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Comparison of Centrifugation, Dissolved Air Flotation and Drum Filtration Techniques for Harvesting Sewage-grown Algae

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ABSTRACT

Three different techniques of harvesting microalgae from four pilot scale (125 m^2) and two demonstration ponds (1200 m^2) have been investigated. The processes included centrifugation, chemical flocculation followed by flotation and continuous filtration with a fine-weave belt filter. None of these processes was completely satisfactory. Centrifugation gave good recovery and a thickened slurry, but required high capital investment and energy inputs. Dissolved air flotation was more economical, but, if the recovered algae were to be incorporated into animal feed, the use of flocculants such as alum could have undesirable effects on the growth rate of the animals. This problem could be overcome by the use of non-toxic flocculants. The continuous filtration process had significant advantages in energy efficiency, economics and chemical-free operation. The only drawback of this process was that the efficiency depended on the size and morphology of the algae.

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Key words: Microalgae, harvesting, centrifugation, filtration, dissolved air flotation.

INTRODUCTION

High-rate algal ponds have been studied for many years as a means of waste water treatment and resource recovery in the form of protein-rich microalgal biomass.[1-3] The Singapore Algae Project reported here was designed to study the treatment of piggery wastes using high-rate ponds. The facilities developed on an area of about 50 hectares include a comprehensive system of waste management, primary pig waste collection and separation, a biogas digester, high-rate algal ponds, alternative harvesting facilities, feed-mill and an analytical laboratory.[4] The unique integration of the research facilities allows the concept of high-rate algal ponds to be thoroughly investigated by researchers of various expertise ranging from waste management to animal nutritionists and veterinarians. The open system of algal ponds comprised 4 small pilot ponds, each of 125 m^2 in area and 2 demonstration ponds, each of 1200 m^2. The design was ideal for tropical conditions and was found to withstand rough operating conditions over 5 years without any major problems.[5] Harvesting of microalgae is an important part of an efficient treatment system because the suspended solids in the pond effluent consist mainly of algal cells which need to be removed in order to upgrade the effluent and to yield the algal biomass. Different methods have been tested at various places with varying degrees of success.[6] However, so far no method has been exclusively effective in achieving the desired reliability and low cost in operation. Among the methods reported, chemical flocculation with lime or alum followed by separation of the flocs by sedimentation or dissolved air flotation (DAF) seems to be the most economical.[7] In Singapore, three different techniques of harvesting microalgae were tested: centrifugation, flocculation followed by dissolved air flotation and continuous filtration through a fine weave. Their effectiveness and economic feasibilities are described in this paper.

CULTURE INSTABILITY AND POND PRODUCTIVITY

A wide variety of algal species is present in the high-rate ponds.[8] Instability of the algal cultures and fluctuations in algal flora are often observed owing to a number of factors. Some of these, e.g. operational conditions and invasion by natural grazing organisms such as rotifers and *Moina*, can be controlled to a certain extent, while the effects caused by other factors, e.g. climatic and physico-chemical changes in the pond due to the organic content in the waste from the pig farm, cannot be easily controlled. Species like *Oscillatoria, Micractinium, Spirulina* and *Scenedesmus* are desirable for harvesting purposes because of their larger size and more complex shape as compared with the single cellular forms such as *Chlorella* and *Oocystis*, which are difficult to concentrate.

Algal biomass productivity levels in the ponds vary quite widely during the year (see Fig. 1). High levels, of up to 60 g m^{-2} day^{-1}, have been achieved during periods of sunny weather, whereas during the rainy season towards the end of the year, the productivity level dropped below 10 g m^{-2} day^{-1}. On the average, the high-rate algal ponds in Singapore produced about 23 g m^{-2} day^{-1}. This represents a productivity level much higher than some reported from California[9] and is equivalent to those reported in Thailand.[10]

CENTRIFUGATION

The use of centrifugation is not a new concept as the process is widely used in the food industry and for algal harvesting.[11] In view of the relatively low concentration of solids and presence of the smaller species of algae (*Chlorella* and *Oocystis*) predominating in the pond, a disc centrifuge (Alfa Laval Model BRP× 207 SG7/P) was used.

