WASTE TREATMENT BY ALGAL CULTIVATION

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ALTERNATIVE CULTURE AND TREATMENT SYSTEMS

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ABSTRACT

Shallow, paddle-wheel mixed, raceway-type ponds (high rate oxidation ponds, HROP) are generally used in the treatment of wastewaters with algae. Recently however, several other types of algal culture systems have been developed which have potential application for the tertiary, or higher, treatment of wastewaters. These include hyperconcentrated algal cultures, immobilised cell systems, dialysis cultures, tubular photobioreactors and algal mats. Depending on the particular application of the algae to wastewater treatment and the ultimate use of the algal biomass, these systems may be much better suited than the 'standard' HROP pond system.

KEYWORDS

hyperconcentrated cultures, immobilised cells systems, tubular photobioreactors, dialysis cultures, algal mats.

INTRODUCTION

Almost all algal systems used for wastewater treatment to date are either deep ponds (oxidation ponds) or, more commonly, large, shallow, paddlewheel-driven raceway-type ponds (high rate oxidation ponds) (Shelef et al., 1980; Soeder, 1980; Abeliovich, 1986; Oswald, 1988a, b, c). The latter pond types are also the main systems used for the commercial cultivation of microalgae for...
fine chemicals, food or feed (Curtain et al., 1987; Borowitzka and Borowitzka, 1989a, b, 1990). Although these types of culture systems are effective, they have several limitations which are also important to the use of algae for wastewater treatment. These limitations are:

1. relatively low light utilisation efficiency,
2. low algal densities (usually < 1 g dry wt.l⁻¹),
3. little effective control over temperature, pH or O₂ concentration.

Furthermore, unless the algae are able to grow in extreme environments such as high salinity (e.g. Dunaliella) or high pH (e.g. Spirulina), it is difficult to maintain a reliable 'pure' algal culture. These limitations have resulted in the development of several alternative algal culture methods, and some of these also have potential applications in wastewater treatment or in the use of wastewaters as a nutrient source for the production of algal biomass.

Most studies of algae and wastewater have concentrated on the use of the algae for the removal of nutrients from wastewater, and the utilisation of the algal biomass produced has been only a secondary consideration. However, as pointed out earlier (L.J. Borowitzka, this volume), microalgae are also sources of a wide range of valuable compounds.

HYPERCONCENTRATED CULTURES

Hyperconcentrated cultures are cultures with an algal biomass > 1.5 g.l⁻¹. On a small-scale, experiments with hyperconcentrated cultures have shown that these can accelerate the removal of nutrients compared to 'normal' cultures. Algae for such experiments are concentrated by flocculation and settling using a flocculant such as chitosan (Lavoie and de la Noüe, 1983; Morales et al., 1985). Cell concentrations of up to 1.9 g dry weight.l⁻¹ have been obtained for Oscillatoria sp. grown on sewage sludge (Hashimoto and Furukawa, 1989). Working with Scenedesmus obliquus cultures, Lavoie and de la Noüe (Lavoie and de la Noüe, 1985) have shown that greatly nitrogen removal was greatly accelerated for 1.9 g dry weight.l⁻¹ cultures compared to normal density cultures of 0.5 g dry weight.l⁻¹. They have also demonstrated that the rate of removal of ammonium and phosphorous in these hyperconcentrated cultures was proportional to algal concentration and independent of the obvious light limitation due to self-shading. Although this work has been carried out only on a small scale so far, the use of such hyperconcentrated cultures would require smaller pond areas, or would permit a reduced residence time, both of which have potential advantages. The engineering and economic feasibility of such systems on a large-scale remains to be determined.

IMMOBILISED CELL SYSTEMS

Immobilised cell systems have the advantage of allowing high concentrations of algae to be maintained and minimise the need for harvesting. Therefore, they have great potential for tertiary treatment of wastewaters. A recent review (Tyagi and Vembu, 1990) summarises much of the available data on such systems. Immobilised systems have been tested for nutrient removal from wastewater. For example, Chevalier and de la Noüe (1985) immobilised two species of the green alga, Scenedesmus, in κ-carrageenan beads, and used these to remove nutrients from wastewater. The growth of the immobilised cells was the same as those of free-living cells, and the uptake of
nitrogen and phosphorous was also similar for free and entrapped cells. Robinson et al. (1989) have also examined the phosphorous uptake kinetics of *Chlorella emersonii* immobilised in Ca-alginate beads. In this system they have achieved average uptake efficiencies of 44% with secondarily treated effluent. Improved uptake rates are expected with improvements in reactor design and possibly also with selection of more efficient algae. The main drawback to such a system at present is the high cost of the inclusion materials, and further studies are needed to find a cheaper alternative material. One promising material is chitosan flakes which have been used to immobilise *Phormidium* with some success (de la Noüe and Proulx, 1988a, b) and polyurethane foams have also been used (Largeau et al., 1988).

