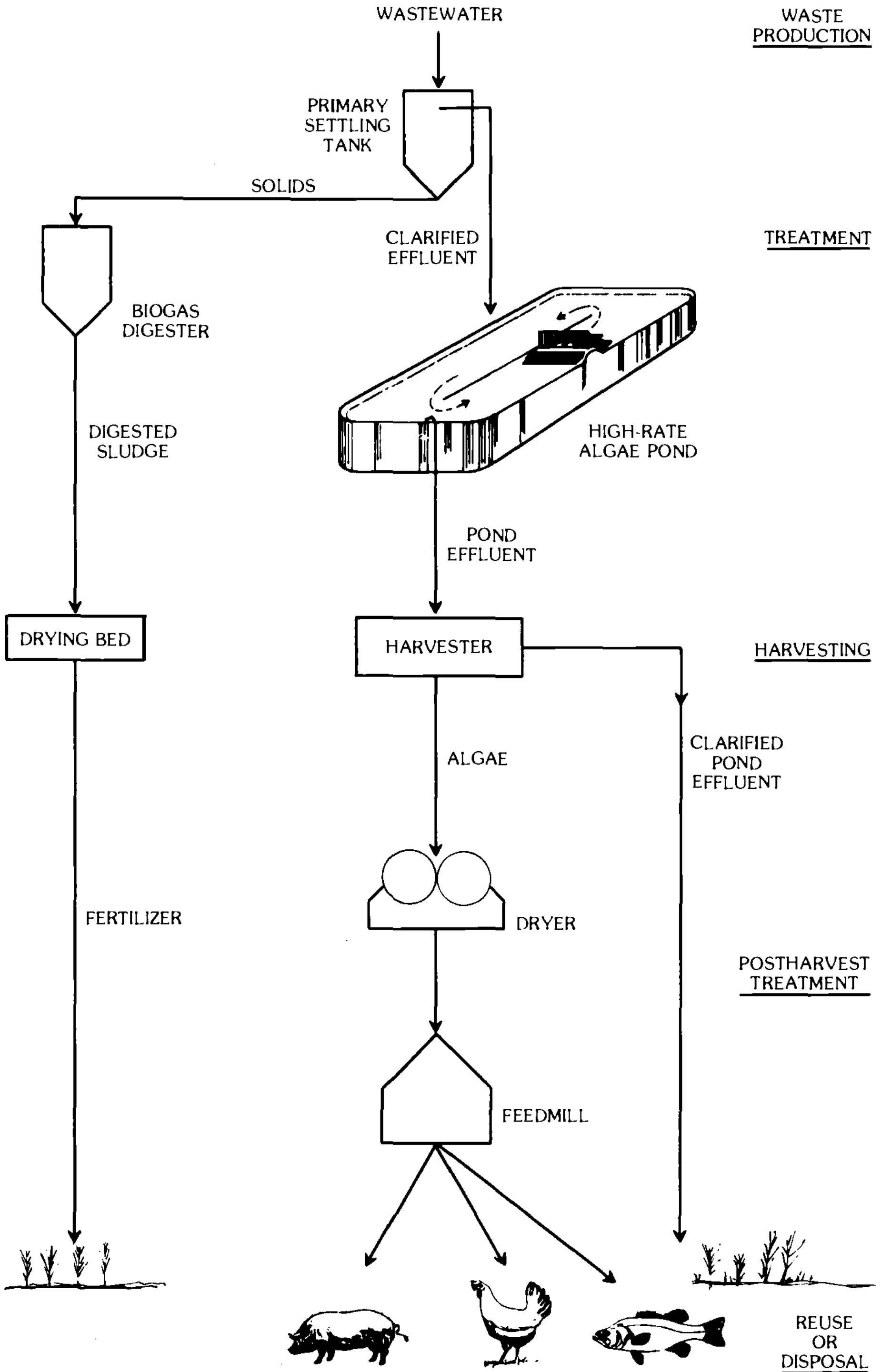


Fig. 1. Scheme for wastewater treatment and resource recovery through algae production in a high-rate pond.

The algae recovered are heat-sterilized and dried in the sun or in drum dryers. Drying may not be required where wet-feeding of algae is feasible.

The Future

The treatment and recycling of wastewater achieves several purposes: primary among them is sanitary disposal of wastewater. Also there is recovery of valuable resources in the form of protein and water. The water discharged from high-rate algae ponds is suitable for irrigation, fish culture, or cleaning and maintenance of animal shelters. This last use would reduce the farmers' need for additional supplies of costly water. As well, the settled solids, after biogas digestion, produce sludge suitable for use as agricultural manure.

The provision of feed for fish and livestock constitutes more than 50% of total operating costs of a farm. Harvested algae provide a valuable protein source for animal feed. Production of algae protein can therefore contribute markedly to the livestock economy, particularly in areas that are dependent on imports of soybean products for animal feed. If agricultural and aquacultural practices are to be rapidly expanded in developing countries to provide supplies of much-needed animal protein, then the above process is an attractive proposition if an economical, reliable system can be achieved.

High-rate algae ponds have been built on a demonstration scale in the USA, Israel, Australia, and Singapore. The main drawback has been the development of a satisfactory harvesting technology that is both economic and efficient. There is a need also to develop techniques for pond operation that allow for a controlled and stable cultivation of algae and a high degree of process stability. Feeding trials of recovered algae as a protein replacement in livestock diets are needed so that appropriate feeding levels can be established.

With these considerations in mind, the Primary Production Department of Singapore entered into a cooperative research venture with IDRC. The project "Pig Wastewater Purification, Reclamation, and Algal Protein Recovery by a High-Rate Pond System" was initiated in September 1977 to purify pig wastewater through a high-rate pond system incorporating water reclamation, minimum environmental pollution, and maximum algal protein recovery and utilization as animal feed. A second phase of the project is now under way to develop equipment and processes for harvesting algae grown in high-rate ponds.

High-Rate Algae Pond

The high-rate algae pond is designed to maximize utilization of sunlight. During photosynthesis, the algae produce oxygen, which is used by bacteria for biodegradation of waste organics fed into the pond as sewage, night soil, piggery waste, or industrial effluent. In turn, algal requirements for nutrients such as phosphates, ammonia, and carbon dioxide are met by bacterial metabolism. Rapid conversion of waste nutrients into algae is enhanced because the algae are dispersed throughout the pond's depth and have a very high photosynthetic efficiency; also they are small and have a large surface-area-to-cell-volume ratio. To maximize algal productivity while maintaining wastewater treatment efficiency, pond depths are shallow, water detention periods are short, and waste loadings are high.

The removal of nutrients from wastewater is mandatory when effluents are discharged into open bodies of water that are subject to eutrophication or when water reclamation by groundwater recharge lowers the quality of the groundwater. Nitrogen and phosphorus are considered to be the key nutrients that must be removed. Although conventional methods of removing them are expensive and technically complex, algae can also be used to "strip" nitrogen and phosphorus from wastewater as a tertiary process.

Recent studies in Israel (27) show that inflow of sewage can be held constant while the pond's depth is varied to offset detrimental seasonal changes in climate. During the summer, the pond is kept shallow (20 cm) and wastewater detention short (2 days), whereas in the winter, the depth and consequently the detention are increased to 60 cm and 6 days. During colder, overcast conditions the algae grow more slowly; therefore, the sewage must be detained longer for adequate treatment and maintenance of a sufficiently high algal population density. Operating at greater depth reduces the extent of dilution and "washout" of algae from the pond during periods of heavy rainfall.

In Singapore, the depth of the pond was held at 20 cm, and the detention period was varied between 16 and 4 days. Algal productivity on piggery wastewaters varied between 5.4 and 25 g/m^2-day. In Thailand (20), ponds were successfully operated at as low a detention as 1 day, and although algal concentrations were reduced, yields were high (more than 40 g/m^2-day in periods of good weather). Later work in Thailand (6) indicated that using dilute sewage produced poorer, possibly nutrient-limited, yields at 3 days detention and 50 cm depth (15.7 g/m^2-day). Solar radiation levels recorded in the fall in Israel are close to those existing in Southeast Asia, and biomass productivity of the Israeli high-rate pond treating sewage in Haifa during 1 year's continuous operation was high (Table 1); however, care should be taken in interpreting the results. The biomass harvested from the pond comprised both algae and a bacteria/organic colloid mix. Although difficult to analyze directly, the algal biomass component was found to be about 57% of the total biomass (total suspended solids).

Table 1: Operational data from four seasons of operation of ponds with variable depths and detention times in Haifa, Israel (27).

	Fall 1978	Winter 1978/79	Spring 1979	Summer 1979	Average
Pond depth (cm)	40	50	35	25	37.5
Retention (days)	3.4	4.25	2.9	2.0	3.14
Pond effluent biomass (mg/l)	385	240	400	440	366
Biomass production (g/m^2-day)	45.3	27.7	48.4	55.0	44.2
Algal biomass production (g/m^2-day)	24.7	11.0	29.0	35.6	25.2
Solar radiation (cal/cm^2-day)	418	335	540	653	488
Algal solar conversion efficiency (based on total irradiance)	3.25	1.81	2.95	3.00	2.84
Total seasonal (yearly) biomass production (t/ha)	41.2	24.9	44.5	50.6	(161)

Total biomass productivity is an appropriate measure of pond performance, in that it is the total biomass that is harvested and used as livestock feed. Protein analysis is normally of the total biomass and not only of its algal component. Crude protein levels in the total biomass are normally higher than 50% and comprise both bacterial and algal protein.

Being functions of flow through the pond, biomass productivities tend to be highest at shorter detention times and greater depths, provided the algae do not reach the stage of being "washed out" of the system. Where dissolved-air flotation is used, a denser algal culture is desirable because this lowers the amount of chemical coagulant required to floc a given quantity of algae. Attempts to reach high yields by reducing detention periods result in lower concentrations of biomass in the pond but greater flow rates from the pond. This method tends to conflict with the desire to have high concentrations of biomass in the pond effluent to reduce the cost of harvesting by chemical coagulation. On the other hand, if mechanical harvesting is successful, the costs of operation are offset by the throughput. In this case, high pond productivities, low algal concentrations, and short detention periods may well be compatible with economic harvesting.

The objectives of minimizing land requirements and harvesting costs while attaining high productivity and high quality biomass cannot be achieved simultaneously. Trade-offs must be accepted so that optimal operating conditions of the pond may be achieved.

Some mixing of the high-rate pond is considered necessary. Ponds in California were originally designed for rapid mixing by large pumping units (23). In Singapore and Thailand, mixing is accomplished by paddle wheels. After considerable field experience, but few controlled experiments, it is now believed that vigorous mixing shocks the culture. For this reason and because of energy requirements, mixing should be minimized. This is confirmed by Thai research with experimental ponds (18). However, there are cases where mixing is necessary. Pond stratification is detrimental and is best broken up by slow laminar flow along the pond channels, which avoids stirring up the bottom deposits that have been suggested to have an inhibitory effect on algal growth.

