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PROTEIN FROM ALGAE - AN ASSOCIATED INDUSTRY [1]

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Although the lagoon culture of algae is a development of the twentieth century, a large proportion of the world's animal population has always depended on sources of microalgae for food. The suggestion that this natural system should be adapted to increase food supplies for Man is, therefore, a reasonable one, and consequently much attention has been focused on the possibility of producing algae in the manner of an agricultural crop.

The productivity of algal cultures is potentially extremely high, and the growth of algae in non-sterile out-door cultures is no more complex than the production of vegetable crops. However, if a dependable, high growth rate is required then particular attention must be given to illumination factors, availability of mineral nutrients and carbon dioxide levels. Although the techniques required to control these factors are already known, their manipulation in any particular ecological context will depend on a number of considerations. In particular, the procurement of controlled supplies of raw materials, for example, fixed nitrogen or carbon dioxide, is of paramount importance. This problem might well be overcome by integrating a system for algal culture with a petro-protein complex, so that the waste products of the latter could be utilised to stimulate growth of the algae.

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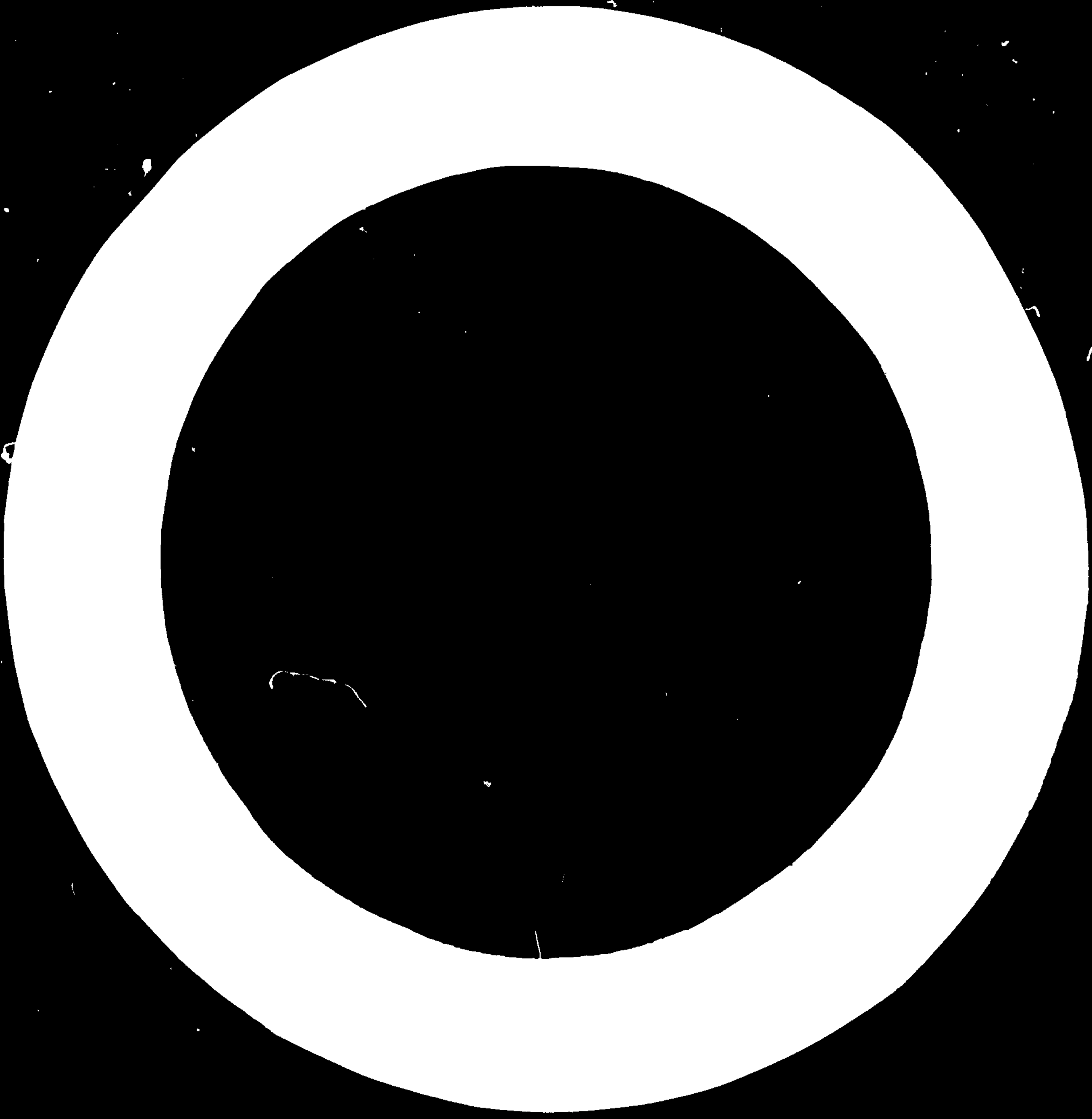