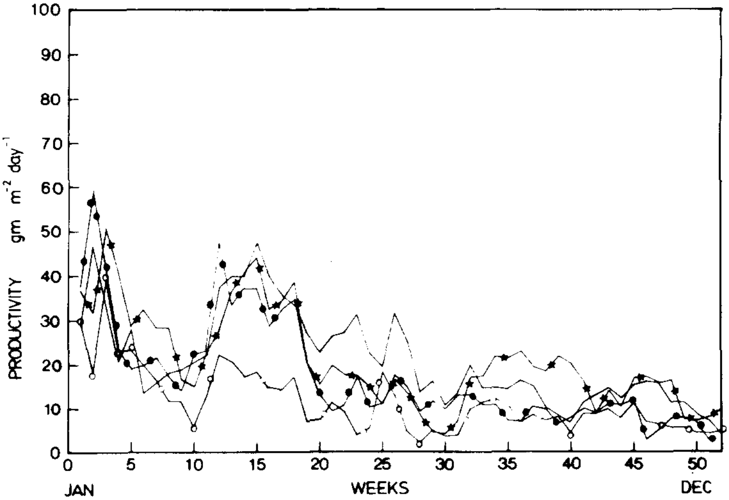

Fig. 1. Productivity of high-rate algal ponds at Singapore; ★ = Pond A, ○ = Pond B, ● = Pond C, — = Pond D.

Experimental work was carried out to determine the efficiency of recovery, the nature of the thickened slurry, the throughput and the power consumption. The conclusions reached from these studies were that the centrifuge is effective in harvesting algae with recovery in excess of 90% and that the recovery is directly dependent on the flow throughput. The thickening effect of the disc centrifuge was also impressive giving slurries of between 4 and 5% dry solids content. Further work carried out with an improved design of a solid bowl decanter gave slurry with a dry solids content in excess of 15%.

The particular model used could handle up to 4 $m^3 h^{-1}$ of effluent. However, in order to achieve a high recovery, only 2 $m^3 h^{-1}$ can be harvested efficiently. The flow throughput is dependent on the algal species in the pond with small species corresponding to a lower effective throughput. The use of centrifugation for harvesting the relatively low concentration (0·04–0·07%) of total suspended solids in the pondwater is restricted by the high cost of power required in handling large quantities of water. On average it was found that the energy demand was 1·3 kWh m^{-3} of pond water. High removal rates of algae correspond to lower BOD_5 (biological oxygen demand measured after 5 days incubation at 20°C) values in the clarified effluent from the disc centrifuge. The unfiltered BOD_5 of the pond mixed liquor was 300 mg $litre^{-1}$. The mean BOD_5 of the clarified effluent from the disc centrifuge was found to be higher (100 mg l^{-1}) than that of the effluent from the other two systems of harvesting.

DISSOLVED AIR FLOTATION (DAF)

Although the design of equipment for dissolved air flotation is well established for sewage sludge thickening, its application to algal harvesting is still relatively new. To increase the particulate size of the algal biomass, which is important for this method, flocculants are added to bind the cells together to facilitate settling. Air bubbles, passed into the solution, will adhere themselves onto the particulate mass, thus increasing the buoyancy and causing the algal particles to float to the surface where a compaction zone is formed. A common problem encountered with dissolved air flotation systems is that oversized bubbles break up the floc. To achieve the required size of air bubbles, a saturation tank is necessary to obtain a supersaturated solution of air in water. The algal float which is formed on the surface of the flotator and which would be allowed to stand for a period of time is intermittently scraped into a collection trough, while the clarified water usually flows out via a weir discharge. The hydraulic flow pattern of the DAF is of primary importance to the efficient function of the system.

A simplified mathematical model can be represented as:

$$\frac{A}{S} = \frac{RC_S\,(f(p+1)-1)}{QS_i}$$

where

$\frac{A}{S}$ = Air/solids ratio (kg of air per kg of solids)

$\frac{R}{Q}$ = recycle ratio, i.e. recycle flow rate ($m^3\ h^{-1}$)/waste water flow rate ($m^3\ h^{-1}$)
C_S = Saturation concentration of air in water at 30°C (litre m^{-3})
p = Operating pressure (atmospheres)
f = Proportionality factor which is a function of the saturation tank
S_i = Influent suspended solids concentration (mg $litre^{-1}$)

In order to design an effective prototype DAF, a pilot scale model was built to determine the relevant design parameters (Fig. 2). Typical results of the pilot operation are given in Table 1. The following parameters were calculated and form the basis of the prototype design: A/S ratio = 0·02 to 0·04, f = 0·3 to 0·6 and p = 3 atmospheres (45 psi).