Reduced algal concentrations and inefficient wastewater treatment have been associated with predation by rotifers, such as *Brachionus*, and cladocera, such as *Moina, Daphnia,* and *Diaphanosoma*. In most high-rate algal ponds this has been a problem only during short periods (6). Predation is of serious concern in Singapore (12) and Florida (13). One method of controlling zooplankton predators that leaves no toxic residues is raising the pH of the pond through lime addition. The effectiveness of this method has been demonstrated in Singapore (11). However, several zooplankton can survive in pH levels even higher than 10 (13) and lime addition of a pH adequate to kill predators may cause undesirable shifts in algal populations and reduced productivity. High zooplankton mortality was achieved in Florida by the addition of ammonia, which in its free ionic form at 17.6 mg/l killed almost all rotifers. An ammonia level of 20 mg/l was suggested. The advantage of this method of predator control is that it uses a relatively inexpensive chemical that is biodegradable and is a naturally occurring algal nutrient.

More recently, experiments in Singapore have indicated that *Moina* can be reduced to undetectable levels by continuous mixing. It is possible that the *Moina* are in fact drowned due to a lack of oxygen at night because the mixing prevents them from coming to the surface to obtain oxygen or eliminates the thin layer of oxygenated water at the surface in which *Moina* can obtain oxygen at night. Other possibilities are that continuous turbulence fatigues the *Moina* or that they are killed by toxic elements in the stirred-up bottom deposits.

At acceptable organic loadings (expressed as kg BOD/ha-day), the high-rate algal pond coupled with dissolved-air algae harvesting is consistently capable of reducing BOD levels in domestic sewage to less than 20 mg/l (18, 27). Should the effluent be discharged into open water, prevention of eutrophication may become a consideration, and strict limitations on nutrients entering the receiving water may have to be imposed. The concentration of nitrogen in such surface waters should be less than 0.1 mg/l and the concentration of phosphorus less than 0.01 mg/l.

A high-rate pond used to treat domestic sewage normally reduces nitrogen levels to less than 30 mg/l and phosphorus to less than 1 mg/l. A second-stage, high-rate pond can be incorporated into the process to treat clarified effluent from the primary high-rate pond's flotator. Initial results with secondary growth ponds indicate that it is possible to grow algae on clarified effluent and reduce nitrogen to 1.5 mg/l and phosphorus to 0.45 mg/l at 3 days' detention (27). Dilution in the receiving water body can further reduce these concentrations to the required levels. Although introducing secondary ponds incurs additional costs, nutrient stripping by other waste treatment processes is even more expensive.

Harvesting

The high-rate algae pond effluent is green and laden with algal cells, bacteria, and colloidal organic matter. The concentration of suspended solids varies from 100 to 500 mg/l depending on operating conditions in the pond, the climate, and the quality of the influent sewage. Harvesting algal biomass from the effluent is desirable both for recovery of algae to be used as livestock feed and for improvement in the quality of the effluent, whether it is reused in agriculture or discharged to the environment.

The pond's biomass is made up of small dispersed particles, largely algae and bacteria — both proteinaceous. In the past, the minute size of the algal cells has given rise to problems in harvesting. Many techniques have been tried, including centrifugation, filtration, chemical coagulation, and settling. Most have been abandoned as being either too expensive or inefficient. Three methods have been shown at the laboratory and pilot-plant scale to have considerable potential: continuous belt filtration; chemical coagulation and flotation; and autoflocculation.

A fourth approach using fish as a natural harvester was investigated by researchers in Thailand but is considered to have less potential. The fish have a low efficiency in harvesting the algae, and the algae can be produced more cheaply for fish feeding either in the fish pond itself or in a conventional oxidation pond before being fed into the fish production pond.

Continuous-Belt Filtration

Past efforts to filter oxidation pond and high-rate pond effluents have encountered numerous difficulties; hence, most recent efforts in algae harvesting have tended toward chemical coagulation and flotation (16, 21). Conventional microstrainer fabric is too coarse to filter effectively most of the unicellular green species found in high-rate ponds. The small size of microalgae requires fine filter fabrics that blind quickly and are difficult to clean.

A continuous-belt filter for harvesting algae using a precoat of paper fibre was developed and tested in the USA (3) and Australia (5). While precoat filtration approaches were successful technically, the use of a precoat caused undesirable operational complexity and increased costs. As a result of the experience gained during the previous work and the availability of new fine-weave synthetic fabrics (5 μm range), fine-weave cloth rather than the precoated filter belt is being investigated in harvesting trials in Singapore (4).

The belt-filter arrangement to be tested in Singapore is shown in Fig. 2. The belt consists of a fine-weave, polyester fabric, having a nominal mesh opening of 5–16 μm, that is bonded to edge strips that are used for belt guidance. A zipper splice allows both belt replacement and changing of the belt to suit the charac-

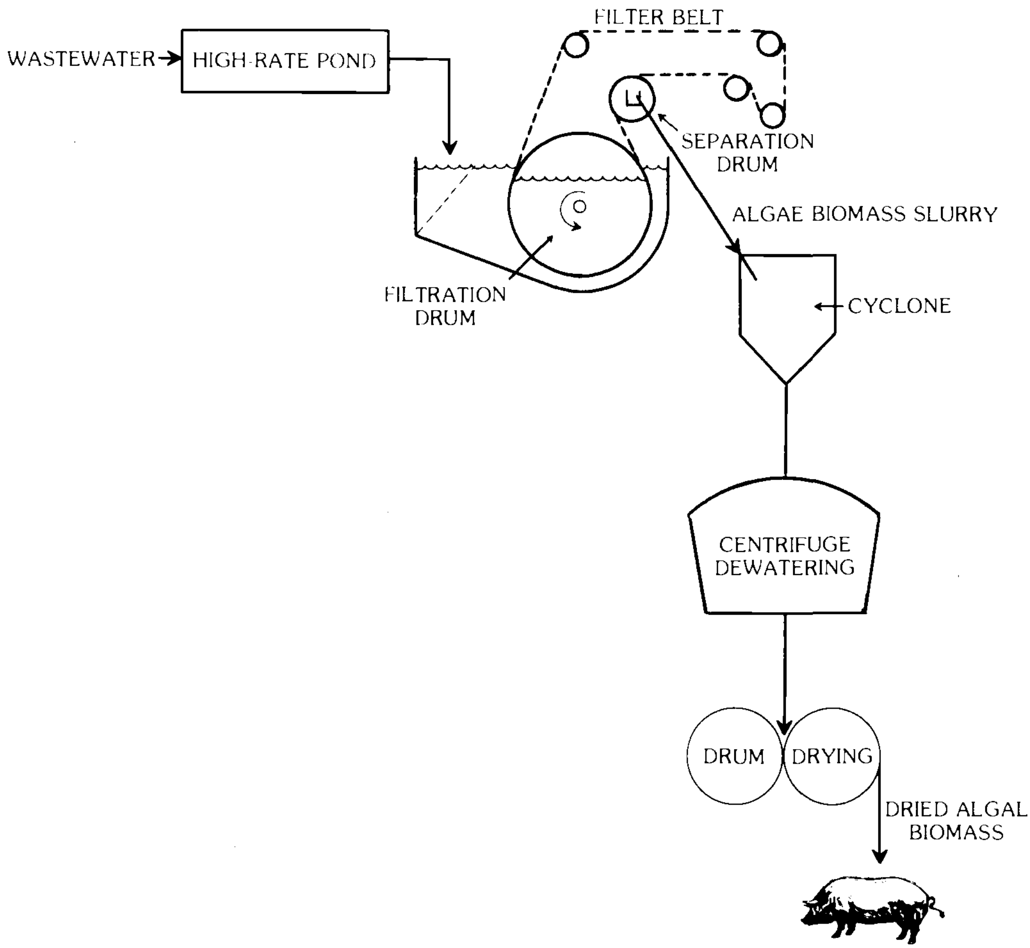
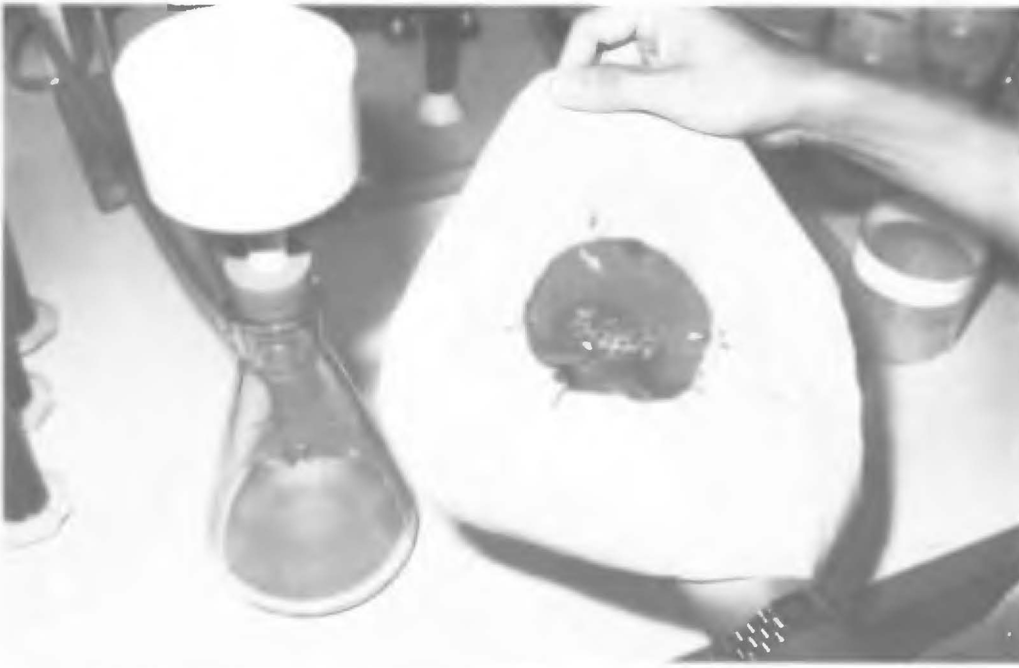


Fig. 2. The steps involved in continuous belt-filtration harvesting.

teristics of the algal species being harvested. The belt is supported on the perforated cylindrical wall of the filtration drum (2 m diameter × 1 m nominal width for the pilot harvester), and the algae are deposited on the outer surface of the fabric as the effluent flows through the cloth and into the drum. Liquid levels outside and inside the drum are maintained by a float valve on the influent line and pivoting discharge pipe to give the desired water pressure drop across the fabric. After leaving the filtration drum, the belt passes around a 0.3-m diameter separation drum in a reverse direction so that the algal solids are on the inside of the belt in contact with the perforated drum wall. A suction box positioned within the separation drum and sealed to the drum wall is connected to a vacuum blower through a cyclone separator. The applied vacuum causes most of the algal solids to be drawn off the belt into the suction box and cyclone, where the algae are collected and periodically removed. The belt is then washed by water showers and returns over a series of rollers to the filtration drum.