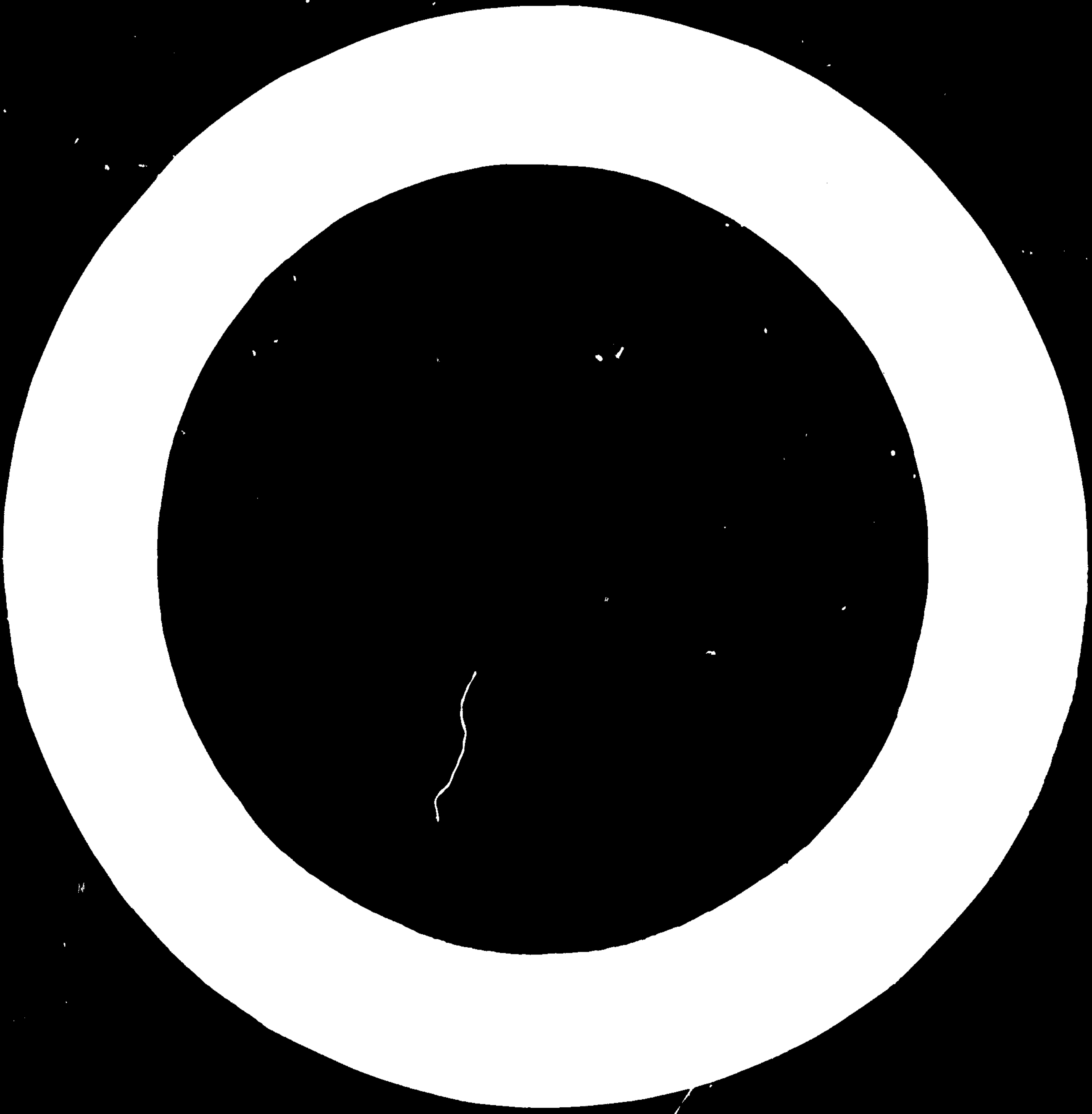

A number of avenues for the utilisation of the algae are available, and the information released concerning feeding trials is encouraging. These evaluations have covered both human dietary needs, and the feeding of ruminant and non-ruminant animals. However, little attention has been paid to the potential value of algae as a supplement in the production of balanced animal feeds. Thus, the vitamin B_{12} content, for example, of certain algae is high compared with the level in yeast, and hence algae could well be of value for the fortification of feed mixtures based on petro-protein.

If the projected costs for large-scale lagoon culture are accurate, then there is little reason to doubt that, either as a feed for domestic animals or for human food direct, the algae can make a significant contribution to future protein needs.

PROTEIN FROM ALGAE - AN ASSOCIATED INDUSTRY

INTRODUCTION

Much of present day thought in respect of protein malnutrition centres around the hope that the problem can be alleviated by increasing the production of plant proteins. It is, of course, a rather artificial solution, because there is sufficient protein available in the world (Ref. 13), if only it could be distributed. However, the obvious solution is unlikely to prove effective, and hence the immediate aim must be to increase the production of protein in areas where it is needed.

One approach is to increase agricultural productivity through improved husbandry, and concomitantly the introduction of high-yielding varieties of staple crops. Certainly, the so-called "green revolution" had its adherents, and when it is considered that a crop, such as chick-pea (Cicer arietinum), can sell at around 13 cents/kg of protein (Ref. 1), the prospects for traditional agriculture look encouraging. If populations were stable, then there would be room for optimism, but current estimates (Ref. 18) suggest that the world's population could double by 2000 A. D. It is for this reason that so much attention is being focused on "novel" sources of protein. Protein from oilseeds, leaf protein and fishmeal concentrates have all been examined as possible ingredients for animal feed-stuffs or for human food direct, but one of the most exciting developments has been the "arrival" of "single-cell protein".