The above data were used to formulate the design of a 12 $m^3\ h^{-1}$ (peak flow 25 $m^3\ h^{-1}$) DAF prototype unit having a volume of 9·75 m^3 and a surface area of 7·22 m^2. To improve the mixing of the suspended solids with that of the flocculants, a flocculator was incorporated, consisting of a horizontal cage paddle running at a speed of about 25 rpm. The flocculant was added to the pondwater using a diaphragm metering pump. The dosage rate was controlled manually according to the influent flow rate. The flocculator has a reaction time of less than 3 minutes which was found to be sufficient to attain stable large flocs.

Different flocculants, viz. alum, polyacrylamide polymers (cationic, anionic and neutral) of different molecular weights, and chitosan were tested under varying pH and mixing conditions using standard jar test procedures. Chitosan is manufactured by the hydrolysis of a cheap source of chitin (exoskeleton of crustaceans) and can be prepared on a small scale using crab or prawn shells which are abundant in the tropical areas. Although alum was found to be the most effective flocculant for clarifying the water, the residual aluminium renders the algal product undesirable as an animal feed.[12] Alternative synthetic polyacrylamide

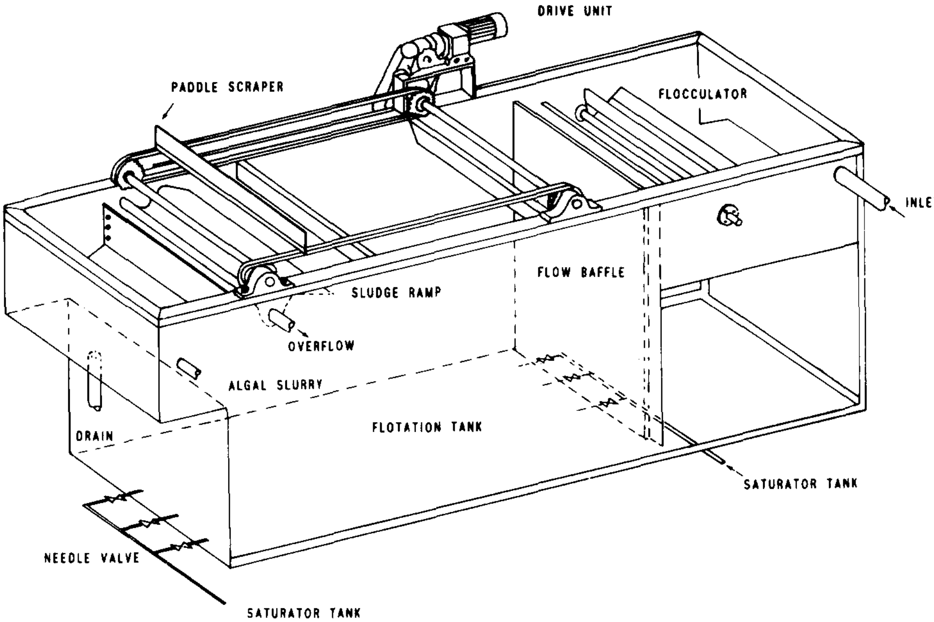

Fig. 2. Design of a pilot plant unit for harvesting algae by dissolved air flotation.

base polymers are not effective at economically low dosage rates. Furthermore, the long term effects of polyacrylamide toxicity to man and animals are not known. Flocculation of algae can also be achieved by either increasing the pH to about 10 or lowering to below 2. However, the high cost and potential toxicity of acids and alkalis do not permit their effective use on a large scale.