Immobilised algal cells can also be used for the removal of heavy metals from waste waters, and in this application they have the advantage of simplifying the removal of the heavy metal contaminated algae from the system.

**DIALYSIS CULTURES**

In dialysis culture the algae are separated from the nutrient-containing medium by a semi-permeable dialysis barrier. Low-molecular weight compounds diffuse across this barrier in response to a concentration gradient (Jensen, 1976; Marsot et al., 1991). High cell density cultures can be maintained for prolonged periods in systems with a high membrane surface area/culture volume ratio, and the algal cells show very efficient rates of nutrient utilisation (Ney et al., 1981; Marsot et al., 1991). One advantage of dialysis culture is that it can serve to exclude inhibitory substances and it also allows the microbiologically pure culture of the algae. The latter is particularly important for the production of high quality algae for human consumption.

Such a system has, as yet, not been applied to the use of wastewaters for algal culture, however this type of system deserves critical evaluation.

**TUBULAR PHOTOBIOREACTORS**

One of the most promising areas in the development of new reactor types are the tubular photobioreactors. Basically, these reactors are a closed system consisting of a clear tube within which the algae grow. The algae are circulated by means of a pump and the system also has a gas exchange unit where CO₂ can be added and photosynthetically produced O₂ is stripped from the medium. If necessary, a heat exchanger is also added to either cool (in tropical areas) or heat (in temperate areas) the culture. Figures 1 and 2 show the layout of such reactors.

The concept of tubular reactors is not new. Simple tubular reactors were already tested by Davis and coworkers (1953), and many of the modern systems derive from the work of Pirt (Pirt et al., 1983), although similar systems had been used in Czechoslovakia at Trebon earlier to grow *Chlorella* (pers. comm).

Two basic kinds of systems are presently used consisting either of (a) straight tubes arranged flat on the ground or in long vertical rows (Pirt et al., 1983; Pirt, 1986; Torzillo et al., 1986; Bocci et al., 1988; Chaumont et al., 1988), or (b) of tubes spirally wound around a central support (Robinson, LF et al., 1988; Borowitzka and Borowitzka, 1989b) or a similar helical structure (Lee and Bazin, 1990). The tubes can be of glass, Perspex or PVC, and diameters range from about 24 cm to 24 mm. It is
interesting to note that most systems are now tending to use the narrower diameter tubes, since these appear to have better hydrodynamic properties and result in improved productivity. Circulation of the algal culture is by means of diaphragm, peristaltic, lobe or centrifugal pumps or by an airlift. From an engineering point of view, the circular reactors are easier to construct, and occupy less land area per unit volume.

These photobioreactors have been used on a pilot scale to grow a wide variety of algae including *Spirulina*, *Porphyridium*, *Chlorella*, *Dunaliella*, *Haematococcus*, *Tetraselmis* and *Phaeodactylum*. In our studies, biomass concentrations of $> 3$ g.L$^{-1}$ have been achieved. The high productivity and biomass can be attributed to the small optical cross-section of the tubes thus maximising light utilisation and a very effective mixing regime. These reactors also have the advantage of almost linear scale-up, unlike paddle-wheel and similar ponds, where scale-up presents major difficulties (Borowitzka and Borowitzka, 1989b).

The straight, horizontally arranged systems have ranged from small laboratory-scale units (Materassi *et al*., 1980; Bocci *et al*., 1988; James and Alkhars, 1990) to the 1000 m$^2$ pilot plant at Cadarache in France (Chaumont *et al*., 1988). Figure 1 shows the layout of such a system. One problem with large systems of this design is that the long tubes require adequate support and flat surfaces. This problem was overcome in the Cadarache plant by floating the tubes in a large pond. By attaching a flotation system to the tubes, temperature of the cultures could also be controlled by either floating...
the tubes at the surface of the pond where they would heat up, or immersing them wholly to cool them.

The coiled tubular bioreactors of the BIOCOIL design of Biotechna Plc have the advantage of being much easier and cheaper to construct and also show better mixing characteristics and higher productivities that straight tubes (Hishino et al., 1991). Figure 2 shows the layout of such a system.

Tubular reactors have several potential problems which affect algal productivity. These are

(1) temperature control;
(2) Control of O₂ and CO₂;
(3) Growth of the algae on the inner surface of the tubes;
(4) Adequate circulation speeds without damage to the relatively fragile algal cells.

