Harvesting of Algae Grown on Raw Sewage

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Abstract

Harvesting of algae comprises three separate but interdependent process stages, i.e. separation, dewatering and drying.

An algal production pond of 260 m^2 (0,4 m depth) was operated with raw sewage. Dissolved air flotation was used in conjunction with aluminium sulphate as flocculant to obtain a slurry containing 2 to 3% of dry solids and with a cationic polyelectrolyte a slurry containing up to 8% dry solids was obtained. The latter slurry showed superior dewatering characteristics in comparison with the alum derived slurry.

Pilot-scale tests have confirmed that photosynthetically produced oxygen, which reaches concentrations in excess of 20 mg ℓ^{-1} during daylight hours, may be harnessed to effect spontaneous flotation, whch may serve as a viable alternative to the dissolved air flotation technique. If this technique is combined with polyelectrolyte flocculation, the cost of separation, dewatering and drying can be reduced significantly. The quality of the final product is improved in terms of lower ash content.

The major harvesting costs are associated with the drying process so that overall costs can be reduced by improving the efficiency of moisture removal in the separation and dewatering stages.

Introduction

The ever-increasing demand on the world's food supplies has necessitated the optimization of production techniques and the establishment of fresh nutrient sources. The recovery of nutrients from waste effluents is but one alternative being investigated to ensure a continued supply of protein.

Feed products such as soya bean and fish meal, which compare favourably with traditional protein sources, may be supplemented by algal culture.

The National Institute for Water Research (NIWR) has been investigating the feasibility of algal culture in domestic wastewater for several years. This paper highlights results pertaining to the definition and optimization of some of the engineering parameters which are important for the practical implementation of the process. The main emphasis is on the physical and chemical parameters involved in separating biomass from the growth medium, but general guidelines regarding hydraulic design considerations and cost aspects are also provided.

Experimental Facilities

Algae are cultivated at the Daspoort Experimental Station of the NIWR, Pretoria by introducing raw sewage (screened on a 6-mm wedgewire screen) into a 260 m^2 pond, which has been partitioned into meandering channels. The depth of the biomass in the pond is controlled at a specific value in the range 0,3 to 0,5 m. A flow velocity of about 12 m s^{-1} is maintained by means of a variable speed paddle wheel. The design and operation of the pond are similar to that of the intensive algal wastewater system being studied by Shelef, Moraine, Meydan and Sandbank (1976 and 1977). The sequence of harvesting from the pond to the final stages of product processing and a general outlay of the float cell used are shown in Figures 1 and 2 respectively.

The upward flow in the reactor zone (flocculation zone) of the cell is in the order of 23 m h^{-1} while the downward flow in the clarification zone is about 4 m h^{-1}, both at a design feed rate of 6 m^3 h^{-1}. Algal float sludge is removed intermittently at preset time intervals (1 to 2 h) by means of chain-driven scraper blades geared down to move at 250 mm min^{-1}. Air saturation of the recycled float cell effluent in the saturator vessel takes place at a pressure of approximately 450 kPa, the throughput ranging from 10 to 40 ℓ min^{-1}, depending on the recycle ratio.

Secondary dewatering of the concentrated algal sludge is effected by means of an 0,4 mm stainless steel wedgewire screen (2 000 mm x 500 mm). The dewatered algae are dried at approximately 120 °C by means of a double-roll steam-heated drum drier.