Published reports indicate that chitosan can be effective in flocculating microalgae.[13] Nigam and Venkataraman reported that a dosage of 50 mg $litre^{-1}$ of chitosan produces very large stable flocs and resulted in 95% algal removal.[14]

In Singapore, a similar dosage of 50 mg $litre^{-1}$ of chitosan was used. Initial results indicated a consistent algal recovery rate of 98%. On average, the BOD_5 of the clarified effluent was found to be below 70 mg $litre^{-1}$ and the COD_5 (chemical oxygen demand) to be less than 150 mg $litre^{-1}$. In terms of waste treatment, the DAF system for harvesting algae combined with chitosan as flocculant appeared to be superior to that of centrifugation. The suspended solids of the effluent were also lower than those of clarified effluent from centrifugation. Comparison of operating cost indicated that the DAF system using chitosan or alum as the flocculant was less expensive than centrifugation.

TABLE 1
Summary of DAF Operations

Influent			Recycle			Effluent								
$m^3 h^{-1}$	pH	TSS ($mg\ litre^{-1}$)	$m^3 h^{-1}$	Pressure (atm)	Alum[a] ($mg\ litre^{-1}$)	TSS ($mg\ litre^{-1}$)	BOD ($mg\ litre^{-1}$)	COD ($mg\ litre^{-1}$)	Removal TSS (%)	Float ($g\ litre^{-1}$)	Run (h)	Wet algae (kg)	Drum dried algae (kg)	Power[c] (kWh)
3·0	8·0	680	1·8	3·5	100	530	345	760	22	97·9[b]	1·0	7	—	1·7
3·0	8·2	590	1·5	3·5	150	420	400	721	29	46·0	3·0	56	3	4·9
3·0	8·0	650	1·5	3·5	200	380	320	651	42	43·1	3·0	63	3	4·5
3·0	7·9	1055	1·5	3·5	250	425	320	760	60	43·3	2·5	59	2	3·2
3·0	8·3	750	1·5	3·5	300	374	335	666	50	39·5	3·0	85	3	4·6

[a] These runs were made without pH adjustment.
[b] The float was allowed to stand over an hour and secondary float thickening took place.
[c] Power consumption excluding drying.
TSS, Total suspended solids.
BOD, Biological oxygen demand.
COD, Chemical oxygen demand.

FILTRATION HARVESTER

The concept of using filtration to separate algal cells had been investigated since the early seventies. Micro-strainers were found to be quite effective but because of the backwash requirements, the algal slurry produced was rediluted. Benemann *et al.*[6] reported favourable recovery rates in excess of 80% but found that the blinding of filters imposed a serious problem. Blinding refers to the rate at which the deposited algal matter clogs up the pores thereby reducing the rate of filtration across the filter cloth. Several improved designs had been claimed by various manufacturers for micro-strainers. Dodd[15] started working on his concept of a reversed belt micro-strainer in the early seventies and developed a paper precoat harvester in Australia. The concept of using a fine weave polyester filtration harvester was tested in Singapore where a 1·8 m diameter drum of 1·02 m width was fabricated and put into operation (Fig. 3). The basic features of this harvester had been described previously by Dodd.[15] Essentially, the belt traverses the drum and water