**Temperature Control**

Although this has been perceived as a major problem in tubular reactors, considering that they are very similar in design to solar hot water collectors, practice has shown that temperature can be

![Diagram of BIOCOIL-type tubular photobioreactor](image)

Figure 10. Schematic layout of the BIOCOIL-type of tubular photobioreactor.
controlled easily. Temperature control can be either by the floating tube method used at Cadarache, by spraying water over the tubes to allow evaporative cooling, or by using a heat exchanger and a cooling system. The latter approach appears to be the most economically effective. In cool climates, the heat exchanger system can also be used to heat the cultures. Such a system was used by Biotechna Plc at their pilot-scale plant at Luton, U.K., and which used the waste heat generated by a brewery.

**$O_2$ and $CO_2$ Control**

Algal cultures require $CO_2$ for photosynthesis. Photosynthesis also produces $O_2$ which, at high concentrations, will inhibit photosynthesis and therefore also productivity. In order to strip effectively the culture of $O_2$ and add sufficient $CO_2$, tubular reactors require efficient gas exchange towers and quite a lot of research is focusing on this at present. The need for regular gas exchange also limits the length of the tube through which the algae must pass. This aspect of the design of tubular photobioreactors appears to have been resolved through the use of manifolds to split the culture over several parallel tube systems (Robinson, LF et al., 1988).

**Fouling**

Fouling of the internal surfaces of the tubular reactor reduces the light utilisation efficiency of the algal culture due to shading, and also decreases the nutrient uptake efficiency. In narrow-tube photobioreactors, fouling can be prevented by maintaining the flow-rate above a certain speed; the required flow rate will depend on the particular algal species and growth conditions. The spiral tubular photobioreactors also appear to be less prone to fouling due to the particular hydraulic flow conditions which exist in a curved tube compared with a straight tube.

If fouling does occur, the tubes can be cleaned by circulating small beads of polystyrene foam or similar material within the tubes without interrupting the normal culture.

**Circulation**

A major area for continued research is the method of providing the flow rate required. Existing systems use a wide range of pumps or airlifts, and as yet no particular type of pump seems to be more effective than any other. It is clear, however, that pumping can be a major limiting factor to the productivity of some algal species due to cell damage which occurs. It is therefore necessary to study the effects of different pumping systems on a range of algae and to understand better the hydrodynamic environment within pumps and, furthermore, more effective airlifts need to be designed. It will also be very likely that different algal species will have different optimal pumping systems.

**ALGAL MATS**

All the systems considered so far have used microalgae. An alternative system for nutrient removal from wastewaters is to use attached macroalgae or other aquatic plants. One such system is the algal mat system developed by Adey (Adey, 1982), and which is being used to remove nutrients from large tropical aquarium systems such as those at Reef World and at James Cook University in Townsville. In this system, the algae (a range of turf-forming species such as *Enteromorpha*, *Cladophora*, *Sphacelaria*, *Ectocarpus*, *Ceramium*, *Polysiphonia*, *Herposiphonia* and *Oscillatoria*) are
grown on a net or mesh and the nutrient-rich water is passed over them. The algae containing the nutrients are regularly removed by mechanically removing them from the mats.

Although this system has proven very effective in controlling the nutrient levels in the aquarium water so that even corals, which are very sensitive to elevated nutrient levels, can grow, it does require a large surface area and is very labour intensive. In certain months of the year the natural daylight also has to be supplemented with artificial lighting to maintain an adequate rate of nutrient removal.

Other aquatic plant based systems have also been proposed for nutrient removal using aquatic plants such as water hyacinth, *Typha* and *Phragmites*, however all of these systems have been shown to be less efficient than algal systems (Werblan *et al.*, 1978; Wolverton, 1982; Finlayson, CM and Chick, 1983; Finlayson, M *et al.*, 1987).

**CONCLUSIONS**

Algae can be used in wastewater treatment for a range of purposes, including

(a) reduction of BOD;
(b) removal of N and/or P;
(c) removal of heavy metals.

The high concentrations of N and P in most wastewaters also means that these wastewaters may possibly be used as a cheap nutrient source for algal biomass production. This algal biomass could be used for

(i) for methane production;
(ii) for composting;
(iii) for the production of liquid fuels (pseudo-vegetable fuels);
(iv) as animal feed or in aquaculture;
(v) for the production of fine chemicals.

The different purposes, and the various applications to which the algal biomass may be put, as well as other factors such as climate, are likely to require different culture systems. The systems described above are some of the major alternatives to the more conventional high rate oxidation pond systems. With increasing pressures to not only treat wastewaters to reduce the BOD, but to also remove nutrients to avoid eutrophication of the dams, lakes, rivers and seas into which the effluent is discharged, consideration of these systems and their application should be part of any rational evaluation of the available waste treatment alternatives.

**REFERENCES**