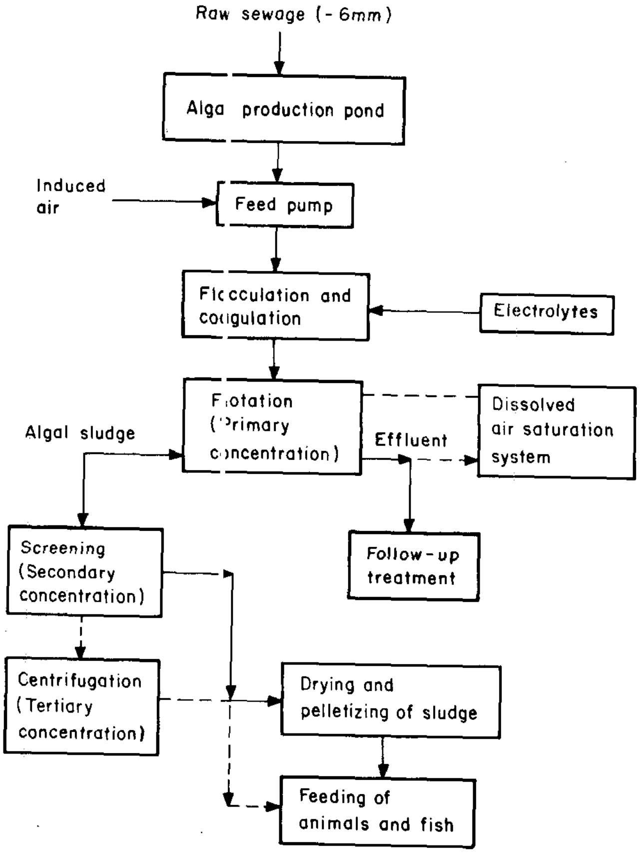

Figure 1
Flow diagram for biomass harvesting and processing

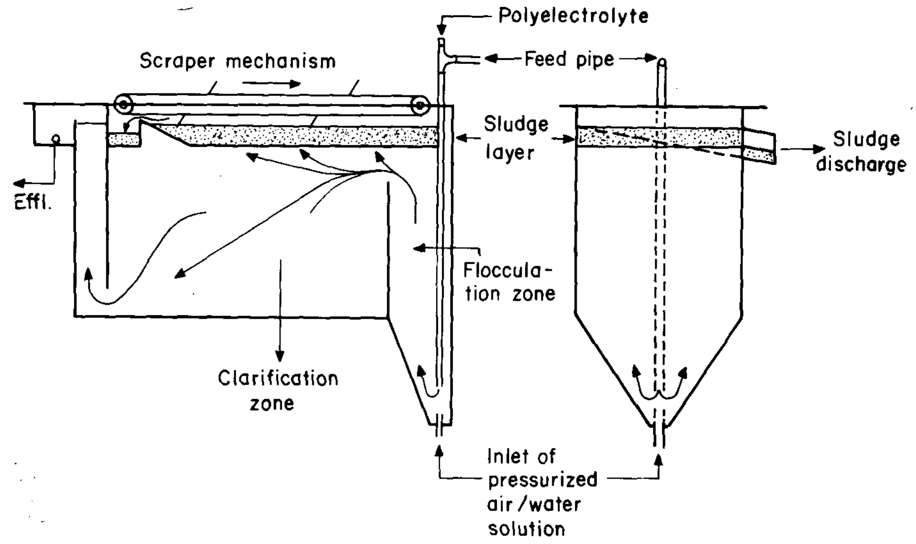

Figure 2
Diagram of float cell used for harvesting of algae

Experimental Procedure

Pond Operation and Monitoring

The production pond was operated batch-wise, mainly for the control that this approach afforded with respect to factors such as maximising algal concentration input to the harvesting section and nutrient stripping from the raw sewage, and determining the optimum retention time for a specific period of the year. Batch production also eliminated the need for a storage step between the pond and float cell.

At start-up, the pond was filled to 0,4 m with screened raw sewage, followed by the addition of approximately 10 m^3 of an algal suspension with a suspended solids concentration of approximately 350 mg ℓ^{-1} and a chlorophyll α concentration of 4 500 $\mu g\ \ell^{-1}$. During subsequent harvesting approximately 75% of the pond volume was drained, whereafter the pond was refilled to the original depth and the cycle restarted.

A comprehensive monitoring programme was designed to elucidate the chemical and physical parameters of importance in algal production. Temperature, pH, dissolved oxygen, turbidity and evaporation measurements were taken at two-hourly intervals while power consumption data and the concentrations of suspended solids, volatile solids, chlorophyll α, chemical oxygen demand, ammonia, nitrate, nitrite and orthophosphate were determined diurnally. Algal concentration and determination of species were done weekly.

The biomass was harvested when the growth was judged optimal as regards the biomass and chlorophyll α concentration. This condition was characterized by ammonia concentrations below 1 mg ℓ^{-1} and oxygen concentrations above 20 mg ℓ^{-1}. Three flotation techniques namely dissolved air flotation (DAF), dissolved oxygen flotation (DOF) and induced air flotation (IAF) were used for harvesting. Sludge concentration was compared in each case under similar electrolyte concentrations.

Recycle ratios for the DAF process ranged from 1:9 to as high as 1:4 at a feed rate of 100 $\ell\,min^{-1}$. Sludge was removed at intervals of 15 min, one and two hours respectively. In an effort to improve moisture removal a 0,2 mm wedgewire screen was suspended underneath the discharge chute. Water draining through the screen was collected in a plastic receptacle, and the sludge overflow in tared buckets.

After dewatering the algal mass was stored overnight before drying. Float cell effluent was discharged for further treatment to the municipal sewage works.

Results and Discussion

Monitoring of Biomass Production Pond

The physical and chemical parameters pertaining to the algal pond operation during the period December 1979 to July 1980 are presented in Table 1. The effects of reduced pond temperature (26 °C to 10 °C) and insolation (2481 to 1470 J $cm^{-2}d^{-1}$) on production are shown in Figure 3. For example, after 4 days' retention in December a rapid increase in dissolved oxygen (DO) and a concomitant decrease in NH_3-N concentrations were observed, along with a 2,5 unit increase in the pH value. By comparison, 10 days' retention was required in June to obtain the same degree of reduction in NH_3-N concentration. About eight to ten days, instead of five, were required to attain the same DO concentration (17 mg/ℓ) as experienced in summer.

