Description

This invention relates to biomass production and is particularly concerned with a photobioreactor and a method of biomass production employing such a photobioreactor.

The long term commercial potential of producing useful products by photosynthesis techniques using simple plant matter, such as algae and seaweed, has been recognised for some time. Indeed the ability of simple single cell organisms, such as blue green algae, to utilise sunlight, carbon dioxide and the inorganic constituents of sea water to produce more complex matter played an essential part in the evolutionary process. Many attempts have been made to harness the ability of simple organisms to produce complex materials.

Open channel cultivation of algae has been attempted to produce a biomass for animal or human consumption. Not surprisingly, this comparatively crude method has proved impracticable for production of pure high grade products because of such problems as invasion by hostile species (sometimes producing dangerous toxins), other pollution (such as dust), difficulty in the control of such variables as nutrient ratios, temperature and pH, intrinsically low yield because of escape of carbon dioxide to the atmosphere and inefficient use of light to illuminate only the top portion of the biomass.

It is known from GB-A-2118572 to employ a photobioreactor which comprises a plurality of straight transparent tubes arranged substantially horizontal one above the other in a vertical stack. The tubes are connected together in series and a synthesis mixture is caused to flow downwardly through the tubes in a turbulent manner. The tubes are illuminated by natural light whilst the synthesis mixture is passed through them. A biomass synthesis product is withdrawn from the mixture.

The present invention seeks to provide an improved photobioreactor and a biomass production process which can be carried out on a substantial commercial scale with reduced land usage and improved operating efficiency.

According to a first aspect of the present invention, a photobioreactor comprises an upstanding core structure; a substantially transparent tube supported on the core structure so that, in use, the exterior of the tube is exposed to natural light; means for causing a synthesis mixture comprising living plant matter together with essential nutrients for growth of the plant matter to flow under turbulent conditions through the transparent tube; and means for withdrawing a biomass synthesis product from the mixture; characterised in that the core structure is of substantially cylindrical form, the transparent tube is wound helically on the outside of the core structure, and light is encouraged to penetrate into the tube in the region of contact between the tube and the core structure.

The means to encourage light penetration may comprise providing the tube and/or the core with light reflecting means adjacent the area of contact between the tube and the core structure. The light reflecting means are suitably provided by interposition of a material, such as aluminium foil, between the core structure and wound tube. As an alternative, the core structure may be painted white and/or provided with a reflective surface, for example, of small glass balls known as balotini. Alternatively, or in addition, the core may be of sufficiently openwork construction to allow sufficient light to penetrate to the underside of the tubing. To assist light penetration, reflecting means, such as mirrors, may be positioned adjacent the top of the core structure. Alternatively, sufficient illumination within the core may be provided by the inclusion of some form of artificial light source within the hollow centre of the core, such as vertical fluorescent tubes. Such additional illumination may be employed continuously or only when necessary, for example, at night or in very gloomy conditions. Such additional lighting may be set to give flickering illumination to maximise light usage.

It will be appreciated that the core is not necessarily truly cylindrical and may, for example, be in the form of a truncated cone. Such a shape can be efficient for light utilisation in tropical countries where the sun shines vertically downwards, the conical structure minimising shadow formation. Preferably, the method and apparatus are adapted for continuous production with means being provided for recycle of the synthesis mixture.

According to a second aspect of the present invention, a method of biomass production comprises causing a synthesis mixture comprising living plant matter together with essential nutrients for growth of the plant matter to flow under turbulent conditions through a substantially transparent tube supported on an upstanding core structure; exposing the exterior of the wound tube to natural light and withdrawing a biomass synthesis product from the mixture; characterised in that the synthesis mixture is caused to flow upwardly along the tube which is wound helically on the outside of the core structure and light is encouraged to penetrate into the tube in the region of contact between the tube and the core structure.

The method may be carried out under aerobic or anaerobic conditions. Thus, carbon dioxide or air may be supplied to the tube, or other gases, such as oxygen or air/oxygen mixtures, may be employed dependent on the synthesis product desired. Some plant synthesis reactions proceed anaerobically, in which case no such gaseous imput

is required.

In one preferred form of the invention, the fact that some biomass synthesis reactions proceed aerobically while some proceed anaerobically can be utilised by providing two or more reactors, as described above, operating in series, a first reactor (or bank of reactors) being used to carry out an anaerobic reaction which leads to evolution of gas, such as carbon dioxide, which, after separation of the first product biomass, is used in a second reactor for an aerobic reaction utilising the gas.