Fine-weave fabrics capable of trapping microalgae tend to clog or blind quickly and give thin cakes; hence, it is desirable to operate the separator at rel-



A laboratory demonstration showing the results of algae filtration on a fine-weave fabric.

atively high peripheral drum speeds. The drum is submerged to about 85% of its height. Gravity assists in holding the algae cake on the fabric as it leaves the liquid surface.

The percentage of open area in fine weave fabrics is only about 4% for fabrics with 10 μm openings and 1% for those with 5 μm openings. Although the algae cake causes the greatest resistance to effluent passage through the filter, the small openings are difficult to clean once the fabric becomes clogged, especially if it is allowed to dry. After suction removal of the algae, the belt can be washed by water sprays on both sides of the fabric. This process can be supplemented by chemical or ultrasonic cleaning. Such supplemental steps should seldom be necessary under normal operation. The purpose of the separation drum is to remove the algae cake by suction rather than by backwashing, which would cause severe dilution of the thin cake. This machine is expected to produce a higher percentage of solids than the precoat machine tested in Australia, but it is not possible to forecast the algal slurry solids concentration accurately until the new filter is operational. The solids concentration that can be produced is also a function of cake thickness, which depends on how easily the algae are filtered. Readily filtered species such as *Micractinium* and *Oscillatoria* develop thicker cakes and hence give higher concentration than less readily filtered species.

The fine-weave fabric has considerable advantages over other harvesting methods in that it requires a relatively low energy input and no chemicals. It is very efficient when harvesting the larger species of algae common to high-rate ponds, such as *Micractinium*, but has problems of blinding with the smaller species such as *Chlorella* and is incapable of removing the tiny blue-green *Synechocystis*. Although its capital costs tend to be marginally higher than dissolved-air flotation, operating expenditures are the lowest of any harvesting technique with the exception of natural settling. The Singaporean belt filter has been designed to handle pond effluent from 3000 m^2 of ponds at a throughput of approximately 15 m^3/h and requires under 10 m^2 of fabric. The throughput rate varies greatly with the type of algae — with easily filtered species such as *Scenedesmus* this rate could probably be doubled. For more difficult species such as *Oocystis* it would probably be less. The rate of pond operation and the consistency with which the larger algal species can be grown will have the greatest bearing on the technical feasibility of this harvest method.

Dissolved-Air Flotation

Research in Thailand (19), Israel (28), and more recently in the USA (13) has demonstrated the reliability of dissolved-air flotation as a viable harvesting technique. However, the cost of proven chemicals required for flocculation is a major component of the overall cost.

As illustrated in Fig. 3 algal-laden, high-rate pond effluent is coagulated by the addition of aluminum sulfate (alum), while the pH is controlled by the addition of acid. Air is added in the form of minute bubbles from a pressurized dissolved-air chamber; the bubbles attach themselves to the coagulated flocs of suspended algae, bacteria, and colloidal matter. After further flocculation in the flotation chamber, these flocs rise to the surface where they can be scraped off. Extended residence on the surface allows water to drain out of the float. Further dewatering is achieved in the float thickener, which is simply a storage chamber in which the float is held and removed on a batch basis. The water contained between the flocs that make up the float drains by gravity to the bottom of the chamber and is periodically siphoned off. After thickening, the solids concentration of the float is 7–9%, which is still too thin for drum drying. Further dewatering by centrifuge brings the solids concentration to 15%; the float is then dried to 90% solids before being incorporated into livestock diets.

The dissolved-air flotation method harvests between 85 and 90% of the algal biomass. Flocculation is the heart of the process. If adequate flocs are not formed, they cannot be attached to the minute bubbles of air that lift them to the surface. Although it is important to add enough alum and acid, the amount of chemicals used must be kept to a minimum in view of their cost. Provided the standards set on effluent water quality are not too stringent, it is best to reduce the amount of chemicals to an economic level so that there is a trade-off between the algae allowed to escape from the system and the chemical requirements. Normally, the economic optimum is to maintain the pH between 6 and 6.5 and to use between 100 and 150 mg/l alum, depending on such factors as suspended solids concentration, alkalinity, and phosphorus in the water.

Attempts have been made to reduce costs by the use of less expensive chemicals or those requiring lower concentration to achieve flocculation. Polyelectrolyte flocculants have been developed by the food processing industry and are used in conventional water-supply treatment. These have been investigated in some depth (20) and have shown promise when used in combination with alum. Cationic polyelectrolytes are of greatest interest, with several new types being developed and introduced on the market each year. A new cationic polysaccharide-based polyelectrolyte was demonstrated at the meeting. It successfully

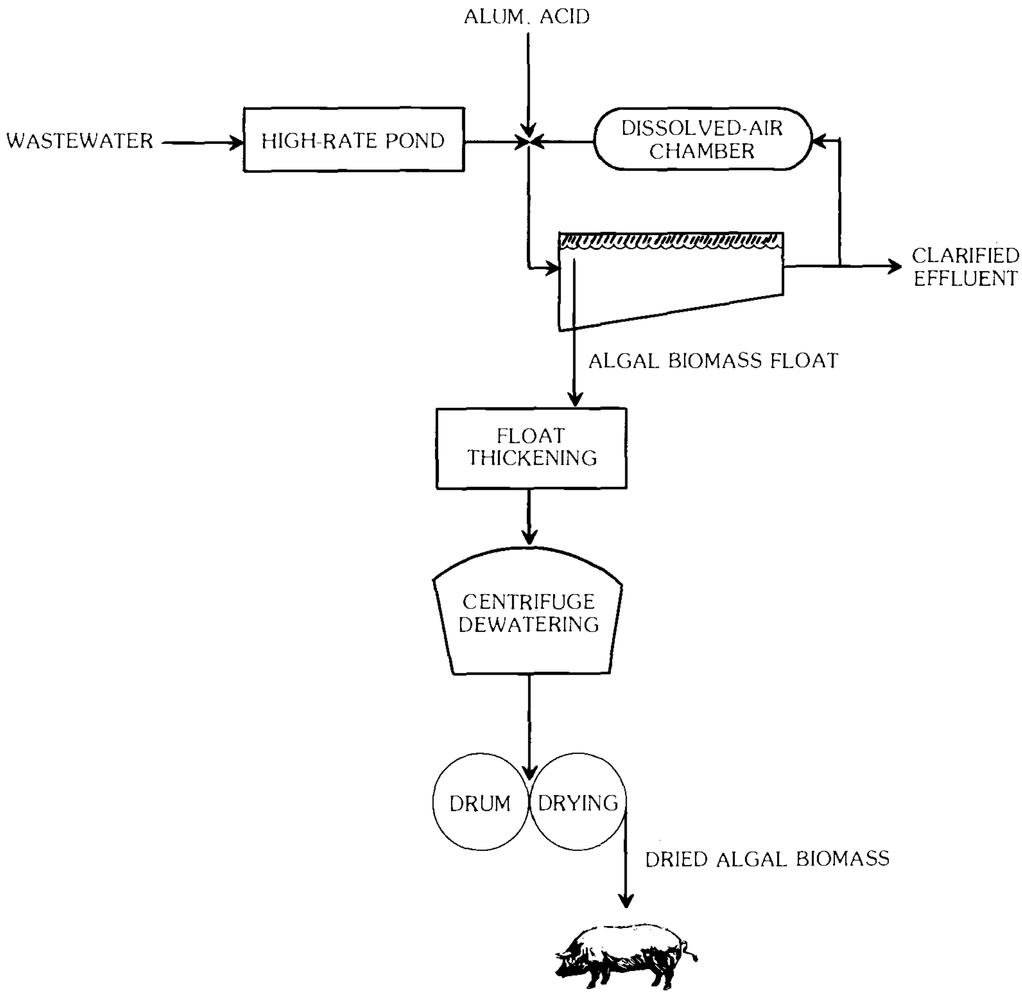


Fig. 3. The dissolved-air flotation method.

flocculated the Singaporean high-rate pond effluent at levels as low as 2 mg/l. Although this particular polyelectrolyte is not yet being marketed and no price is available, it offers potential for a breakthrough in algae harvesting. Chitosan, a natural flocculant taken from the shells of marine crustacea also holds potential as a low-cost chemical for algae harvesting.

Autoflocculation

Autoflocculation is a term used for the settling of algae with the help of natural coagulation or bioflocculation — without addition of chemicals. Not much is known of the physicochemical processes involved and even less is known about how autoflocculation can be induced and incorporated into a controlled, rapid-harvesting system (2).

The pilot-scale centrifuge used to dewater the algal floc (courtesy Primary Production Department, Singapore).

Algae appear to autoflocculate under stress conditions. Intensive sunlight, high pH, and low nitrogen levels have been associated with autoflocculation. The mechanism most probably involves the formation of magnesium hydroxide flocs and the excretion of polysaccharides by the algae and bacteria.

Natural settling, including autoflocculation, is being used as a harvesting technique on a pilot scale in India, the Philippines, and the USA. In Mysore, *Scenedesmus* produced on clean water media is allowed to settle overnight after 6 days' growth in a separate pond (32). The water is carefully decanted before dawn so that a thick algal biomass layer (10% solids) is left on the bottom of the pond. Workers collect the algae by sweeping. This method is the least expensive harvesting technique and has been successfully employed on sewage-grown algae in the Philippines (1). It does require a large amount of land (1/3 of the high-rate pond area), however, and would be most applicable in small algae farms using a batch process.

Growth, Harvesting, and Effluent Quality

In designing the high-rate pond and the harvesting and postharvesting processes, it is important to achieve as close to an overall economic optimum as possible. Given the predetermined criteria of influent flow and quality, land area availability and topography, effluent quality requirements, climate, clarified effluent and algal biomass by-product marketability, and input unit costs, one can manipulate many process variables and even processes themselves to maximize return on the investment.

As previously indicated, short detention periods in the pond are desirable as they lead to increased productivity. Although they also imply more dilute cultures, their effects on the economics of the belt filtration method should be no worse than on the dissolved-air flotation method. Although higher volumes of effluent

The pilot-scale dissolved-air flotation unit being tested in Singapore.

would have to be drawn through the fine-weave fabric, the surface area of the filter would not have to be increased proportionately.

Belt filtration yields effluent that is somewhat inferior to that from chemical flocculation followed by dissolved-air flotation. The flocs trap colloidal particles that would pass through the filter fabric and therefore the effluent that is produced has a BOD consistently less than 15 mg/l when treating sewage. If the effluent is to be used in agriculture and if transfer of pathogens is not considered a problem, the effluent from the belt filter can be used directly. Should higher quality water be required for reuse or groundwater recharge, the effluent could be sent through a slow sand filter that incorporates an active biological layer at its surface or the effluent could be impounded for extended periods in ponds or large reservoirs before discharge or reuse.