The increase in pH value is assumed to be due to the photosynthetic binding of carbon dioxide. Kok (1952) presented the following equation to indicate reactions for CO_2 uptake under conditions of excess NH_3-N:

$$6{,}14\ CO_2 + 3{,}7\ H_2O + NH_3 \xrightarrow[\text{energy}]{\text{light}} C_6 . 14\ H_{10} . 3\ O_2 . 24\ N + 6{,}9\ O_2 \ \ldots\ldots\ [1]$$

McCarty's (1969) equation is slightly different although the ratio of the main components in algae is the same:

$$106\ CO_2 + 81\ H_2O + 16\ NO_3 + HPO_4 + 18H^+ + \text{light} \longrightarrow C_{106}H_{181}O_{45}N_{16}P_1 + 150\ O_2 \ \ldots\ldots\ [2]$$
(algal biomass)

TABLE 1
VALUES FOR PHYSICAL AND CHEMICAL PARAMETERS OBTAINED DURING OPERATION OF ALGAL PRODUCTION POND

Date	Period (days)	DO mg ℓ^{-1}	pH	Temp °C	Susp solids mg ℓ^{-1}	Algal production rate g m^{-2} d^{-1}	Chlor α mg ℓ^{-1}	NO_2+NO_3	NH_3-N	PO_4-P	COD
December	Start	0,2	7,9	22,5			520	<1,2	18,4	5,2	128
1979	Finish (8)**	16,2	10,3	26,0	353	15,7	3443	<1,2	2,0	4,4	152
January	Start	10,1	9,3	23,0	160		N.D.	<1,2	5,2	3,0	184
1980	Finish (10)	14,1	9,8	27,5	262	7,9	3117	<1,0	0,4	2,4	88
February	Start	0,3	7,9	24,8	180		753	<0,8	6,4	3,6	112
1980	Finish (10)	9,2	10,0	26,0	385	11,6	4034	0,6	<0,2	1,2	118
March	Start	12,3	9,2	25,0	139		978	0,4	11,6	3,8	100
1980	Finish (10)	12,5	9,4	23,1	278	8,3	2628	0,4	3,6	3,6	100
April*	Start	0,3	8,0	18,7	105		143	—	28,0	11,6	200
1980	Finish (10)	13,1	9,0	17,3	280	10,9	2343	1,6	15,4	4,0	96
May	Start	1,1	8,2	17,5	140		1008	0,6	14,8	7,8	134
1980	Finish (9)	13,6	9,5	15,5	270	9,6	3738	4,6	2,6	5,2	110
June	Start	8,4	8,5	11,9	158		1996	0,6	14,4	7,2	124
1980	Finish (9)	13,3	9,5	9,3	270	9,0	4411	4,6	1,0	5,2	110
July	Start	7,2	9,3	10,7	280		—	<0,6	15,8	4,6	144
1980	Finish (9)	15,0	9,1	12,4	284	11,0	3937	4,0	<0,2	3,4	98

* Pond drained for repairs
** ( ) Retention time in days
The average unfiltered COD value for the period December 1979 to July 1980 was approximately 600 mg ℓ^{-1}

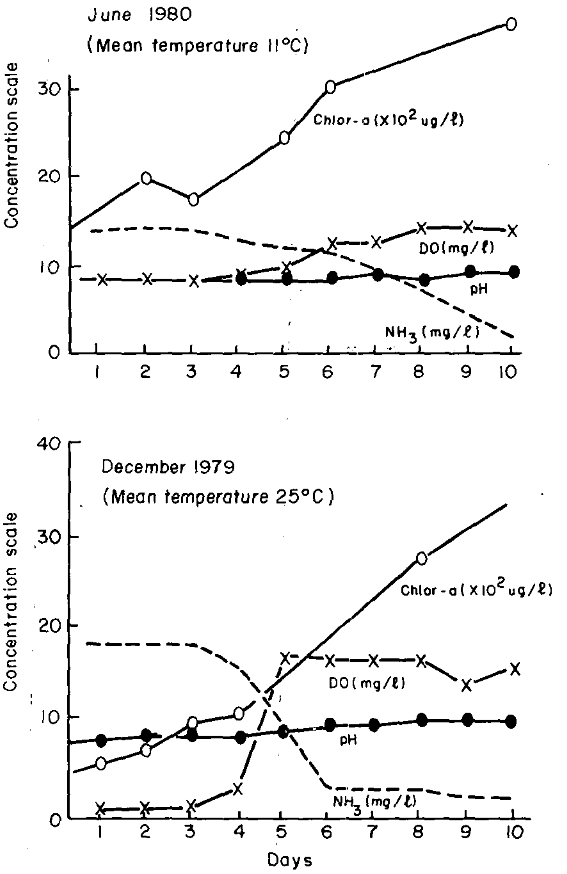

Figure 3
Salient parameters pertaining to summer and winter operation

TABLE 2
ALGAL SPECIES ENCOUNTERED IN THE PILOT-SCALE PRODUCTION POND

Month (1980)	Algal species	Distribution %	Concentration of algae mg ℓ^{-1}
January	*Micractinium* *Selenastrum* Other species	55 39 6	873 x 10^5
February	*Micractinium* *Selenastrum* Other species	28 67 11	650 x 10^5
March	*Micractinium* *Selenastrum* Other species	15 80 5	3 012 x 10^5
April	*Micractinium* *Selenastrum* *Chlorella* Other species	21 59 19 1	1 870 x 10^5
May	Not determined		
June	*Micractinium* *Selenastrum* *Chlorella* Other species	38 38 23 1	2 164 x 10^5
July	*Micractinium* *Selenastrum* *Chlorella* Other species	52 38 6 4	1 140 x 10^5