Ammonia gas may be used as the or as one of the nitrogen sources. The use of controlled ammonia injection has been found to be beneficial in minimising the growth of unwanted microscopic species, such as bacteria, amoeba and rotifers. It is believed that the presence of ammonium salts and ammonium ions inhibits such growth, while acting as a nutrient source for the growth of plant material such as Spirulina (blue green algae).

Alternatively, or in addition, such growth may be prevented by the use of selective ultraviolet irradiation of portions of the tube, such irradiation being applied internally or externally of the tube.

The nutrients for the synthesis may be provided at least in part by waste effluents such as those from sugar plants or petroleum refinery wastes or other high BOD carbohydrate wastes, the wastes thus being purified in the process, so that the biomass produced is a valuable byproduct of the effluent treatment process.

A particularly preferred tube material is polyethylene, especially low density polyethylene, which has excellent light transmission properties and low cost. It also has the valuable advantage of being resistant to attack by the biomass medium.

The invention will now be described by way of example with reference to the accompanying drawings wherein:

Figure 1 is a diagrammatic view of a photobioreactor in accordance with the invention;

Figure 2 is a sketch illustrating the layout of a plurality of such reactors;

Figure 3 is a flow diagram of an alternative method of biomass production;

Figure 4 is sketch of a modified bioreactor; and

Figure 5 is a flow diagram of two banks of photobioreactors operating in series.

The photobioreactor shown in Figure 1 comprises a core structure 2 (shown in dotted lines) which is upstanding and substantially cylindrical. The core structure may provide a continuous outer surface and be formed for example of hollow concrete sections. Dependent on the size of the reactor, the concrete sections may have internal access steps to enable inspection and maintenance personnel to enter the interior and reach apparatus positioned at the top part of the core structure. Alternatively, the core structure may be of openwork construction, for example it may be constructed of metal supports such as those known under the trademark "Dexion", or alternatively the core may be of cylindrical shaped metal mesh construction.

The support structure is faced with a layer 4 of a light reflective material such as aluminium foil. Over the light reflecting layer 4 is a spirally wound tube 6 of substantially transparent material. A preferred material is polyethylene, preferably of low density, as such tubing has excellent light transmission properties, low cost, and can be readily extruded and wound in long lengths. Polyethylene also has the advantage of good corrosion resistance and can withstand the chemical conditions of the reaction mixture to a much greater extent than a material such as stainless steel, which has conventionally been used in bulk fermentation methods. However other plastics materials such as methyl methacrylate or transparent polyvinyl chloride can be used, or even non plastics materials such as glass if capable of withstanding the conditions of use. The layer 4 of light reflective material may not be necessary in some circumstances if the tube 6 itself is half-silvered or otherwise treated so that it has a light reflecting surface adjacent the core structure 2. Pegs (not shown) may project from the core structure 2 to support the tube and prevent slippage of the windings.

If the core structure is of sufficiently open construction, the layer of light reflective material may not be needed as sufficient light will penetrate to the underside of the tubing. In order to allow sufficient light penetration to the interior of the core structure, the plastics tube windings should be spaced at least one quarter of the tube diameter apart. Suitably the tubing is wound at an angle to the horizontal of for example 3°.

If desired for reasons of strength, the tubing may have a reinforcing outer coating, for example of clear resin. This is especially valuable if it is desired to carry out the biomass production under considerable pressure.

The core structure may be solid, for example an existing tank which may be given a reflective surface and which optionally carries a mesh structure on which the tube windings are arranged. If desired, an outer mesh supporting structure may be additionally provided around the windings. The tanks may be of any desired diameter, e.g. from 2 to 5 meters.

The lower end of the core structure 2 is mounted in the ground and the lower end 10 of the tube 6 extends through the ground to a control pumping device generally indicated at 12. Pumping device 12, which can contain a diaphragm pump or any

other suitable type of pump, is connected to supply lines 14 for, for example, carbon dioxide and/or air, nutrients and a nitrogen source, such as that provided by ammonia, ammonium salts, urea, compound fertilizers etc. The supply lines may conveniently be computer controlled. An outlet tube 15 carries the synthesis mixture from pumping device 12 up a central tube 16 arranged to extend up the hollow centre of core structure 2 to a header tank 18. Header tank 18 can contain any suitable launder means (not shown) to enable a product stream to be withdrawn on line 20. For example, more concentrated product rising towards the top of the mixture in the launder may be withdrawn by means of a weir device. Alternatively other separation means, such as a hydrocyclone, can replace the header tank 18. Line 20 is shown as extending from the side of header tank 18; however it may equally well extend down the centre of core structure 2 so that product is withdrawn at the base of the structure. The header tank also contains a purge system to remove excess air and recover the oxygen produced.