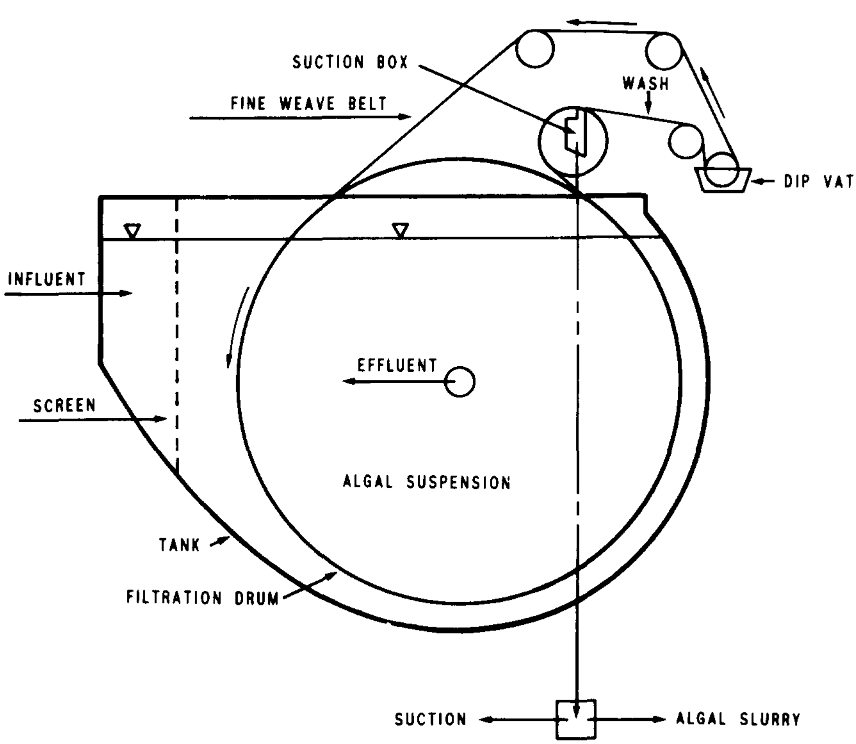

Fig. 3. Schematic diagram of fine weave belt filter.

flows into the drum through the perforations. Filtered liquid accumulated in the drum flows out via a 'goose-neck' pipe into a flow measuring device. The belts are maintained in tension by means of a series of unplasticised polyvinylchloride cylindrical rollers. Backwash nozzles are aligned at the most effective angle to ensure appropriate cleaning of the belt so as to reduce the blinding rate. The 12 μm filter cloth had an economic life exceeding 500 operation hours despite its intermittent use. Excessive use of chemicals for belt washing reduces the belt life and clearly indicates that continuous operation of the harvester gives better performance.

The efficiency of the harvester can be expressed in terms of three criteria, i.e. flow throughput ($m^3\ m^{-2}\ h^{-1}$), recovery rate expressed as percentage of total suspended solids (TSS) reduction and slurry content expressed as percentage of total solids (TTS).

In the first series of experiments, the belt speed was shown to affect both the capacity and slurry concentration. A reverse Dutch weave filter having a 12 μm pore size gave a throughput of up to 17 $m^3\ h^{-1}$ when the belt speed was 22 m min^{-1}. This is equivalent to about 14 litres $m^2\ min^{-1}$ throughput. Using a slower belt speed of 5 m min^{-1}, about 12 $m^3\ h^{-1}$ were achieved corresponding to higher throughput of up to 45 litres $m^2\ min^{-1}$. A linear relationship between throughput and belt travel speed was obtained when the results were plotted on a log–log scale as shown in Fig. 4. The slurry concentration, however, was inversely proportional to the belt speed. The range varied between 1·5% and 3% total solids. The recovery was found to be independent of the belt speed and a constant algal recovery of about 80% of the incoming total suspended solids was obtained.

Power requirements measured averaged between 0·3 and 0·5 kWh m^{-3} of pond water treated giving about a 60-fold increase in slurry concentration from about 0·05% to about 3% solids. The use of flocculants did not improve performance especially when *Chlorella* was the dominant component of the biomass.

Using the belt filter, BOD_5 reduction between the mixed liquor and effluent is from 350–500 mg $litre^{-1}$ to 70–200 mg $litre^{-1}$. The effluent discharged by the harvester has a characteristic brown colouration possibly due to the bacterial biomass and the lignin material from pig waste. The most difficult problem encountered with the filtration harvester was linked to the changes in the dominating algal species in the pond. The *Micractinium* cells, which are about 12 to 15 μm in size and form clusters of 3 to 4 cells with long protruding spines, were ideal for separation with the filtration harvester. Similarly, *Oscillatoria, Spirulina* and *Scenedesmus* were amenable to harvesting with the mechanical