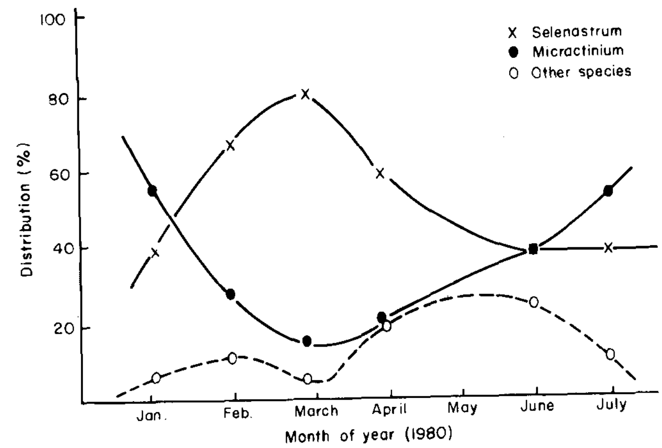

Figure 4
Composition of algal population in Daspoort pond

TABLE 3
CHANGES IN ALGAL SPECIES DURING A TWO-YEAR PERIOD OF CONSTANT POND OPERATION, IN HAIFA, ISRAEL
(Moraine et al. (undated))

Period		Species dominating
Fall	1974	*Micractinium*
Winter to Spring	1975	*Scenedesmus*
Summer to fall	1975	*Oocystis**
Fall	1975	*Scenedesmus*
Spring	1976	*Scenedesmus*
Summer	1976	*Micractinium*
to		
Spring	1977	*Micractinium*
Winter (3 months)	1977	*Euglena*
February	1977	*Micractinium*

*Other significant genera determined during this period were: *Micractinium* up to 50%, *Francea* up to 30%, *Phytoconis* up to 60%.

The algal species and concentrations encountered in the production pond during the period indicated are recorded in Table 2 and illustrated in Figure 4. No definite pattern has emerged but indications are that the algal population mainly consists of *Selenastrum* and *Micractinium*.

The results obtained can be compared to those established in Israel over a period of two years by Moraine, Shelef, Meydan and Levin (undated) (Table 3). Neither *Micractinium* nor *Selenastrum* appears to favour any definite season of the year for predominance.

Coagulant Selection

The selection of a coagulant is a matter of prime importance in designing a feasible and economically acceptable method of biomass harvesting. Aluminium sulphate (alum) has been used in most cases published. Golueke and Oswald (1965) carried out extensive tests to optimize alum dosage for algal removal and water quality of supernatant obtained in pilot-plant studies. Friedman, Peaks and Nichols (1977) evaluated a range of coagulants which included cationic polyelectrolytes, lime and alum. Both Golueke and Oswald (1965) and Friedman, Peaks and Nichols (1977) found alum to be an effective coagulant in the pH range 5,0 to 7,0 although its effectiveness decreased as the pH was raised above 7,0. Shelef, Moraine and Oron (1977) found the optimal pH range for flocculation-flotation to be between 5,5 and 6,0 at alum dosages of between 80 and 150 mg ℓ^{-1} depending on alkalinity and concentration of phosphates. In all the cited cases it was found necessary to adjust the pH to below 7,0 (5 to 7) in order to obtain optimum coagulation and recovery of algae. With no pH adjustment (hydrochloric or sulphuric acid being used) the ratio of alum required to biomass present was found by Friedman, Peaks and Nichols (1977) to be about 1:1. This finding is in accordance with experience at Daspoort.

Alum as a coagulant has several disadvantages of which poor dewaterability of the gelatinous float product is the most important. The relatively high pH values prevalent in algal culture necessitate pH adjustment to approximately 6,5 using expensive hydrochloric or sulphuric acid. The use of alum also leads to an undesirable increase in mass and ash content of the final product (see Table 8). Solubilization of aluminium at the low intestinal pH value of animals such as pigs is claimed to have toxic effects so that removal by acid leaching in the pH range 3 to 3,5 is required.

TABLE 4
COMPARISON OF RESULTS OBTAINED ON USING ALUM AND PRAESTOL 444K FOR FLOCCULATION

Parameter		Control	Concentration of alum (mg ℓ^{-1})				Concentration of Praestol 444K (mg ℓ^{-1})			
			30	60	90	120	1	2	3	4
Turbidity (NTU)		15,5	18	18	18	17,5	13	15	15	15
pH		8,84	8,40	7,91	7,57	7,24	9,16	9,15	9,16	9,17
CST*		15,3	17,4	15,4	17,0	18,3	14,6	13,4	13,6	12,1
PO_4-P)		2,9	2,1	1,3	0,7	0,4	2,3	2,2	2,2	2,2
$NO_3 + NO_2$)	Filtered	1,8	0,9	1,3	1,1	1,4	2,0	2,0	2,0	2,0
COD)	Samples	63	58	53	46	42	62	61	59	58
NH_3-N)		6,9	6,9	7,0	7,2	7,0	5,2	5,1	5,3	5,2

*CST = Capillary suction time in seconds.
The alum used in the above test is of commercial grade and was dosed as aluminium sulphate [$Al_2(SO_4)_3$ 18 H_2O], making no allowance for water of crystallization when the 1% by mass solution was prepared.