A cost-sensitivity analysis (see page 25) can be carried out to determine the economic effects of such key variables as pond detention time; depth; loading; productivity; and harvesting technology including chemical dosage and dissolved-air recycle ratio (in the case of dissolved-air flotation), fine-weave fabric pore size, differential head, and belt speed (in the case of mechanical filtration). Product quality and postharvest variables, such as solids requirements before final drying, can also be assessed through cost-sensitivity analysis, which is an extremely valuable tool in engineering and economic design.

Dewatering and Drying

Centrifugal dewatering and drum drying are established industrial processes that account for a large part of the overall costs. In particular, energy costs for drum drying are very high. Drum dryers will operate with a solids input of up to 15% so every effort should be made to dewater the algae to this point. Alum flocs retain considerable amounts of water and will not drain by gravity beyond a level of between 7 and 9% solids. Polyelectrolyte flocculation, on the other hand, pro-

Algae being dried with a double-drum dryer.

vides a float that has better dewatering characteristics. The dewatering centrifuge used successfully in Israel and Singapore is an automatic desludging disk centrifuge with clarifier bowl able to dewater the float from 7 to 15% solids.

Drying the product to a moisture content of 10% can be achieved on a double-drum sump dryer that can be automatically fed. If pretreatment of the wastewater includes sludge treatment by digestion, energy costs can be reduced if the methane-containing biogas from the digester is directly fed into the steam generator.

Solar drying can also reduce the costs of energy for fuel. In Florida, the dissolved-air flotation float is solar dried on a flat black cloth without prior centrifugation. Partial dewatering is achieved by drainage through the supporting cloth. A plastic cover allowing horizontal passage of air effectively raises the temperature of the algae and improves the drying rates. The area required for drying beds of this type was estimated to be equivalent to some 12% of high-rate pond area (13). Several research projects in developing countries are investigating improved methods of small-scale solar drying of agricultural crops. One such experiment on rice drying at the Asian Institute of Technology in Bangkok passes solar-heated air through a bed of rice. The air, which is heated under plastic sheets by the sun, produces temperatures as high as 50 °C and rapid rates of drying. Experiments of this type may well be adaptable to algae drying and deserve attention.

Utilization

Food production in the form of single-cell protein, in particular algae, offers an attractive possibility in the search for alternative sources of protein. Algae systems have been designed to treat municipal, agricultural, and industrial wastes. A major advantage of these systems is that a mixed culture of algae can be grown on the treated effluent without chemical fertilizers or additional carbon sources. These systems treat the waste and produce protein-rich algae (see 9, 10, 33 for more detail).

Chemical analyses to determine the value of waste-grown algae for animal feed have indicated that the algae contain more than 50% protein on a dry-weight basis and that they are a good source of essential amino acids (Table 2). As well, algae are rich in water-soluble vitamins. In particular, algae are high in carotene, which is required in poultry rations to impart a desired colour to the flesh and eggs.

The protein efficiency ratio (PER), which is a simple and useful test to perform, is normally used to approximate the nutritive quality of proteins. In Singapore (22), rats were used in estimations of the protein efficiency ratios of two different algae. The rats were fed isonitrogenous diets at 10% crude protein levels, and the results showed lower PER values for the two algae species than those for soybean meal and casein, indicating that the protein quality of the algae was somewhat inferior. It has been suggested that the algal protein was less nutritious because of either the species or the processing methods used.

Processing does play an important role in the utilization of algae as feed. For example, in the Singapore study, drum drying was cited as a possible cause for reduced PER values. If algae are dried too long at high temperatures, the lysine they contain may complex with free sugars or with cell walls and thus become less available to livestock. It has also been found that during processing it is essential to rupture the tough cell wall to release the nutrients from the cell. This can be accomplished by drum drying but not by sun drying.

Feeding Trials

Research has been conducted on the potential of algae to replace other more expensive protein sources in rations for fish, poultry, and pigs. Full-scale feeding trials are expensive and time-consuming; however, they are the most accurate method of establishing the nutritive value of feed for these classes of livestock.

In Israel (27, 30), drum-dried algae were fed to two cultured species of freshwater fish, *Cyprinus carpio* and *Tilapia galilea*. In these studies, the algae were used as a replacement for the fishmeal portion of the pelleted diets. Growth rates, weight gain, and general health of the fish were equal or superior to fish fed on the standard commercial diet. A phosphate additive further enhanced the weight gain of the algae-fed fish.

Table 2: Essential amino acid content of steam-boiled and drum-dried waste-grown algae compared with soybean meal and the FAO recommended levels (g/16 gN) (22).

	Algae			
	Steam boiled	Drum dried	Soybean meal	FAO
Arginine	5.24	4.68	6.99	—
Cystine	5.65	3.64	—	—
Histidine	2.02	1.68	2.41	—
Isoleucine	2.91	3.27	5.46	4.0
Leucine	5.99	6.84	7.42	7.0
Lysine	5.66	3.85	6.33	5.5
Methionine	0.94	0.81	1.30	3.5[a]
Phenylalanine	3.75	4.07	4.80	6.0[b]
Threonine	3.47	3.84	3.71	4.0
Tyrosine	3.06	3.33	3.05	—
Valine	4.33	3.80	5.24	5.0

[a] Methionine + cystine.
[b] Phenylalanine + tyrosine.

Poultry have also been given diets containing sewage-grown algae. In Singapore (22), day-old chicks were fed algae as a replacement for soybean in their diets. Feed efficiency decreased, and mortality increased (the vast majority of deaths occurring during the first week of life) at the highest levels of replacement. However, up to one-third of the soybean was replaced by algae without significant differences in feed efficiency or mortality. All broilers fed algae diets displayed dark gold pigmentation of their shanks, skin and meat.

A colour effect was also noted in Israel when algae were fed to broiler chicks and laying hens (27). In this case, the more algae that were fed, the deeper was the coloration of the skin and yolks. At a level of 25% algae replacement of soybean meal, there was no significant difference in the rates of weight gain and the general health of chicks fed algae, compared with those fed standard commercial rations. In fact, if the diets containing algae were introduced after the chicks were 4 weeks old, half the soybean meal could be replaced by algae, although the animals showed more intense colour development.

In the United States, when 15–20% of soybean was replaced with algae in the diets of broiler chicks, growth rates were depressed (13). However, some success was obtained in the U.S. when algae were used to replace soybean in pig diets. On a lysine replacement basis, final weights were equal to controls at a level of up to 30% soybean replacement. Higher replacement levels produced lower final weights (13).

Replacement of soybean in pig diets has also been tried in Singapore (22). At high levels of algae (15.5%) in the diet, growth rates and feed efficiency decreased. However, animals receiving diets with 52% of the soybean replaced by algae exhibited daily weight gains not significantly different from those of the controls. Digestibility trials have indicated that increased levels of algae reduced digestive efficiency. Nonetheless, success at the 52% replacement level is encouraging.

Another interesting feature reported from Taiwan (17) and elsewhere, has been enhanced growth of various animals fed algae as a supplement. It has been suggested that the algae provide a growth factor that is not available in standard rations or that the algae have some antibacterial properties. More work is required to determine the mechanism behind this improvement.

Toxicity

Although good results have been obtained in feeding trials, there has been some concern about toxicologic and pathogenic properties, especially with respect to long-term effects. Studies with pigs in Singapore (22) and with poultry in Israel (27) have found no toxic component in the algal biomass, in the flesh of the algae-fed animals, or in their edible organs.

Nucleic acid levels in algae (4–6%) are lower than in other sources of single-cell protein such as fungi, yeast, and bacteria where the levels can reach 10–20%. Concern has been expressed about the effect of high levels of nucleic acid uptake because of reports of increased serum uric acid levels, as well as gout and kidney-stone formation, in humans. However, the waste-grown algae are not intended for direct human consumption, and feeding trials with pigs have indicated that nucleic acids are not a problem.

The possibility that algae-fed animals may have toxic levels of aluminum has been very carefully checked because large amounts of alum are often used during algae harvesting. Alum in the algal biomass has been found to raise the ash content to levels as high as 30%; however, no evidence has been found through research carried out in Israel (27) or the United States (13) of any toxic effects. The principal adverse effect of the aluminum precipitate seems to be dilution of the organic matter and thus lowered energy content and digestibility of the feed. Development of new flocculating agents, specifically polysaccharide electrolytes and chitosan, may reduce the need for alum. Harvesting by mechanical filtration being developed in Singapore eliminates the problem altogether.

Role of Postharvest Processes

Of the many factors affecting the potential use of algae in animal rations, perhaps the postharvest processes play the most significant role. For example, postharvest processing for green algae must break down the tough cell walls that cannot be broken down by monogastric animals. Drum drying accomplishes this but introduces the concern, expressed previously, that, due to the heat, lysine may form complexes with free sugars or cell wall components that make it unavailable to livestock. If green algae are sun dried, the cell walls normally remain intact and must be ruptured by some other means. Blue-green algae present less of a problem because their cell wall is comparatively easily digested.

Work with fish, pigs, and poultry has shown that the physical nature of the algae feed influences its degree of utilization. For example, better results have been obtained with pelleted feeds than with meals and with wet slurries than with dried algae. More work is required to exploit these advantages.

It is possible to use algae to replace soybean and fishmeal in animal diets. What remains is to determine the optimal levels of replacement. Although up to

52% of soybean has been successfully replaced in pig grower diets and higher levels may be possible with amino acid supplements, it is probable that lower levels of replacement are more practical and would still mean considerable cost savings in livestock protein. Even at such reduced levels of replacement all the algae that could be produced in Singapore would be utilized.

Economic Analysis

In any technological investigation it is wise to carry out an economic analysis of the various processes and configurations that are being studied. This not only provides a rough estimate of overall economic viability (particularly in the earlier stages of research) but also highlights the steps and variables that will be the most costly and therefore deserve research emphasis. One can conduct further analysis of the system using a hypothetic model that varies operating parameters to determine consequent changes in costs of the system. Termed sensitivity analysis, this tool is used to identify the more sensitive variables and subprocesses as priorities for further research.

By coupling economic and sensitivity analyses, one obtains a tool that is particularly well suited to an operation such as sewage treatment and by-product formation that is made up of several subprocesses with many variables. It can, in fact, be used to optimize the entire process to provide maximum benefit for the investment made.

An economic sensitivity analysis of a high-rate algae pond was carried out by Tahal Consulting Engineers Ltd in 1978 for the Israeli National Council for Research and Development. The town of Nahariya was used in a conceptual model. With a population of 33 000, the town was predicted to produce approximately 10 000 m^3/day of sewage in 1985, the year for which the analysis was carried out. The sewage was estimated to be about 500 mg/l BOD in strength and to contain up to 400 mg/l alkalinity (as $CaCO_3$).