The potential of protein production by the fermentation of waste carbohydrate materials has attracted a great deal of research interest (Ref. 17), but economically viable processes have only been established in a limited number of locations. The absence of large volumes of available substrate is the main reason that carbohydrate fermentations are not, at present, commercially attractive; an objection that does not arise in relation to the production of petro-proteins. The exploitation of another source of protein, the algae, is also not limited by considerations of substrate, and it is appropriate, therefore, that the production of algal protein should be considered in the present context; particularly as some of the waste products of petro-protein production might be utilised to boost productivity of the algal source.

I PRODUCTION OF ALGAE

If land, suitable for the construction of an artificial lagoon, is available and also adequate supplies of water, it could be argued that traditional agriculture should have precedence. However, as a cheap source of protein, the attraction of the algae in comparison with higher plants is two-fold. Firstly, the protein content of algae averages out around 50% (Ref. 9), and some species may exceed this value. Secondly, the algae have a much higher specific growth rate than higher plants. The pratical importance of this point is illustrated in Figure I.

On the curve relating to algae, it can be seen that the quantity of material P2 - Pl) removed by a harvesting operation will take time $(t_2 - t_1)$ to be replaced. In the case of the higher plants, regrowth of a much smaller amount of material (P4 - P3) would take the same length of time $(t_4 - t_3 = t_2 - t_1)$. The cycle of harvesting and regeneration could take place a number of times during a growing season, and hence the difference between yields could be multiplied several times. The potential productivity of an algal system is illustrated in Table I.

The yield figures for the two algae are from measurements obtained in pilot-scale lagoons. Nevertheless, there is little doubt that, given the right environmental conditions, yields of the magnitude could be obtained on a commercial scale.

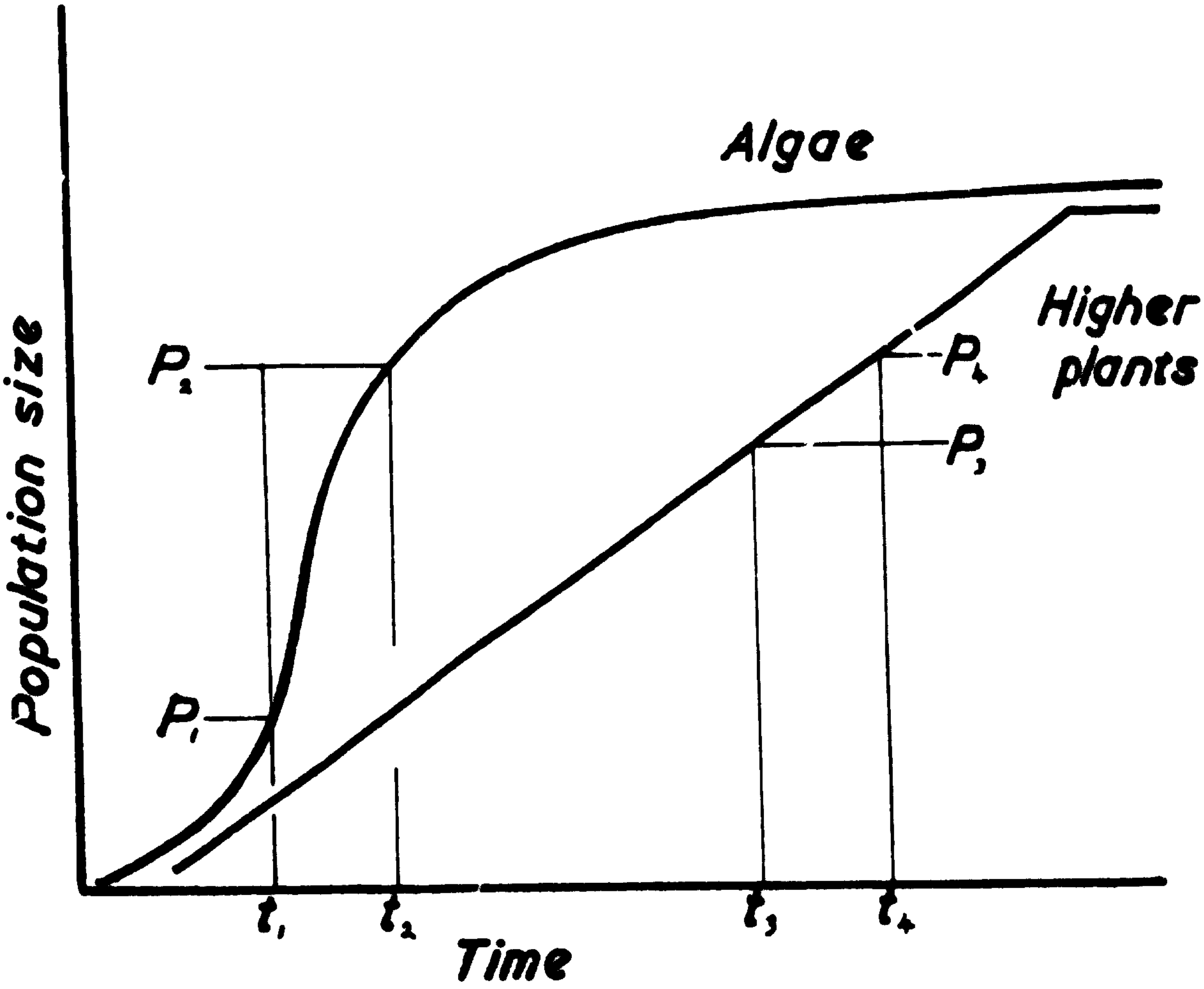

Fig. I. Comparison of hypothetical yields of algae and higher plants during one growing season