Several cationic polyelectrolytes were investigated at laboratory scale as possible alternatives to the use of alum. The results obtained with the most promising cationic polyelectrolyte are compared with alum in Table 4. Increasing alum addition from 30 to 120 mg ℓ^{-1} results in a gradual reduction in pH (8,40 to 7,24) and in phosphate concentration (2,1 to 0,4 mg ℓ^{-1} PO_4-P). Polyelectrolyte, on the other hand, caused only a slight reduction in chemical oxygen demand (COD) and orthophosphate concentration with a slight increase in pH value (8,8 to 9,2). The lower capillary suction time (CST) values give an indication of how the filterability has been improved compared with that of the control (21% improvement at 4 mg ℓ^{-1} Praestol 444K) whereas the decline of filterability is 20% for alum, resulting in a total difference of approximately 40% in favour of using the polyelectrolyte. Visual observations showed that the polyelectrolyte floc is always larger and more stable than that formed by using alum. More important, the polyelectrolyte flocs float spontaneously and compact rapidly into a layer approximately 5 mm thick in less than one minute. By comparison the alum floc rises slowly, resulting in an algal concentrate layer up to 50 mm thick after three minutes. These results were subsequently confirmed on pilot scale.

Pilot-scale Harvesting of Algae

The development of efficient and economical harvesting methods is of paramount importance in ensuring the viability of biomass production in wastewater. It has been estimated that approximately 40% of operating and 12% of capital costs involved, are used in this stage of the production process (Volesky and Tsantrizos, 1978). It therefore seems warranted that much more attention should be devoted to improving the existing technology of algal harvesting methods. In the studies conducted by the NIWR, two techniques in particular received attention, namely dissolved air flotation (DAF) and dissolved oxygen flotation (DOF). The desirability of introducing an induced air flotation (IAF) stage (Van Vuuren, Stander, Henzen, Van Blerk and Hamman, 1968) in conjunction with DOF, was also investigated.

Dissolved Air Flotation

For comparison purposes two pilot float tests were carried out using alum and a strongly cationic polyelectrolyte respectively. Recycle to feed ratio was maintained at 1:4 in each case. Sludge was scraped off for five minutes at hourly intervals. Results are shown in Table 5. The superiority of the polyelectrolyte is clearly indicated by the higher percentage solids in the float. The 5,7% solids content obtained by using 5 mg ℓ^{-1} polyelectrolyte compares favourably with the 1,9% obtained when using 130 mg ℓ^{-1} alum, and represents an improvement of 67%.

Combined Dissolved Oxygen and Induced Air Flotation

With the dissolved air saturator system isolated from the flotation unit, flotation tests were conducted utilizing the high oxygen concentrations (>20 mg ℓ^{-1}) in the biomass.

It was initially attempted to effect flotation using alum at a dosage rate of 130 mg ℓ^{-1}. However, flotation using DO only was unsuccessful even at concentrations of 200 mg ℓ^{-1} alum, and the test was discontinued. Subsequently the cationic polyelectrolyte, Praestol 444K, was introduced at concentrations ranging from 4 to 7,5 mg ℓ^{-1}. Tables 6(a) and 6(b) give the results of a composite float obtained by using DOF in the period from 10h00 to 20h00. Electrolyte was dosed at concentrations of 7,5, 5,9 and 3,8 mg ℓ^{-1} during the three successive periods of four hours each.

The DO concentration progressively increased from 13,4 to 14,6 mg ℓ^{-1} at 12h00 and then declined to 7,3 mg ℓ^{-1} at 22h00. The drop in biomass recovery during this period (from 85,1 to 56,3%) tended to follow the electrolyte dosage, as can be seen in Figure 5. By increasing the electrolyte dosage to 7,5 mg ℓ^{-1} biomass recovery was improved from 47 to 60%. It is clear from the above that harvesting algae by utilizing the excess DO generated in the pond during the day, and for periods up to six hours after sunset, is a feasible process.

IAF was introduced in the test at 23h00 and continued for

TABLE 5
BIOMASS CONCENTRATION BY MEANS OF DAF COMPARING ALUMINIUM SULPHATE AND POLYELECTROLYTE AS FLOCCULANTS

Time	Float cell pH		Algal pond det. Temp. °C		Algal pond det. DO mg ℓ^{-1}		Total mass floated kg (wet)		Dry solids in sludge %		Electrolyte (mg ℓ^{-1})	
	A	P	A	P	A	P	A	P	A	P	A	P
10h00-11h00	7,68	9,21	22,5	25,2	8,4	9,9	147,7	21,05	1,7	3,0	106	2
11h00-12h00	7,89	9,49	24,5	27,3	9,0	11,3			1,9	4,6	106	2
12h00-13h00	7,93	9,64	26,5	28,5	7,7	12,0	123,5	19,80	1,8	5,5	138	7
13h00-14h00	7,87	9,96	27,5	30,0	7,4	12,4			1,9	5,2	138	7
14h00-15h00	7,45	10,03	28,0	30,0	7,0	12,2	152,7	30,50	1,8	6,1	139	4
15h00-16h00	7,51	10,25	28,5	30,0	9,2	11,9			1,8	6,8	139	4
16h00-17h00	7,71	10,31	28,0	28,8	6,6	10,8	177,8	38,2	2,0	5,4	138	8
17h00-18h00	7,56	10,30	28,0	28,0	3,0	11,2			2,2	7,4	138	8
	7,70	9,90	26,7	28,5	7,3	11,5	601,7	109,6	1,92	5,73	130	5,3