Nahariya's Town Council wanted to consider alternatives for its wastewater treatment. The conventional and best-known method that was considered was the aerated lagoon system coupled with polishing ponds. Although providing no feed by-product and an inferior quality of treated water, this is an established and relatively simple-to-operate process. Alternatively, the Council was interested in the high-rate algae pond system that offers potential for resource recovery and reduced energy consumption and is a more logical solution from an agro-economic point of view.

To prepare an economic analysis, the engineering consultants collected details of topography, subsoil characteristics, water quality, input costs, and design parameters; they then designed models of the two treatment methods and calculated and compared the costs.

For this population, the high-rate pond requires an area of 6.7 ha and, in summer, operates at a depth of 40 cm and at a flowthrough or detention time of 2.5 days. During the other seasons, the depth is varied in response to lower temperatures and reduced sunlight so that oxygen and algae production are maximized. Three ponds are required and are constructed with gravel bottoms and corrugated asbestos cement sheet partitions. Experience has indicated that the

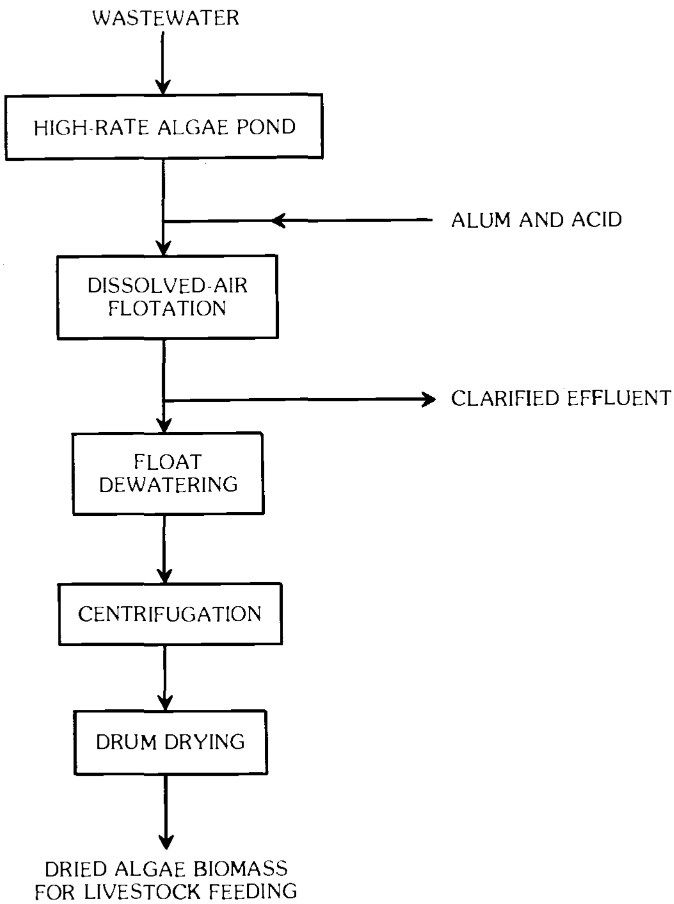


Fig. 4. The high-rate algae pond process used in the economic analysis.

process (Fig. 4) will produce some 1196 tonnes of biomass (at 10% moisture content).

The effluent enters the high-rate pond and, after treatment, is clarified by dissolved-air flotation requiring an estimated 150 mg/l alum and 300 mg/l sulfuric acid. The clarified effluent is predicted to be satisfactory in quality and at least as good as that produced by the aerated lagoon/polishing pond process. A thickening step is next: the algae float is held in tanks from which the water drains. This yields a biomass with 7% solids. A centrifuge is used to further dewater and concentrate the algae to 15% solids before it is pumped to a double-drum sump dryer, which dries the algae to 90% solids — the concentration required for satisfactory storage.

Costs are of two kinds: initial capital costs and recurrent costs. The initial capital for land, equipment, and construction is usually borrowed and in the analysis its cost was represented as annual repayments over the life of the investment (assumed to be 20 years). The interest rate selected for the analysis was 6%, which was felt to reflect the costs of funds allocated from public funds for development projects of this nature. The overall capital costs were estimated at Israeli

£66.6 million, the annual repayment at I£5.48 million. This latter amount was broken down into subprocess costs. Recurrent costs, which are largely associated with operational expenses, were estimated on an annual basis (Table 3), and the total of capital and recurrent costs was calculated to be I£12.3 million.

The aerated lagoon with polishing ponds was also subjected to economic analysis. The total investment was estimated at I£51.7 million, or I£6.6 million annually. Because the quality of effluent from this system is inferior to that from the high-rate pond after treatment by dissolved-air flotation, this cost was conservatively considered as the alternative price of producing a comparable effluent. The high-rate pond system would provide two main benefits: the production of both algae and reclaimed water. It was assumed that the cost of water production was equivalent in the two systems, so the difference (I£12.3 million minus 6.6 million) was considered to be the cost of algae biomass production (I£5.7 million or I£4.75/kg of algae produced). If the algae were sold at this price plus marketing costs, then the high-rate algae pond would be competitive with the aerated lagoon as a treatment method.

Table 3 indicates that the most costly items in the high-rate algae pond system are capital and operating expenses, the chemicals used for harvesting the algae, and the drum dryer. It would be useful to know what impact research into improving the processing steps would have on operating expenses. As an example, better operational control of algal flocculation might allow the amount of chemicals to be cut back to an average of 100 mg/l alum and 200 mg/l acid; modification of the flotation and thickening processes might increase the solids concentration of the algal slurry being drum dried from 15 to 20% thereby reducing energy requirements for drying; and the drum dryer's capital cost could be reduced by a decrease in its drying surface area from 40 m^2 to 28 m^2. These

Table 3: Capital and recurrent costs shown as percentages of total annual costs for the high-rate algae pond system.

	Annual costs 10^3 I£(1973)[a]						
	Capital	Maintenance	Labour	Energy	Fuel & water	Chemicals	Total
High-rate ponds	3181 (26)	609 (5)	875 (7)	519 (4)	—	—	5184 (42)
Dissolved-air flotation	620 (5)	120 (1)	375 (4)	65 —	—	2035 (17)	3215 (27)
Secondary flotation	47 —	9 —	125 (1)	1 —	—	—	182 (1)
Centrifugation	527 (4)	163 (1)	50 —	67 (1)	—	—	807 (6)
Drying	987 (8)	306 (3)	437 (3)	68 —	990 (8)	—	2788 (24)
Land	120 (1)	—	—	—	—	—	120 (1)
Total	5482 (44)	1207 (10)	1862 (15)	720 (5)	990 (8)	2035 (17)	12296 (100)

[a] Percentage of total annual costs are shown in parentheses.

improvements would result in cost reductions of I£0.75 million a year for the dissolved-air flotation process and 0.46 million a year for drum drying. The total annual cost would then be I£11.1 million, and the cost of the algae component would be reduced by more than 20% to I£4.5 million or I£3.73/kg.

This type of analysis highlights important cost parameters that at first glance may appear to have little to do with the cost of production. In this respect the standards for the quality of treated wastewater are very influential. The quality of treated effluent from an aerated lagoon with polishing ponds is inferior to that produced from the high-rate pond system because secondary regrowth of algae in the polishing pond is not removed before the water is discharged. Should the Town Council set higher standards that are more comparable to the quality of the effluent produced by the high-rate pond process, that is to levels comparable to those produced by an extended aeration process, the economic comparison would change drastically. The cost of treating Nahariya's sewage by extended aeration is estimated as I£7.8 million a year. Subtraction of this cost from the total annual cost of high-rate pond processing (I£12.3 million) results in a reduction in the estimated cost of algal production to I£3.8/kg, a reduction similar to that achieved by assumptions about improvements in the flotation and thickening processes.

Great care should be taken in interpreting the results of any such analysis. These examples illustrate only a very simple approach to economic analysis and highlight some of the more costly components of the system that may deserve priority in research toward cost reduction. As important perhaps are the guidelines that indicate the component processes that should *not* receive further research investment. Investigators are too often attracted to processes that offer scientific breakthroughs or that lend themselves to interesting innovations but result in little reduction to costs of the overall process.

These examples also underline how sensitive the analysis is to local conditions. It is important to remember that economic analyses are normally relevant only to the situation for which they are made and are not universally applicable. Indeed, separate analyses must be made for each situation.

The analytic method in the Israeli example is useful to both the researcher and the decision-maker because it approximates costs and provides a means to compare alternative methods. However, it ignores several factors related to the national economy and might well result in an erroneous investment decision. Thus it should be supported by a cost-benefit analysis based on the national economy. To assess the true costs and benefits of the process, one must first investigate and accommodate all relevant factors, such as taxes, subsidies, commissions, and other forms of internal transfer payments. Also, one must consider foreign exchange. Some equipment and chemicals must be imported and paid for in foreign currency, which is often scarce. The official exchange rate used in converting such costs into local currency does not usually reflect the real value of foreign currency. Imported items are priced according to their international value. These are called traded items. Local costs, nontraded items and labour, should be reduced by a standard conversion factor (0.85 in Israel) so that they reflect the desirability of using locally manufactured goods and services. This is termed shadow pricing. Internal transfer payments such as taxes should be subtracted from the cost of nontraded items.

Comparisons of alternative processes can be made through a cost-effective analysis in which initial and recurrent costs are set out in a table after being adjusted to reflect their true cost to the economy. All future recurrent costs can be discounted back to their present-day values by use of a capital recovery factor and then added to initial costs for an estimate of total costs over the life of the project.

The benefits of the project are estimated as being the market value of the algal biomass and water less commission and taxes. The net present value of each alternative treatment process is then estimated as the present-day value of benefits less costs. An internal rate of return is calculated as being the interest rates that would have to be imposed if the net present-day values of each alternative were zero. The process exhibiting the highest rate of return is selected as being the most appropriate one from the national economy's point of view. The cost-benefit ratio is determined by dividing the present values of benefits by costs. These cost-benefit ratios are used in comparisons of alternative processes at a selected interest rate.

Two approaches to economic analysis have been discussed. The first in greater detail by giving an example of a high-rate pond system as compared with a conventional treatment process for an Israeli town. This is useful as a rough guide for the researcher and town authorities. Before any investment decision is made, however, a detailed economic analysis incorporating shadow pricing should be carried out. This technique more accurately reflects national interests and might well reverse the decision in favour of one treatment process, especially where there is a by-product that would otherwise have to be imported.

Singapore: A Case Study

In an effort to solve a water shortage problem in Singapore, the government has designated 60% of the island as a catchment area for rainwater. This has resulted in the relocation of the majority of the pig farms around the Ponggol and Serangoon basins. The pig and poultry system is highly successful in Singapore; however, approximately 14 million litres of pig wastewater and 1000 tonnes of poultry excreta are produced each day. Proper treatment and disposal of these wastes is therefore a serious public health and environmental concern.