Table 1. Potential productivity of selected crops-yield figures of protein/unit area/growing season

Source of Protein	Yield (kg./ha./yr.)
Beef	60
Wheat	300
Clover leaf	1,680
Chlorella pyrenoidosa	15,700
Spiruline platensis	24,300

(after Vincent, 1971)

II TYPES OF ALGAE

The algae which have been most widely studied in this context are two unicellular organisms, Chlorella spp. and Scenedesmus spp., and the filamentous algae, Spirulina: examples of two of these genera are illustrated in Plates 1 and 2. It is relevant, in connection with the proposed exploitation of the algae as a food source, to point out that these genera have been selected almost by chance. Thus, both Chlorella spp. and Scenedesmus spp. are standard laboratory "tools" of the biochemist, while Spirulina claims fame as a food of the Aztec Indians. The logic behind the selection of these genera for further study is evident, but it does mean that the potential value of many other species has been ignored; this is particularly true of the variety of genera inhabiting tropical and sub-tropical lagoons.

Thus, a genus, such as Gonium (see Plate 1) could well prove to be of interest, because not only does it lack the rigid cell wall characteristic of many Chlorophyceae, but the colonial form could be advantageous in terms of harvesting. Similarly, a genus like Spirogyra (see Plate 2) with its extensive mat of filaments, might be an attractive prospect in situations where a labour intensive project is desirable. Obviously, in specific locations, there are attractions in the use of efficient and sophisticated techniques for harvesting algae (Ref. 15), but such an approach is not essential. Thus, in many areas of the world it may be socially desirable to promote projects aimed at reducing unemployment. The potential value of algal culture in this context has received scant attention, despite the fact that a number of genera would allow the use of extremely primitive harvesting and processing procedures.

III CONDITIONS OF GROWTH

The most favoured form of cultivation will, for reasons of economy, be an open lagoon, and three variations of this system have been examined:

a) A Natural Lagoon

The natural lagoons which occur in many areas of the world could well be adapted to low capital/labour intensive developments. The introduction of mineral nutrients might be required to stimulate entrophication, or to select for certain species with especial physical or nutritional characteristics, but beyond this, no attempt would be made to artificially influence the natural growth rates of the selected algae. The products of such developments would be primarily for local use, so that equipment requirements for processing would be minimal. Limited developments of this type are already in existence, for example at Lake Chad (Ref. 10), and similar forms of resource utilisation could be established elsewhere.

b) Modified Natural Lagoons

In this system, it is envisaged that a natural lagoon, and probably the normal algal flora, would be modified to achieve maximum productivity. It would be important, therefore, to consider not only the need for mineral amendment, but also the desirability of carbon dioxide injection. Similarly, to facilitate harvesting and improve the utilisation of incident light, a system of water circulation might be required; this demand might be fulfilled by the construction of simple booms which could channel the circulation in a given direction. This type of development obviously involves capital expenditure, but the benefit from improved production could well repay the additional outlay.

c) Artificial Lagoons

This system is obviously the most capital intensive, involving as it does the construction of extensive concrete and polyethylene lagoons. The physical form of these structures has already been described elsewhere (Ref. 15) (loc. cit), but it is clear that these systems must achieve high production rates to provide an economic return. Control over the production, harvesting and processing stages must be of the highest standard. If these requirements are met, then this form of intensive "algal farming" could provide a product at a price that is competitive with other available materials.

The success of any of three systems is dependant on a selected species of algae being able to form a climax community. In artificial lagoons, this aspect of algal culture does not present too much of a problem. Scenedesmus spp., for example, can be maintained as the climax population over many years by a manipulation of the environmental factors. It is clear, however, that any lagoon designated for intensive culture must be treated as a discrete ecological site, and that the environmental and operational conditions must be adjusted to achieve the desired end-point.

IV FACTORS AFFECTING PRODUCTIVITY

It is clear that even the most primitive system will involve a semi-continuous procedure for harvesting. In general terms, this process would aim to maintain a population level at around 50% of the value (P_2) shown in Figure I. The advantage of this approach is that it would enable the selected species to maintain its dominant position in the community. The amount of material available for harvesting at any given time will depend on the environmental conditions, and three factors in particular need to be considered:

i) light
ii) carbon dioxide
iii) mineral nutrition;

it is assumed that selected species will be adapted to the prevailing mean temperature.

i) Light

It is reasonable to assume that, in tropical or subtropical regions, adequate light will be available. Nevertheless, plants are not efficient converters of light energy and it is estimated (Ref. 7) that only around 1% of incident light is utilised by an agricultural crop. In the case of algae, the percentage utilisation may drop even lower, because not only does water "absorb" a portion of the incident light, but also the upper layers of algae may effectively shade those below. This feature is particularly important in relation to the unicellular algae, such as Scenedesmus spp. (see Plate 1), and is well illustrated by the results of Enebo (Ref. 8). In this work, Scenedesmus was grown in cultures, 50 mm. deep, and at a concentration of 1.5 - 2.0 g of algae (dry wt) per litre. Obviously, much of the suspension in such a system would be receiving an incident illumination below the compensation intensity, and this was illustrated by the fact that induced turbulence resulted in a 60% increase in the growth of the algae.