The lower DO values for the alum float were the result of dense cloud cover on the day of flotation.
A = alum
P = polyelectrolyte

TABLE 6(a)
THE EFFECT OF COMBINED DOF AND IAF ON THE RECOVERY AND CONCENTRATION OF ALGAE

Period July 1980	Dosage electro-lyte mg ℓ^{-1}	Temp °C in pond	Dissolved oxygen mg ℓ^{-1}		pH in pond	Suspended solids (mg ℓ^{-1})		Recovery %	Air: solids ratio	Dry solids in sludge %
			Pond	Float cell		Feed	Effluent			
10h00-14h00	7,5	15,5	13,4	7,3	9,54	316	47	85,1	0,0193	5,6
14h00-18h00	5,9	14,4	14,6	7,7	9,68	316	76	75,9	0,0218	6,9
18h00-22h00	3,8	12,5	7,3	5,8	9,38	302	132	56,3	0,005	6,8
22h00-02h00	7,4	10,5	2,5	5,0*	8,87	285	64	77,5	—*	6,6
Average	6,2	13,2	9,5	6,5	9,37	305	80	73,7		6,5

*Volume of air introduced at inlet of pump was not measured
Air for IAF was introduced at 23h00.

TABLE 6(b)
CHEMICAL ANALYSIS OF FLOAT FEED AND EFFLUENT

Period July 1980	NH_3-N mg ℓ^{-1}		NO_2+NO_3 mg ℓ^{-1}		PO_4-P mg ℓ^{-1}		COD mg ℓ^{-1}	
	Feed	Effl.	Feed	Effl.	Feed	Effl.	Feed	Effl.
10h00-14h00	<0,2	<0,2	5,4	1,1	5,1	4,6	143	81
14h00-18h00	<0,2	<0,2	3,0	0,3	6,2	4,1	141	88
18h00-22h00	<0,2	<0,2	3,0	0,3	7,2	4,9	138	94
22h00-02h00	<0,2	<0,2	3,0	0,3	7,5	5,3	159	85
Average	<0,2	<0,2	3,6	0,6	6,5	4,7	145	87

three hours whilst the electrolyte dosage rate was maintained at 7,5 mg ℓ^{-1}. It was estimated that air was drawn in at the pump at a rate of approximately 2 ℓ min^{-1}.

A marked improvement in recovery, from 60 to 84%, was achieved (Figure 5) and maintained for two hours until the test was discontinued.

Results show that flotation by means of DO is possible at concentrations above 10 mg ℓ^{-1}. At concentrations lower than this figure, IAF can be utilized to boost and improve the quality of the float products.

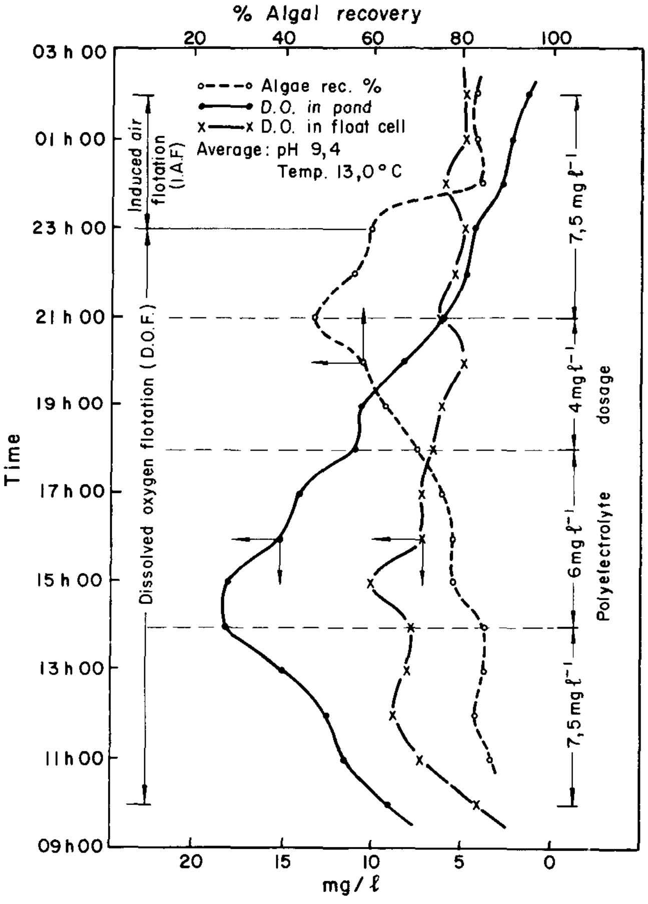

Figure 5
Recovery of algae for various concentrations of dissolved oxygen and polyelectrolyte dosages

Effect of Delayed Sludge Scraping on Dewatering

The beneficial effect of intermittent sludge removal can be seen in Figure 6. Results were obtained during DAF by scraping for five-minute periods after intervals of 15, 30 and 60 min respectively. On using alum as flocculant, a froth-laden sludge layer was formed which was about four times bulkier than the layer formed when using polyelectrolyte. It is reasonable to assume that increased froth concentration in the sludge layer will result in greater water retention. By intermittent sludge removal this water is allowed to drain back into the float vessel.