Interest has been directed toward high-rate algae ponds because they are part of a treatment system that holds considerable potential for the treatment of wastewater and, at the same time, allows recovery of nutrients in the form of algae.

For the past 2 years, the Primary Production Department of the Ministry of National Development, Republic of Singapore, has been testing a pilot-scale wastewater collection and high-rate algal pond treatment system for 1500 pigs at the Pig and Poultry Research and Training Institute. The objective of the project was to establish a high-rate algae pond system for purification of pig wastewater with water reclamation, minimum environmental pollution, and maximum nutrient recovery in the form of algae.

The wastewater being treated by the pilot plant is generated from part of a farm with a 1500 standing-pig population. The pigs are housed in pens with concrete floors that are washed once a day. The wash-water, excreta, urine, and wasted feed flow by gravity through open drains into a series of three collection sumps. The daily collection of wastewater is stored in one of two holding tanks (50 m^3 each) equipped with mixers. From the holding tanks, the raw wastewater is pumped through one to four fibreglass sedimentation tanks at an overflow of about 3.5 m/h. Underflow from the sedimentation tanks is used for anaerobic digestion studies in a 15 m^3 high-rate digester. Settled wastewater is distributed to the high-rate ponds by a fibreglass flow-splitter box.

Four pilot-scale ponds, each 125 m^2, were constructed by April 1978. The ponds have a racetrack configuration with a channel width of 1.5 m. Each pond is equipped with a low-speed paddle wheel mixer. The pond walls are 500 mm above ground and are constructed with precut corrugated asbestos roofing sheets embedded in a concrete trench. Except for the area near the mixer and a depressed section used to collect excess settleable solids, the pond floor was constructed in five steps: the surface material was stripped away and the exposed clay rolled; a 20-mm layer of sand was then spread over the clay surface, followed by 50 mm of crushed rock and a final rolling with a light roller. The ponds have been in continuous operation since May 1978. By September 1979, two additional demonstration ponds (1230 m^2 each) with 7-m channel width were constructed.

One of the recently constructed demonstration-sized ponds used for mass production of algae in Singapore.

The four pilot ponds were fed daily with settled wastewater from the sedimentation tanks. Pond feeding started at about noon and continued for about 2–3 h as required to give the desired organic loading. Due to variations in wastewater strength and the time required for BOD analysis, the operating variable used was feeding duration at a fixed settled wastewater flow rate. The duration of feeding was selected based on preceding BOD ranges, weather conditions, and the condition of the ponds as assessed by daily visual inspection of pond colour, presence of predators, and dissolved oxygen. Since November 1979, daily estimations of settled wastewater total solids have also been used to set feeding duration. The volume of settled wastewater fed to the ponds was supplemented with clean water, which was added to the ponds as required to bring the pond level back to the nominal operating depth after withdrawal and feeding. The amount of withdrawal was set by desired detention (based on outflow), which was one of the variables studied. Thus the amount of make-up water was dependent on rainfall and losses from evaporation and seepage. The clean water diluted the strength of the settled wastewater.

The nominal operating depth in the ponds was maintained at 200 mm, thus giving a nominal liquid volume of 25 m^3 per pond (excluding the fixed storage in the depressed section below the pond bottom). Trials with greater depths indicated that 200 mm was less likely to favour the growth and dominance of motile algae such as *Euglena*, which tend to form a scum over the ponds during periods of no mixing and lead to excessive light reduction.

The high-rate ponds were slow-mixed intermittently once every 4 h for 15–30 min. During mixing, the velocity was 18–20 cm/s. Since November 1979, continuous mixing of the ponds at reduced velocities has also been introduced.

Samples from the pond were collected and analyzed at least three times a week. Whenever the predator *Moina* was noted in the ponds, the samples were passed through a coarse screen that removed *Moina*. Its weight was excluded in solids determination. Analyses included solids content (total suspended solids, TSS; volatile suspended solids, VSS); biochemical oxygen demand (BOD_5); chemical oxygen demand (COD); total Kjeldahl nitrogen (TKN); ammoniacal nitrogen (NH_3-N); and nitrate/nitrite nitrogen (NO_3/NO_2-N). Field measurements of pH, dissolved oxygen, pond depth, and weather conditions were made daily. Microbiological examination of the pond contents was carried out three or more times a week.

Algae from these high-rate ponds were harvested by centrifuge. Owing to the flow limitation of the centrifuge, only small quantities of the algae could be harvested for analysis and feeding trials in pig, poultry, and rats. Postharvest processing of the algae was by steam cooking or drum drying.

The pilot ponds were started in May 1978. They were filled with clean water to 100 mm depth and then seeded with a small volume (less than 200 l) of pig wastewater containing *Chlorella* spp. The wastewater was derived from a series of small ponds used for earlier studies. Freshly settled pig wastewater was then fed into the ponds to bring the level up to 200 mm in 8 days. Shortly afterward, the alga *Micractinium* outstripped *Chlorella* and became the dominant alga. Between June 1978 and February 1979, the pilot ponds were producing almost pure cultures of *Micractinium*. This alga grew in colonies of four or more cells with radial spines extending more than five times the cell diameter. The colonies were too large to be ingested by rotifers such as *Brachionus* spp., but zooplankton such as *Moina* spp. could consume them. There was no clear relationship between algal colony counts and the suspended solids, as the sizes of the colonies varied greatly.

As the result of severe zooplankton predation by *Moina* spp. in late February 1979, the *Micractinium* culture was decimated. Attempts to suppress the zooplankton by increasing organic loading and, hence, inducing anaerobic conditions in the ponds for short periods were not effective. The organic phosphate pesticide Naled was effective in killing *Moina* at 1 ppm in jar-tests (25) but, when applied to the ponds, had negligible effects on the *Moina* population. The high organic matter in the ponds may have been responsible for reducing its effectiveness, but it was not tested at higher levels because the addition of a pesticide to high-rate ponds adds a toxic residue to the harvested biomass meant for feed application. Lime to raise the pH to 9.3 or higher was tested and found very effective in killing *Moina* in the ponds. Unfortunately, as a result of frequent lime addition in February–March 1979, the *Micractinium* population was replaced by a tiny blue-green alga, as yet unidentified. This alga first appeared in March 1979, giving the pilot ponds an unnatural brilliant green colour.

The pilot ponds were therefore drained and restarted without inoculation of algae. Residual blue-green algae caught in the voids of the crushed rock pond bottoms quickly reestablished themselves as the dominant alga. Following an unstable period of several weeks, larger algae such as *Micractinium, Chlorella, Ankistrodesmus,* and *Oocystis* spp. began to reappear in the ponds. By 5 April 1979, these algae were present in sufficient numbers to be counted. Starting in April with the ponds having an average of 0.8×10^5 algal counts/ml, the algal population rose gradually until an average of 6.3×10^5 counts/ml was reached in July 1979. This increase was observed in spite of frequent periods of heavy predation by *Moina* spp. Differential cell-counts showed that *Oocystis* was the dominant alga (80–90%) in the four pilot ponds from April to May. Other algae seen during this period were *Micractinium, Scenedesmus, Ankistrodesmus,* and *Chlorella* spp. After May, changes in the algal flora became apparent. Although still accounting for 60–75% of the total algae counts, *Oocystis* was giving way to *Ankistrodesmus* in some of the ponds. In pond D, *Ankistrodesmus* became the dominant alga. In early July, *Oscillatoria* was first observed and this filamentous alga soon became the dominant species in all the pilot ponds and also the larger demonstration pond when it was started in September 1979. *Micractinium* began to reappear shortly after low speed continuous mixing was introduced in November and became dominant in the two pilot ponds and the demonstration pond by February 1980.

These observations on the changes of algal flora could not be related to any specific climatic factor or operating parameter except on the occasion when the tiny blue-green algae replaced *Micractinium* following pH adjustment with lime. This could have been a result of die-off of small predators such as ciliates and *Brachionus*, which normally are present and graze on the smaller species. Disappearance of the blue-green alga correlated with the increase of these predators after lime addition was stopped. It appears that algal species dominance in large exposed wastewater loaded ponds is far too complex to be easily controlled. However the biomass productivity of the ponds continues despite changes in species dominance. What is of greater importance is the effect on the required technique of harvesting and degree of harvestability of the biomass. The strong

The storage tanks (in background) and the primary clarifiers used for pretreatment of wastewater fed into the high-rate algae ponds.

cultures of colonial *Micractinium* spp. seen initially in the pilot ponds could be easily harvested by filtration. Filtration would not be feasible for harvesting the small blue-green alga that replaced the *Micractinium* for a limited period following lime addition. Alternative techniques such as chemical flocculation followed by autoflotation may be more appropriate in such cases (13).

Gross biomass productivity is estimated by the total suspended solids present in the daily volume of pond drawoff, which includes algal and bacterial solids. It does not include heavier solids such as large bacterial and algal flocs that settle to the bottom. The gross biomass productivity of the two pilot ponds was determined between July and August 1978. During this period the ponds were loaded with 175 kg BOD/ha-day at a detention time of 16 days. At such a long detention time, the feed volume was sufficient to make up for the daily drawoff of 1.6 m^3. Hence, no clean water was being added to the settled wastewater. The dominant alga was *Micractinium* spp., and there were no predator problems. The average gross biomass productivity values for the two ponds were only 7 g/m^2-day and 4.5 g/m^2-day. It appears that although such a long detention yields dense algal culture in the ponds and removes the need for additional water, gross biomass productivity is too low to warrant such operation where resource recovery is considered important.

The detention time was therefore reduced to 8 days between August and October 1978 by increasing the daily drawoff and adding clean water to the pond to maintain a constant level of 200 mm. Organic loading was maintained at 175 kg BOD/ha-day. Weather conditions from July to October 1978 remained fairly constant. Average gross biomass productivity values during this period for the two ponds were 15.3 g/m^2-day and 18.9 g/m^2-day.

From 25 October 1978 to November 1979, four pilot ponds were in operation despite adverse weather conditions, especially during November 1978 when solar radiation was at its lowest for the 6-month monitoring. A higher organic loading of 200 kg BOD/ha-day was applied to the four ponds, and the detention time was held at 8 days in two of the ponds and reduced to 4 days in the other two. Gross biomass productivity was 16.1 g/m^2-day and 14.3 g/m^2-day at 8 days detention and 19.6 g/m^2-day and 20.5 g/m^2-day at 4 days detention.