It is clear, therefore, that physical agitation can be valuable in increasing the utilisation of light. The incorporation of mineral nutrients will also be facilitated, as will the attainment of a viable, homogeneous culture. This movement of the water may be achieved by mechanical means, for example paddle wheels or pumps, or possibly by the injection of gases (see below). The degree or turbulence will depend on the conditions of culture.

Thus, a slow flow-rate through a lagoon system may be the most appropriate condition to stimulate 'scum" forming filamentous algae, while unicellular ones may benefit if agitation is more violent. However, whatever system is used in practice, there is no doubt that light utilisation and productivity are enhanced.

ii) Carbon dioxide

If a circulation system is employed to improve light availability throughout the culture, then carbon dioxide could well become a limiting factor. The pH value of the culture medium is obviously critical here. Thus, under alkaline conditions, as would be required for *Spirulina* spp., for example, there will be a "reserve" of carbon dioxide in the form of carbonates and bicarbonates. However, under these conditions the concentration of carbon dioxide in solution will be low, and the artificial injection of the gas could prove advantageous. In acid conditions, such as favour the growth of Scenedesmus spp., the essential of ensuring an adequate availability of carbon dioxide is even more marked. It is clear, therefore, that if algal culture can be integrated with an industrial complex capable of supplying carbon dioxide, then the productivity of a lagoon system could be enhanced. All the more so, if the gas injection system could provide the means of inducing the desired degree of turbulence into the culture.

Carbon dioxide can be obtained from a variety of sources in varying degrees of availability. Flue gas from the combustion of fossil fuels is probably the most widely available, but it contains only 8 to 10% (by volume) of carbon dioxide and is generally produced at pressures only slightly above atmospheric. Thus, to be efficiently used in the cultures, the flue gas would have to be compressed to overcome distribution losses and the depth of liquid into which it would be introduced. Hence although desirable agitation would be produced by the oxygen and nitrogen, roughly ten times the power would be required to utilise the flue gas than would be required if pure carbon dioxide were available. This inefficiency factor would be further increased to perhaps twenty times if exhaust flue gases from spray drying were used as the carbon dioxide content can be as low as 5% in this source. Flue gases also may contain sulphur dioxide, which can be up to about 1% by volume depending on the fuel used. This would dissolve in the aqueous phase to give sulphites which may affect growth of the algae.

Substantially more concentrated carbon dioxide is obtainable as a by-product of ammonia production and concentrations in excess of 98% carbon dioxide can be available. Such carbon dioxide is normally close to atmospheric pressure so some compression would probably be required.

However, this would be much more efficient than the compression of flue gas. In some ammonia use patterns this carbon dioxide is effectively free of cost being a waste material but where, for example, urea is the end product, the carbon dioxide may be in deficit or only available in marginal quantities. Loss of agitation effect is unlikely to be significant as there is a rate effect in the dissolving of carbon dioxide, during which time the gas will be present as an agitating agent.

Fermentation is a further source of carbon dioxide. This is frequently available at high purity and hence is used as a source of dry ice. Thus it is unlikely to be available for algae production. However, carbon dioxide from the fermentation of hydrocarbons is not only unsuitable for this purpose, because of the nitrogen and oxygen present, but may be produced at some pressure and could be available in substantial quantities. This could make it attractive to integrate petro-protein and algae protein facilities.

iii) Mineral Nutrients

It is probable that the mineral requirements of both the algae and the micro-organisms involved with hydrocarbon fermentation are broadly similar. Thus, both groups of organisms rely on a source of fixed nitrogen for maximum growth, and other elements, such as phosphorus, sulphur and potassium, must also be supplied in a suitable form.

As these minerals are required for petro-protein production, then their availability for the culture of algae should not prove a problem. In fact, one aspect of the postulated association that deserves consideration is whether the effluent from a fermentor could not be used to provide the minerals required for algal growth. The actual feasibility of the idea can only be discussed, of course, in relation to a specific project, but, in principle, this form of integration has much to recommend it.

In view of the need for fixed nitrogen and phosphorus in particular, there is also the possibility of integrating algae production with nitrogenous and phosphatic fertiliser production as, in both types of fertiliser plant, there are frequently dilute streams of nutrients which impose a disproportionate cost on the production process for their disposal in an ecologically satisfactory manner. It is possible that these streams could supply useful nutrients to the algae production marginally reduce fertiliser production cost and, at the same time, reduce the discharge of effluents.

UTILISATION OF THE ALGAE

a) Nutritional Value of the Algae

The nutritional value of protein foods varies considerably, and is dependant on their actual content of protein, the amino acid composition of the protein and the availability of the protein.

The average protein content of the green algae is, as indicated earlier, around 50%, while the blue-green algae (Spirulina) have a value of 60 - 65%. The actual protein level for any given species, and the composition of the protein, will depend, to a degree, on cultural conditions, but in general the average values are much higher than for agricultural crops.

Amino acid analyses of various species are shown in Table 2, together with the recommended amino acid content of an ideal protein for human consumption.