The profiles in Figure 6 clearly indicate the superiority of the polyelectrolyte floated sludge in allowing the water to drain, resulting in an improvement from 1,8% solids after 15 min to a concentration of 4,6% after one hour, an overall improvement of approximately 150%. Flotation with DOF and a polyelectrolyte improved this figure of 4,6% solids to between 7 and 8%. No pH adjustment of the biomass was carried out prior to the float.

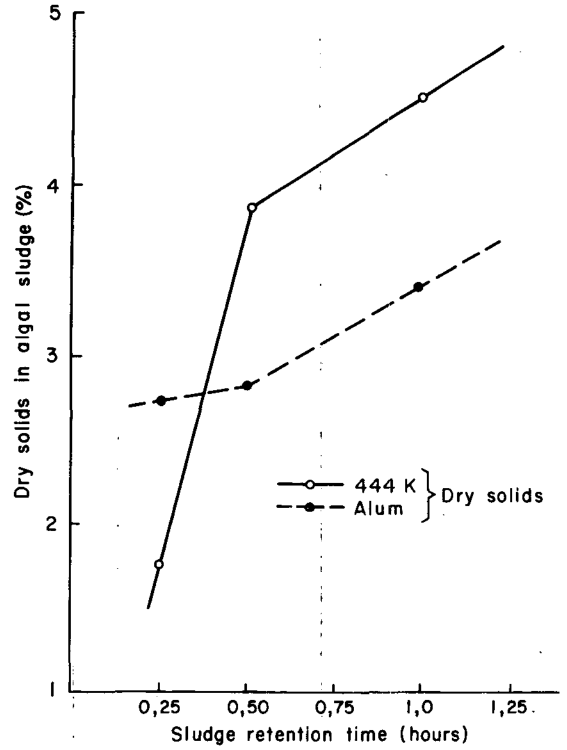

Figure 6
The effect of delayed scraping on percentage solids in float sludge (DAF)

Dewaterability of Floated Sludge

It was observed that if the sludge which was scraped off (7% solids) was allowed to stand in a tank overnight, separation into two phases took place, namely an upper algal layer, with a water phase at the bottom of the conical-bottomed tank. This water could be drained off leaving the sludge in a more concentrated form, an improvement of up to 18% being possible over a period of 16 h. In an effort to capitalize on this tendency the sludge from the float was passed directly over an 0,2 mm wedgewire screen. This improved the sludge solids concentration from 7,0 to 9,5% solids, 10,5% solids being possible after being allowed to remain on the screen for eight hours (35 to 50% improvement)

Centrifugation resulted in a sludge concentrate with approximately 11,0% solids. The addition of up to 200 $\mu g\ \ell^{-1}$ polyelectrolyte did not result in any improvement.

When taking into account that the moisture content of algae plus bacteria is in the order of 80 to 85% (a generally accepted figure and determined at Daspoort to be approximately 85%) then interstitial water would comprise 30 to 40% of the algal float sludge and would prove difficult and expensive to reduce significantly

Capillary action would have to be overcome by alternative means, such as the addition of chemicals which could eventually have a detrimental effect on the protein quality and digestibility of the final algal product. Repeated centrifugation tests substantiated this conclusion. Subjecting the algal sludge to centrifugation (at 9500 r/min for as long as 30 min) resulted in a centrate with a COD value of 200 mg ℓ^{-1} and a solids product still containing 81% moisture. A delay of 18 h in centrifugation can result in a centrate with a COD of 200 mg ℓ^{-1} increasing to 1 000 mg ℓ^{-1} with orthophosphate values increasing to approximately 20 mg ℓ^{-1}. This would conceivably result in a lower protein algal product.

Quality of Dry Algal Product

No effort has been made to optimize drum-drying techniques but drum-dried sludge obtained from floating with alum and polyelectrolyte (Praestol 444K) was analysed. (Table 7).

The sludge sample floated with alum had a higher ash content than that of the poly-floated sludge but even this higher value compared favourably with similar products obtained from overseas workers.

It should of course be attempted to reduce the ash content as far as possible since not only does the ash introduce undesirable constituents into the product but it also lowers the nutritional value.

Micractinium was the predominant algal species in both instances.

TABLE 7
ANALYSIS OF TWO ALGAL SAMPLES

Parameter	Alum float dried by freezing	Poly float drum dried
g 100 g^{-1}		
Moisture	33,0	8,9
Fat	1,5 (2,2)	1,3 (1,4)
Ash	9,7 (14,5)	8,2 (9,0)
Protein	36,2 (54,0)	51,5 (56,5)
Fibre	2,2 (3,3)	4,9 (5,4)
mg 100 g^{-1}		
Calcium	239,0	ND
Magnesium	161,0	
Sodium	27,3	
Potassium	610,0	
Copper	59,4	
Iron	395,0	
Zinc	27,4	
Phosphorus	914,6	
Cobalt	0,36	
Manganese	5,4	

The sample in column 1 was dried after receipt but all values are based on the sample as received. Values in brackets relate to dry basis.
ND = not determined.

Amino acid concentrations are given in Table 8, which has been divided into groups A, B and C. The table is best discussed in terms of the relative distribution as regards total essential, semi- and non-essential amino acids. Regarding the essential amino acids (group A), the alum floats yielded similar results (39,9%) whereas the poly float analysed 2,7% lower. Calculated on a progressive basis, the alum floated product gave the highest value for the essential plus semi-essential amino acid concentrations, totalling up to 57,5 g amino acid per 100 g sample. Generally speaking, the difference is regarded as negligible, more analyses being required on fresh samples to substantiate the initial results.