Flooding of the ponds owing to heavy rain in December 1978 (more than 500 mm in 24 h) resulted in loss of algae culture from the ponds. This coincided with heavy predation by zooplankton, and it took the better part of the month for the ponds to recover from the effects of flooding. Gross biomass productivity estimations were started again in late December 1978 and continued through the end of January 1979. Operating conditions were maintained as before. The calculated gross biomass productivity for 8 days detention was 18.3 g/m^2-day and 19.7 g/m^2-day and for 4 days detention was 24 g/m^2-day and 25 g/m^2-day. During this period, sporadic predation by *Moina* consumed part of the algae biomass. The predation problem progressively worsened and by February 1979, most of the *Micractinium* were consumed by *Moina*. Following lime addition for predator control, a nonfilterable blue-green alga became dominant. Because this alga could pass through the glass-fibre filters used for total suspended solids determinations, gross biomass productivity could not be estimated by this method. Larger species began to reappear in the ponds by April 1979. The average for the four pilot ponds operated at 6-days detention time and 180 kg BOD/ha-day loading was very low, 6.9 g/m^2-day, largely due to persistent occurrence of *Moina* and lime addition for predator control.

In the absence of regular harvesting of algae from pond effluent, treatment performance of the high-rate ponds was estimated by the percentage of reduction in the waste characteristics between the pond influent and filtered effluent.

Treatment performance under various weather, predation, and operating conditions was determined by measures of BOD, COD, and NH_3-N. The results showed that *Moina* predation and detention time are the most important factors in controlling the quality of effluent and treatment performance. Although treatment performance is best at 16 days detention, the low biomass productivity does not favour this method of operation in practice. A detention time of 8 days seems to provide fairly stable conditions in the ponds. At 8-days detention and under good weather conditions without *Moina*, the BOD removal was 89%, COD 76%, and NH_3-N 64%. Effluent quality and treatment performance at 4-days detention were poorer than at 8 days. Frequent *Moina* predation made it very difficult to compare the treatment performance of the ponds. In our experience, effective predator control may be the key to achieving the expected treatment performance of high-rate ponds.

In summary, initial experience with four high-rate algae ponds has shown that using settled pig wastewater at 175–200 kg BOD/ha-day as the only source of nutrients produces an average gross biomass productivity ranging from 5.4 g/m^2-day to 24.4 g/m^2-day. Productivity was higher at shorter detention times. The need for additional water is a problem at short detention times unless water is recycled. A method for recycling water needs to be tested when an algae-harvesting system is developed for the pilot plant.

The most serious problem encountered was the frequent appearance of the algal predator *Moina* spp. Sudden blooms of *Moina* resulted in rapid depletion of the algal population in the high-rate ponds. Elevating the pH to above 9 was effective against the predator; however, this procedure affected algal species dominance in the ponds and reduced productivity. Since November 1979, continuous mixing of the ponds has been introduced and appears to be effective in controlling predation and improving pond stability and productivity. Although this requires more energy than intermittent mixing, the improved performance may more than offset the higher mixing cost. Studies are continuing to determine minimum mixing velocities and energy requirements, and effectiveness in predator control.

Species dominance obviously will have critical effects on the efficiency of any harvesting method. Smaller algae need more efficient harvesting techniques than do colonial or filamentous forms, which can be easily filtered. Methods that can efficiently harvest algae of all sizes would obviate the need to control species dominance in the pond.

The treatment performance of the high-rate ponds in this study was linked to the appearance of the predators, as well as to detention time. Predators that excrete metabolites into the pond add to the BOD, COD, and NH_3-N in the effluent, thus decreasing the treatment performance of the system.

The problem of predators has not received as much attention as other aspects of high-rate pond management and will need to be investigated in detail before the potential of high-rate ponds can be fully exploited.

Conclusions

Pioneers in algae production had hoped that "clean" culture of algae in chemically fertilized water could solve some of the human protein deficiency problems of the world. However, many factors including the accelerating costs of chemical fertilizers and energy acted against the realization of this idea. Recently, efforts have been focused on the production of algae from organic wastes and wastewater as an alternative means of treating wastewater. An additional benefit of these systems is the recovery of proteinaceous algae that can be readily used for animal feeding.

Low technology algae production systems suited for village-level application are being studied in places such as India and Bangladesh. In Israel, high-rate algae ponds are being studied as a municipal wastewater treatment, water reclamation, and algae production system. Similarly there are projects in the Philippines, Taiwan, and Thailand studying the algal system for sewage treatment and nutrient recovery. Besides the potential for protein production, algae can be a source of exotic biochemicals such as steroids, as shown by the research efforts in Malaysia. In the USA and Singapore, high-rate algae ponds treat the effluent from large pig farms and produce algae for animal feed.

The high-rate algae pond system in Singapore still needs further refinements. During the first 2 years of the project, it was shown that algae production from pig wastewater was feasible. However critical parameters such as degree of mixing, detention time, culture depth, zooplankton control, and algal successions still need to be researched for algae production and wastewater treatment efficiency. In the next 2 years the project will be carrying out tests to optimize these parameters.

Currently, the most serious bottleneck in applying algae production technology is the lack of an economic and reliable algae-harvesting process. A technique whereby algae are flocculated by addition of alum and then separated by dissolved-air flotation has been widely used at pilot plants in Israel, the USA, and most recently, Singapore. Although reliable, this technique is costly because of the constant addition of chemicals. Furthermore, the harvested algae contain a substantial amount of the flocculating agent, commonly alum, which may have toxicologic significance.

The use of flocculating chemicals is avoided in autoflocculation. However, the mechanics of the phenomenon are not yet fully understood, and it is difficult to control the process. Autoflocculation is most applicable to the small-scale, batch culture system of producing algae, and extrapolation to large-scale, continuous systems is technically difficult.

The algae project in Singapore is therefore directing a major effort toward overcoming the harvesting bottleneck. It is developing a novel continuous filtration harvester that will produce algae that are free of flocculating chemicals. Because chemicals are normally not required, the operating cost would be lower. Its limitation is that only relatively large algae are filtered out. On occasions when small algae dominate in the high-rate ponds, the harvesting process needs to be modified by the use of a fine-weave filter fabric or by the addition of a small amount of a flocculating agent. This harvesting process will be studied with a pilot-scale machine now being fabricated in Singapore. At the same time, the project will operate chemical flocculation and dissolved-air flotation equipment for comparisons of the systems' efficiency.

The project will therefore be able to carry out a thorough evaluation of algae feeds with and without alum and to determine their nutritional qualities for pigs and poultry. Experience has suggested that algae can replace up to 50% of the soybean meal in the diets of pigs and poultry without inducing significant performance differences. In relation to utilization of algae, the project will study the effect of postharvest processing on the nutrient qualities of the algae. Although drum drying has been the most commonly and successfully used postharvest process, it is costly because of high energy inputs.

Studies will aim to reduce processing cost and to produce algae that are highly digestible. The objective will be improving the economics of algae harvesting and utilization, which has been shown by Israeli workers to be a major component of the algae production cost.

The next 2 years are, therefore, vital because attempts will be made to optimize the critical aspects of high-rate pond operation, algae harvesting, and utilization. Demonstration of technical feasibility is a prerequisite for a reliable economic evaluation, the results of which could have far-reaching impacts on wastewater treatment and resource recovery.

References

1. Adan, B. and Lee, E.W. 1980. High-rate algal growth pond study under tropical conditions. Paper presented at a workshop on high-rate algae ponds held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
2. Benemann, J.R., Koopman, G., Weissman, J.C., Eisenberg, D.M., and Goebel, R. 1980. Development of microalgae harvesting and high-rate pond technologies in California. In Shelef, G. and Soeder, C.J., ed., Production and use of micro-algae biomass, ch. VI. Amsterdam, Elsevier Press. (In press)
3. Dodd, J.C. 1972. Harvesting of algae with a paper precoated belt-type filter. Davis, University of California. (PhD dissertation)
4. Dodd, J.C. 1980. Harvesting algae grown on pig wastes in Singapore. Paper presented at a workshop on high-rate algae ponds held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
5. Dodd, J.C. and Anderson, J.L. 1977. An integrated high rate pond-algae harvesting system. Prog. Wat. Tech. 9, 713–726.
6. Edwards, P., Sinchumpasak, O., and Ouano, E.A.O. 1980. A study of a sewage fed high-rate stabilization pond in Thailand. Paper presented at a workshop on high-rate algae ponds held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
7. Goldman, J.C. and Ryther, J.H. 1976. Waste reclamation in an integrated food chain system. In Tourbier, J. and Pierson, R.W., ed., Biological control of water pollution. Philadelphia, University of Pennsylvania Press, 197–214.
8. Golueke, C.G. and Oswald, W.J. 1965. Harvesting and processing sewage-grown planktonic algae. J. Water Pollut. Control Fed. 37(4), 471–498.
9. Grisanti, N.E. and Oswald, W.J. 1976. Protein from algae. Session on Processes for New Protein Foods. USA, American Institute of Chemical Engineers National Meeting, 14 April 1976. 25p.
10. Hintz, H.F., Heitman Jr., H., Weir, W.C., Torell, D.T., and Meyer, J.H. 1966. Nutritive value of algae grown on sewage. J. Anim. Sci. 25(3), 675–681.
11. Lee, B.Y. 1979. The utilization of pig wastewater for algal protein recovery in high-rate ponds. Presented to a panel meeting on "Food, Fuel, and Fertilizer from Organic Wastes." Board on Science and Technology for International Development. NRC, NAS: Airlie, Va., 6–8 August 1979.
12. Lee, B.Y. and Dodd, J.C. 1980. Production of algae from pig wastewater in high-rate ponds. Paper presented at a workshop on high-rate algae ponds held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
13. Lincoln, E.P. and Hall, T.W. 1980. Critical factors in the large-scale production of microalgae. Paper presented at a workshop on high-rate algae ponds

held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
14. Lincoln, E.P. and Hill, D.T. 1980. An integrated microalgae system. In Shelef, G. and Soeder, C.J., ed., Production and use of micro-algae biomass, ch. III. Amsterdam, Elsevier Press. (In press)
15. Lincoln, E.P., Hill, D.T., and Nordstedt, R.A. 1977. Microalgae as a means of recycling animal wastes. J. Am. Soc. Agr. Eng., No. 77-5026.
16. Lincoln, E.P., Hill, D.T., and Nordstedt, R.A. 1978. Harvesting algae from lagoon effluent. Agric. Eng. 59, 16–18.
17. Lo, M.C. 1980. Microbial treatment and utilization of night soil. Paper presented at a workshop on high-rate algae ponds held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
18. McGarry, M.G., Lin, C.D., and Merto, J.L. 1973. Photosynthetic yields and by-product recovery from sewage oxidation ponds. In Jenkins, S.H., ed., Advances in water pollution research. U.K. 521–535.
19. McGarry, M.G., Ng, K.S., Leung, N.H., and Lee, T.L. 1974. Wastewater reclamation under tropical conditions. Process Biochem. 9(7), 14–24.
20. McGarry, M.G. and Tongkasame, C. 1971. Water reclamation and algae harvesting. J. Water Pollut. Control Fed. 43(5), 824–835.
21. Moraine, R., Shelef, G., Meydan, A., and Levi, A. 1979. Algal single cell protein from wastewater treatment and renovation process. Biotech. Bioeng. 21, 1191–1207.
22. Ngian, M.F. and Thiruchelvam, S. 1980. A nutritional evaluation of pig wastewater-grown algae. Paper presented at a workshop on high-rate algae ponds held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
23. Oswald, W.J. 1969. Current status of microalgae from wastes. Chem. Eng. Prog. Symp. Ser. 65, 87–92.
24. Oswald, W.J., Lee, E.W., Adan, B., and Yao, K.H. 1978. New wastewater treatment method yields a harvest of saleable algae. WHO Chronicle 32, 348–350.
25. Schroeder, G.L. 1975. Effect of Bromex-50 on plankton population in fish ponds. Bamidgeh — Bulletin of Fish Culture in Israel, March.
26. Shelef, G. 1979. The combination of algal and anaerobic waste treatment in a bioregenerative farm system. Tokyo, United Nations University, Food and Nutri. Bltn. Supp. 2, 105–113.
27. Shelef, G., Azov, Y., Moraine, R., Sandbank, E., and Oron, G. 1980. Waste treatment and nutrient removal by high-rate algae ponds. Paper presented at a workshop on high-rate algae ponds held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
28. Shelef, G., Moraine, R., Meydan, A., and Sandbank, E. 1976. Combined algae production-wastewater treatment and reclamation systems. In Schlegel, H.G. and Barnes, J., ed., Microbial energy production. Gottingen, Erich Goltze KG, 427–442.
29. Shelef, G., Oron, G., Moraine, R., and Azov, Y. 1980. Algal mass production as an integrated part of wastewater treatment and reclamation. In Shelef, G. and Soeder, C.J., ed., Production and use of micro-algae biomass. Amsterdam, Elsevier Press. (In press)