It is evident that, while the algae contain all the essential amino acids, the low content of sulphur-amino acids, i.e. Cysteine/Cystine and Methionine, is an obvious deficit. However, as the algae are being proposed as a dietary component, this deficiency may not create a problem, while the high lysine content of the algae makes them valuable supplements to cereal diets (Ref. 3).

However, it is essential to remember that both humans and animals need "food not just protein" and many discussions of novel foods ignore vitamin and lipid contents completely. Yet, in the production of a balanced diet, the algae could be extremely important, particuarly if the food is basically of vegetable origin. Thus, the algae are known to be an excellent source of B vitamins, and in some species B_{12} (cobalamin) occurs in appreciable quantity; this latter aspect could make the algae a valuable blending material for animal feeds.

Table 2. Amino acid composition of selected green and blue-green (g/100g. protein)

Amino acid (essential)	F.A.O. standard	Algae Spirulina maxima (Ref 4)	 Chlorella ellipsoidea (Ref 19)	 Scenedesmus obliquus (Ref 11)
Isoleucine	4.2	6.0	4.5	3.8
Leucine	4.8	8.0	9.3	8.4
Lysine	4.2	4.6	5.9	5.7
Phenylalanine	2.8	5.0	4.2	5.1
Tyrosine	2.8	4.0	1.7	-
Cysteine/ cystine	4.2	0.4	0.7	0.6
Methionine	2.2	1.4	0.6	1.7
Threonine	2.8	4.6	4.9	5.1
Tryptophan	1.4	1.4	-	1.5
Valine	4.2	6.5	7.9	5.7

The lipid content of "novel" materials also tends to be overlooked, despite the evidence (Ref. 5) that the polyunsaturated fatty acids are essential constituents of an animal diet. Vegetarian animals derive two essential fatty acids from their food, namely linoleic and linolenic. Both are C_{18} molecules, but their structure is such that animals cannot metabolise one from the other. Thus, two separate families of fatty acids, one based on linoleic acid, the other on linolenic acid, are built up within animal tissues, provided that the base materials are available. The observation of Nichols & Wood (Ref. 14) that Spirulina platensis contains over 20% of these acids is, therefore, extremely significant; particuarly in relation to human nutrition. If other algae capable of lagoon culture are similarly endowed, then their use to supplement fatty acid deficient diets could be valuable, irrespective of any protein or vitamin considerations.

b) Acceptability of the Algae

Assuming that the algae can compete economically with other forms of animal feed, there can be little doubt that the material does have potential as a source of cheap protein. Feeding trials with cattle, sheep, poultry and pigs have indicated that the nutritive value of algal protein is relatively high. If thick-walled green algae are used as the feed material, then, as would be expected, ruminants are at an advantage.

Nevertheless, even for non-ruminants, the protein efficiency ratio of Chlorella protein is higher than for most conventional vegetable proteins (Ref. 16).

The possible use of algae to supplement the human diet has also received extensive consideration. Poor digestibility of the algal protein is one problem still to be resolved (Ref. 6), but feeding trials with species of Scenedesmus and Chlorella look promising (Ref. 12).

If the presence of a chemically inert cell wall is the limiting factor, then the answer may be to make more use of the thin-walled, blue-green algae. However, it is worth emphasising that improved methods of processing algae may render the final product more digestible (Ref. 2). It is also possible that other species of algae will prove to be more digestible, and hence the examination of the algal flora of natural lagoons could prove rewarding.

V CONCLUSION

It is clear that the algae have immense potential as a source of cheap protein, yet practical developments in this area have received comparatively little support. One of the main reasons for this lack of interest is that no precise estimates can be made concerning overall economics. Thus, published figures tend to be either optimistic or completely depressing, and hence an objective observer is left with no sensible conclusion. What has yet to be accepted is that algal culture is a complex ecological system, and any proposed development should be examined as a discrete entity. If this approach is adopted, then realistic costing for the production of a specified type of material can be achieved, and, in many parts of the world, the algae could prove to be a valuable source of food.