TABLE 8
AMINO-ACID CONCENTRATIONS ON THREE DRIED ALGAL SAMPLES (AS RECEIVED)

Parameter	Alum float	Poly float
A		
Histidine	0,62	0,74
Lysine	1,50	1,74
Phenylalanine	1,63	1,93
Methionine	0,43	0,21
Threeonine	1,70	1,76
Leucine	2,72	2,85
Isoleucine	1,31	1,14
Valine	1,90	1,92
	11,81 - 39,3%	12,29 - 37,2% (of total)
B		
Arginine	1,94	2,19
Tyrosine	1,07	1,17
Cystine	0,34	0,64
Glycine	1,85	2,13
	5,20 - 17,6%	6,13 - 18,6%
C		
Serine	1,35	1,65
Glutamic acid	3,76	4,28
Aspartic acid	2,46	3,11
Alanine	2,46	3,11
Proline	2,56	2,46
	12,59 - 42,5%	14,61 - 44,2%

Results in g amino acid per 100 g sample (as received).
A = essential amino acids
B = semi-essential
C = non-essential.

Toxicity of Flocculants Used

No published reports are as yet available on the possible toxic effects on animal health of the polyelectrolytes used in this study.

The company supplying the reagent Praestol 444K reports that feeding tests in Germany and Czechoslovakia are in progress. Preliminary tests using this reagent have so far showed no toxic effects at concentrations of up to 5 kg t^{-1} of dry solids in the diet of poultry, over a period of several weeks. Pigs fed on the dewatered unheated sludge containing 444K showed no deleterious effects.

Fish toxicity tests carried out at Huntingdon Research Centre, UK (McCauly 1982) using Zetag 57 and Channel Catfish as the test fish, gave the following results, viz.:

Dosage	% Mortality rate (48 h)
1 mg ℓ^{-1}	Nil
10 mg ℓ^{-1}	Nil
100 mg ℓ^{-1}	70

Polyacrylamides (residual acrylamide level 0,1 to 0,2%) generally are partially biodegradable with no known toxic effects of the breakdown products.

Economic Considerations

There are a considerable number of factors which influence the production cost of algae. Some of the more important factors are:

1. *Pond:* Design, construction material, mode of inducing flow and retention time.
2. *Flocculants:* Type of chemical used, availability and also the concentration of suspended solids in the feed to the harvesting section
3. *Harvesting:* The flotation technique used for harvesting is important, for instance, whether it is DOF, DAF or IAF.
4. *Dewatering:* The method employed for further dewatering the algal sludge, whether it is delayed scraping, centrifugation or screening.
5. *Drying:* Two techniques for the drying of algae have been practised to date. These are drum drying and air drying.

All these factors require optimization to ensure that the production cost of algae can be brought to a level that would render it competitive with other sources of protein such as fish meal. The production cost of the dry algal product is dependent on the feed to the harvesting circuit having as high a concentration of suspended solids as possible. Harvesting at concentrations in excess of this would decrease the overall running costs, for example, at a concentration of 500 mg ℓ^{-1}, production costs (DOF) are reduced from R510 t^{-1} to R408 t^{-1}.

Summary and Conclusions

The following conclusions are drawn from the results:

1. Polyelectrolytes can effectively be used for DAF, giving a sludge containing up to 25% more solids than are obtainable by using alum.
2. Flotation by means of dissolved oxygen is made possible by using a polyelectrolyte as a flocculant rather than alum, probably due to stronger floc binding.
3. With the induction of air at the feed pump (approximately 4 ℓ min^{-1} for a feed of 100 ℓ min^{-1}) it is possible to boost DOF for a period of up to eight hours after sunset, at which time the original DO concentration has dropped to below 8 mg ℓ^{-1}. The main advantage of this mode of harvesting lies in the fact that all the equipment required for DAF is obviated, the process consequently requiring less supervision and maintenance.
4. Retention of the float layer in the cell for more than one hour before scraping, results in a biomass concentration of up to 8% solids, which represents an improvement of approximately 60% on continuous scraping.
5. The polyelectrolyte sludge is amenable to further dewatering on a screen resulting in a solids concentration of up to 12%.
6. Drum drying of the algal sludge resulted in a final product containing up to 56% protein, putting it in line with soya bean and fish meal.
7. An estimated initial capital outlay of 25% is possible on utilizing the DO technique with a possible 11 to 12% saving on running costs, as compared with DAF which requires air/water saturation.

It is clear that optimization of algal production in the ponds is imperative so as to reduce retention times and subsequent loss in water evaporation which was found to be in the order of 7 to

10 mm d^{-1} depending on ambient conditions. Harvesting at the highest possible biomass concentration would result in more favourable economics as a result of improved recovery, reagent consumption and equipment utilization. Further research is required to improve harvesting, dewatering methods and to investigate other means of drying the harvested product, with specific attention being paid to digestibility and toxicity of the final product. Reagents used for harvesting would be subjected to toxicity tests using fish in a biomonitoring technique, as explained by Morgan (1977).

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