30. Technion-Israel Institute of Technology and Sherman Environmental Engineering Research Center with the Fish and Aquaculture Research Station, Ministry of Agriculture, Israel. 1976. Fish feeding experiments with algae. A progress summary of a project "Combined Systems for Algal Wastewater Treatment and Reclamation and Protein Production, October 1975–May 1976." 3p.
31. Venkataraman, G.S. 1979. Indian experience with algal ponds. Tokyo, United Nations Univ., Food and Nutri. Bltn. Supp. 2, 68–72.
32. Venkataraman, L.V., Madhavi Devi, K., and Mahadevaswamy, M. 1980. Freshwater cultivation of algae with possibilities of utilizing rural wastes in India. Paper presented at a workshop on high-rate algae ponds held in Singapore, 27–29 February 1980. Text included on microfiche in IDRC-154e, International Development Research Centre, Canada.
33. Vincent, W.A. 1969. Algae for food and feed. Process Biochem. 3p.

Abstracts of Presented Papers and List of Participants

Abstracts of Presented Papers[1]

A study of a sewage-fed, high-rate stabilization pond in Thailand

Peter Edwards, Onanong Sinchumpasak, and Ely A.O. Ouano

A high-rate stabilization pond is described that is part of a sewage driven, combined waste treatment recycling system consisting of three stages: a 200 m^2 high-rate stabilization pond, a series of 4 m^3 concrete fish ponds, and a maize plot. Because the sewage was very weak, the pond was nutrient-limited and not light-limited. At a detention time of 3 days, the mean phytoplankton concentration was 94 mg/l, and the mean phytoplankton yield 15.7 g/m^2-day or an extrapolated yield of 57.3 tonnes/ha-year. A yield at least double this should be attainable in Thailand without nutrient limitation in a high-rate stabilization pond. The phytoplankton community in the high-rate pond was generally stable but collapsed on two occasions. No seasonal variations in composition of the phytoplankton community were discernible. The land required to treat domestic sewage from a hypothetical city of 100 000 people was estimated to be 8.93 ha, and the phytoplankton concentration and the algal yield were calculated to be 420 mg/l and 32.8 g/m^2-day (120 t/ha-year) respectively, using Thai solar irradiance data.

High-rate algal growth pond study under tropical conditions

B. Adan and E.W. Lee

High-rate algal growth pond systems for waste treatment are usually less expensive to construct and operate than conventional waste treatment systems, are reliable for BOD and nitrogen removal, and provide for nutrient reclamation. For these reasons, a study in the Philippines was made of a high-rate algal pond to determine the feasibility of the system to treat sewage, remove nutrients, and possibly reclaim water and nutrients. The background and theory of the system are provided, and the experiments and their results are explained. The probable significance of these findings to the overall water-management program in Laguna de Bay is also discussed.

Recycling of palm-oil mill sludge discharge nutrients through SCP (*Chlorella vulgaris*) culturing

P.M. Sivalingam

A strain of *Chlorella vulgaris* that thrives well in the adverse conditions of palm-oil mill sludge effluent was isolated. The characteristics for its optimum prop-

[1]The complete texts of the papers presented at the workshop are included in an unedited form on the microfiche pocketed on the inside back cover of this book.

agation in fermented palm-oil mill sludge effluent are as follows: pH, 7; temperature, 35 °C; and fermented sludge dilution, 3–4 times. NO_3^- and PO_4^{3-} additions in the form of $NaNO_3$ and Na_2HPO_4, respectively, at 10 ppm facilitate its multiplication. Growth enhancement effects were also observed for amendments to the salinity and bicarbonate concentrations. It was found through algal culture experiments that *C. vulgaris* could lower the BOD load of fermented sludge from 1080 ppm to 40 ppm, which meets the limits set by the Government of Malaysia. Biochemical analytical evaluation of harvested *Chlorella vulgaris* also demonstrated the possibility of utilizing this species for human consumption, animal husbandry, and fish feeding.

Microbial treatment and utilization of night soil

M.C. Lo (presented by H.W. Huang)

This study is divided into two parts. The first part deals with the efficiency of night soil treatment with photosynthetic bacteria (PSB) and *Chlorella*. The duration of night soil treatment with PSB and *Chlorella* proved to be 20 days faster than the traditional activated sludge or trickling-filter method and 10 days faster than the aerobic digestion method. Furthermore, much less sludge was produced. The second part compares the growth of chickens fed *Chlorella* with the growth results obtained with commercial feeds. With broilers, feed costs were reduced 14–20%, and with laying hens, feed costs were reduced by 18% while 16% more eggs were produced and, on average, the eggs were 5% heavier.

Freshwater cultivation of algae with possibilities of utilizing rural wastes in India

L.V. Venkataraman, K. Madhavi Devi, and M. Mahadevaswamy

Concentrated efforts to utilize algae grown and harvested from fresh water, sewage, and seawater are progressing in India. Indian farmers are increasing the use of blue-green algae as a biofertilizer, and this awareness is helping in efforts to convince and motivate farmers toward profitable uses of algae grown on both fresh water and wastes. Emphasis is being placed on rural applications so that the algal biomass will reach the rural poor either directly as a supplementary food protein or indirectly through animal feeds. Acceptability is a major factor in promoting the use of algae in food; therefore, feed utilization is an immediate objective.

Culture of algae in Bangladesh

F.Z. Majid, Momena Khatun, and Rahima Khatun

Continual use of chemical fertilizers without sufficient organic manure is gradually deteriorating soil quality in Bangladesh. Therefore efforts are being made to use aquatic weeds as a source of organic manure for fertilizer. Also, attempts will be made to supplement livestock feeds with algal protein. Studies to determine the feasibility of this program have been set up. The efforts are designed to develop simple culture methods that will use inexpensive media and indigenous culture vessels such as clay pots.

Waste treatment and nutrient removal by high-rate algae ponds
G. Shelef, Y. Azov, R. Moraine, E. Sandbank, and G. Oron

One of the only economic uses of mass cultures of algae is their growth on organic wastes, from which they produce oxygen for biodegradation of organic matter. Agricultural wastes, particularly animal wastes, can be treated by these algal systems and produce considerable biomass yields that can be harvested as a source of animal proteins. The work in Israel is a comprehensive study of the use of high-rate algae ponds for treatment of municipal wastewaters. It involves extensive laboratory work and outdoor studies with continuous operation of different sized ponds. This has been coupled with extensive animal feeding experiments and nutritional and toxicological studies with fish, broiler chicks, and laying hens.

Critical factors in the large-scale production of microalgae
E.P. Lincoln and T.W. Hall

An algae culture 0.08 ha in area, integrated into the waste treatment facility of a modem swine operation, has been monitored for various critical factors underlying species succession and productivity losses. The blue-green alga, *Synechocystis* sp., which dominates the culture in midsummer, was found to be toxic to poultry and mice but not to swine. Its occurrence was correlated with the climatic conditions of high temperature and sudden reductions in solar irradiance. Grazing by rotifers *Brachionus* and cladocerans *Diaphanosoma* was the single factor most detrimental to productivity. Zooplankton control was accomplished by raising the free NH_3 concentration of the medium to 20 mg/l. Algae harvest averaged 14.9 kg/day of air-dried algal solids with a maximum of 50 kg/day. One year of harvesting at 40% capacity produced 2.02 t corresponding to a yield of 25.3 t/ha-year. Feeding trials of the sun-dried algal product gave acceptable growth up to a limit of 10% of the diet by weight for broiler chicks and about 5% for swine. Monitoring the entire culture system for enteric bacilli showed a substantial reduction of fecal coliforms at the harvest point. No pathogenic forms were found at any point in the system.

Production of algae from pig wastewater in high-rate ponds
Lee B.Y. and Joseph C. Dodd

The construction and operation of several high-rate ponds designed for pig wastewater treatment and algae production in Singapore are described. During the first year of operation, adverse weather and severe zooplankton predation were experienced. Estimates of gross biomass productivity based on filtered suspended solids determination ranged from a maximum of 25 g/m^2-day to a minimum of 4.4 g/m^2-day. Removal of BOD in the absence of predators at a detention time of 16 days was greater than 90%. At a shorter detention time, 4–8 days, the BOD removal was reduced. Appearance of a zooplankton predator, *Moina*, coincided with pronounced deterioration of the pond effluent quality and reduction in biomass productivity.

Harvesting algae grown on pig wastes in Singapore

Joseph C. Dodd.

The harvesting, or initial concentration step, in the integrated high-rate, pond-nutrient recovery system is critical to its technical and economic viability and has presented a major obstacle to commercial implementation thus far. Considerable emphasis has therefore been placed on this aspect in Singapore, and a continuous filtration method is being developed. The operating and construction details of this method, which is based on a continuous fine-weave belt filter, are given.

A nutritional evaluation of pig wastewater-grown algae

M.F. Ngian and S. Thiruchelvam

Few nutritional studies on algae involving farm animals have been done on the nutritive value of sewage-grown algae. At the Pig and Poultry Research and Training Institute, Singapore, the nutritive value of pig wastewater-grown algae was determined with pigs, broiler chicks, and rats. Although the protein quality of the algae was inferior to soybean meal, it was found that 52% of the soybean meal could be replaced by algae in pig grower diets. Levels of 30% replacement in broiler diets decreased growth rate but caused no decrease in feed efficiency or increase in mortality.

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