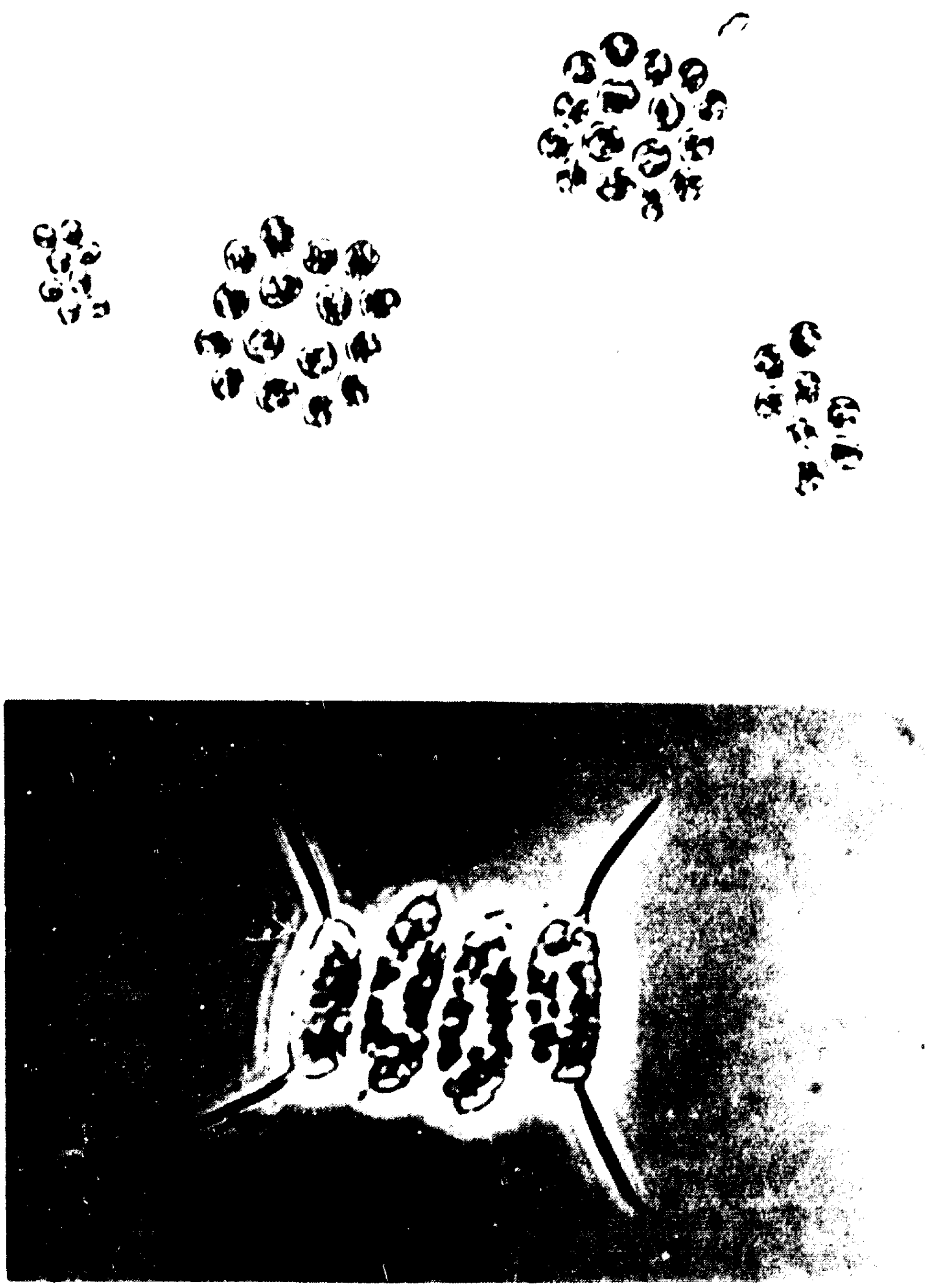

Plate 1 - Algae of potential interest as sources of protein:

<u>Gonium</u> sp. x 250 (above)
<u>Scenedesmus</u> sp. x 1500 (below)