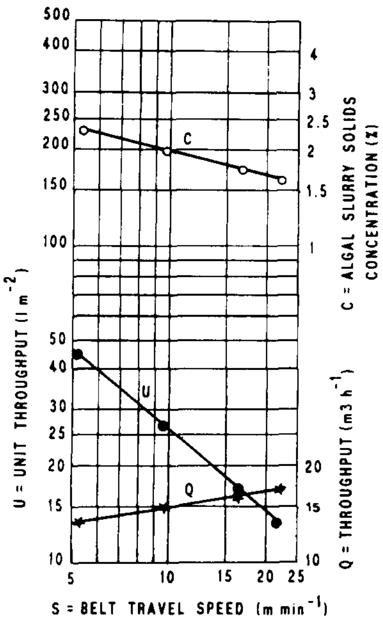

Fig. 4. Performance of belt filter, Q = USB/60, U = 182 $S^{-0.844}$ (from data shown), B = Belt width = 0·95 m (polyester belt fabric porosity: 12 μm).

harvester. *Chlorella, Oocystis, Synechocystis, Ankistrodesmus* and *Raphidium* are more difficult to retain on the belt. They blocked the pores of the fabric easily and any excess pressure caused the cells to pass through the pores. During the period of dominance of the smaller algal species, the throughput capacity of the machine dropped to as low as 2–3 $m^3 h^{-1}$, demonstrating the effect of algal size on performance of the mechanical harvester (Figs 5 and 6). In view of this, it is recommended that the role of flocculants like alum and chitosan be investigated more extensively together with alternative belts to overcome this serious problem. Otherwise, the machine performed extremely well and could be the best method of harvesting microalgae.

CONCLUSIONS

The potential and application of a specific algal harvesting technique depends on careful evaluation of the existing pond conditions and technical availability. In the Singapore project on the treatment and utilisation of piggery waste, three major harvesting techniques were tested with varying degrees of efficacy. Centrifugation was found to be effective but cost intensive and not suitable for large-scale harvesting. Chemical flocculation followed by dissolved air flotation seems promising but

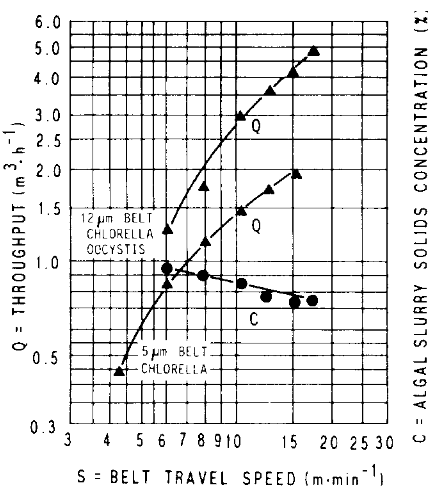

Fig. 5. Filter performance during period of dominance of small algal species.

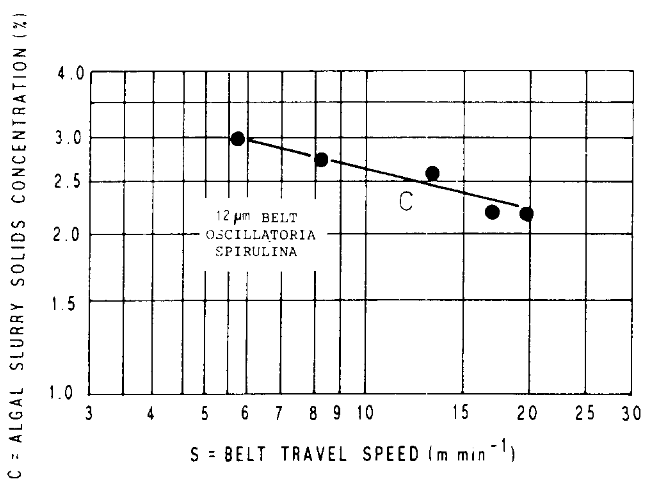

Fig. 6. Filter performance during period of dominance of large-celled algal species.

further tests are required to improve the flocculation using low cost, effective and non-toxic flocculants such as chitosan. The effectiveness of filtration was related to the operational pore-size of the harvester filter and the size of the algal species, i.e. only algae larger than the nominal pore-size of the filter weave can be retained and collected. Despite the limitations of the dissolved air flotation technique and the filter harvester, both these methods are relatively cost-effective due to their lower energy requirements compared with centrifugation.

The use of high-rate algal ponds for the treatment and utilisation of pig waste can be attractive, especially if the cost of harvesting, one of the major costs of the treatment system, can be minimised while achieving optimal performance.

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