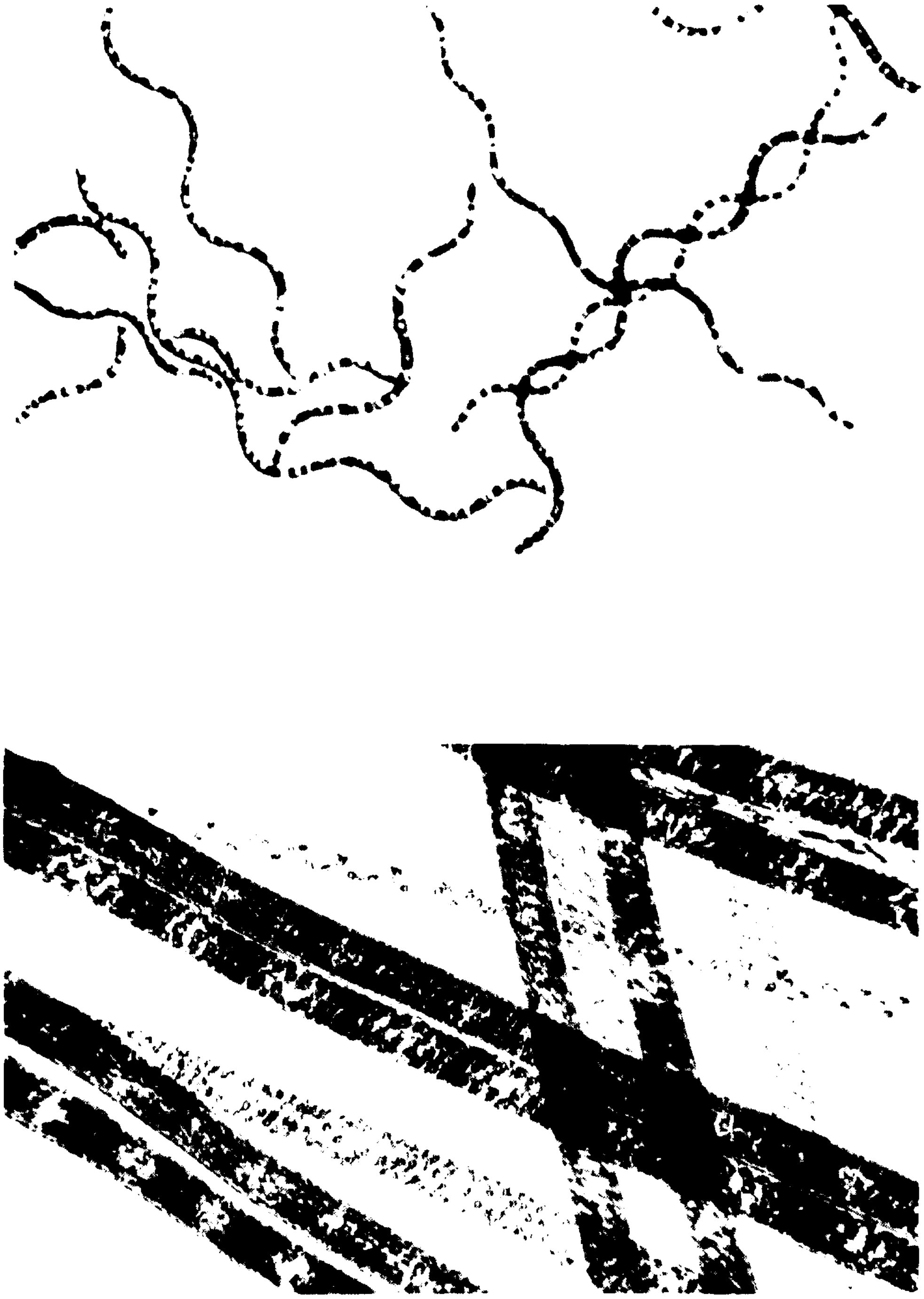

Plate 2 - Algae of potential interest as sources of protein:

<u>Spirulina</u> sp. x 250 (above)
<u>Spirogyra</u> sp. x 150 (below)

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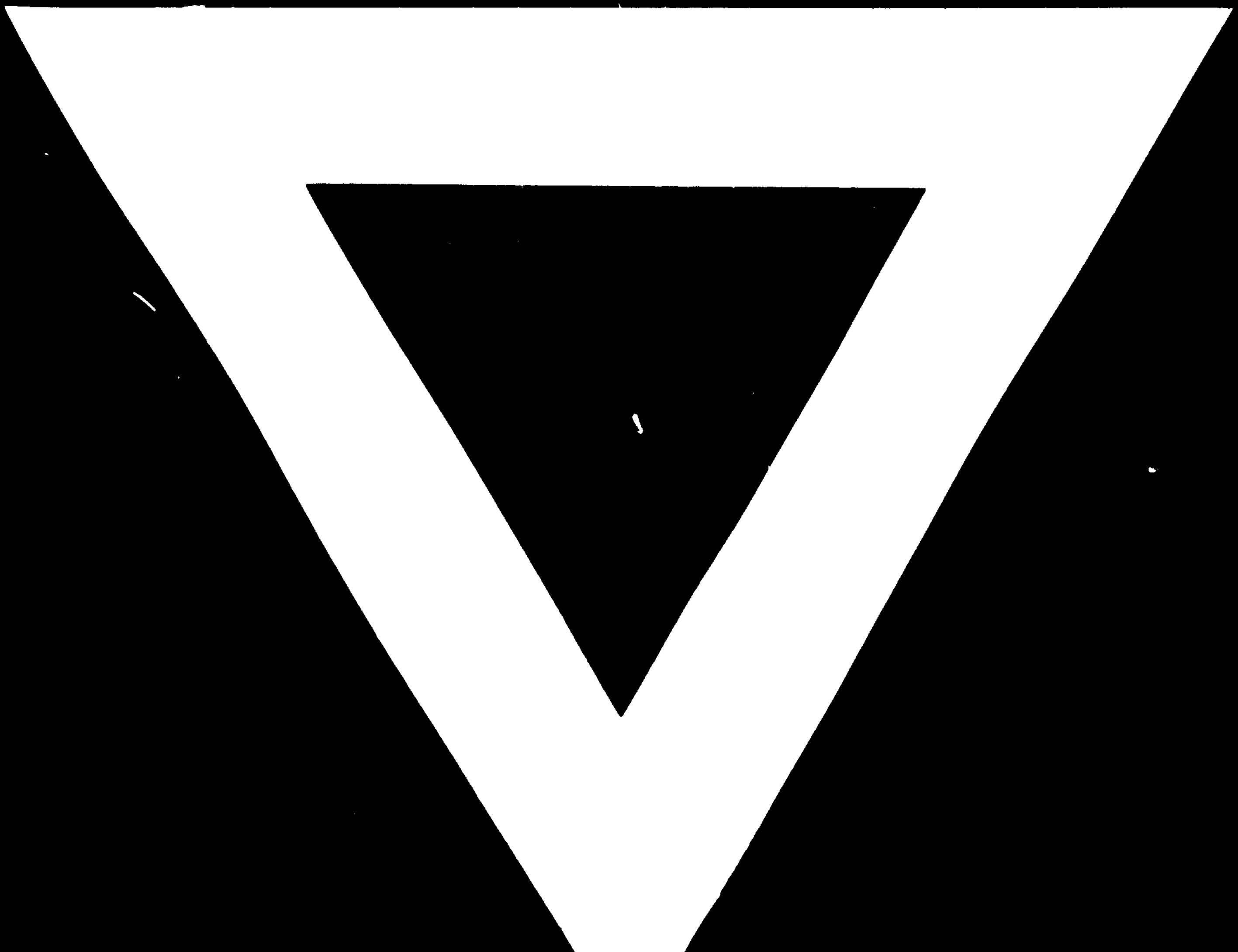

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