It will be appreciated that alternatively the synthesis mixture may be pumped up the coiled tube to the header tank 18, with suitable gases introduced at the base of the coiled tube, the return line 16 from the tank 18 to the pump having, if required, a flowmeter and/or a heat exchanger or like devices incorporated therein. Such a construction is described below with reference to Figure 3.

The product stream on line 20 may pass to any suitable ancillary equipment for treating and/or extracting desired products from the biomass. It is particularly useful to pass the biomass through a solids/liquid or liquid/liquid contactor in cocurrent or countercurrent to a stream of a suitable immiscible extractant. A series of products may be extracted by contacting in a series of contactors with, if necessary, recycle of the raffinate phases between contactors. A suitable extractor is the bucket type contactor known as the Graesser contactor and described in GB patent specification No. 1,145,894 and U.S. patent specification No. 3,649,209.

The dimensions of the photobioreactor will vary dependent on the biomass production being carried out.

One example is the production of biomass from Spirulina (blue green algae). In such a case the overall height of the core structure 2 may be, for example, 8 metres, with a core diameter of 2 metres. The wound tube 6 may then be of low density polyethylene of approximately 30mm diameter, with the central tube 16 being of larger dimensions (approximately 120mm) so as not to impede upward flow under control of the pump. It is calculated that such dimensions allow the core structure to carry approximately 1,347 metres of tubing giving a total surface area of 126 square metres, of which an area of about 100 square metres is effectively illuminated by the available natural light. The capacity of such a reactor is therefore approximately 1,269 litres. Because of the circular cross section of the reactor, a large number of such reactors can be positioned on a comparatively small area of ground as shown in Figure 2. Thus by arranging the reactors in a close packing array, a minimum spacing of only 4 metres still allows maximum illumination of each reactor during daylight and minimises the effects of shadows.

While the above figures are given as an illustration of microbiomass production from Spirulina, it will be appreciated that a macrobiomass production can equally be carried out in a reactor having larger diameter tubing. An example is in carrying out photosynthesis of seaweed. However the diameter of the tubing should remain sufficiently small to encourage turbulence as the material passes downwards through the coil. Turbulence assists in preventing unwanted coating of the inside of the tube, thus increasing the working life of the plant. Preferably the turbulence is such as to give a Reynolds number of at least 2000, more preferably in excess of 3000. Furthermore high turbulence maximises the light usage in photosynthesis, as it allows the cells to receive intermittent exposure to light, thus allowing each cell to benefit from the essentially intermittent nature of photosynthesis.

It has been shown by previous workers that, by using flashing light rather than continuous light, the instantaneous growth rate is increased and the yield per unit of light energy raised in biomass production. Thus in a modification of the bioreactor shown in Figure 1 a discontinuous curtain of highly polished thin and small aluminium shapes is arranged around the core structure 2 spaced therefrom and suspended from suitable means such as a rail at the top of structure 2. Even slight wind vibrates the shapes and results in light flashes over the tube area thus improving the growth rate. Alternatively or in addition, a similar curtain may be arranged within the hollow core. Alternative forms of curtains, such as metallic ribbons, may be employed to give a similar effect. A similar principle may be employed to improve growth rate if illumination, such as fluorescent tubing, is employed within the tube structure. The fluorescent tubes may thus be set to give flickering light action.

The photobioreactor shown has its pumping device 12 buried in the ground so as to maximise the space between each bioreactor, although of course the pumping device could be above ground level. In the example shown in Figure 2 it will be seen that burying the pumping devices gives adequate spacing to allow the passage of servicing

and product collection vehicles between the bioreactors. Such servicing may include provision for coping with extreme weather conditions, for example a heat exchanger included in the circuit and for example, in cold overnight conditions with the possibility of frost, it is possible to install removable insulated jackets positioned over the bioreactors when necessary. Likewise, in very hot conditions coolant can be sprayed on the reactors from external service devices. Alternatively, the bioreactors themselves may include provision for directing coolant spray onto the tubing 6 when desired, such as the provision of a water spray ring at the top of core structure 2 fed by a supply tube passing up the hollow core structure.

In a modification (not shown) of the reactor shown, the core structure 2 is mounted on a rotating platform with means provided for product withdrawal via a central circular launder leading to a tube extending to the base of the core structure. Such an arrangement has the advantage of using the rotational speed to influence flow characteristics in the tube and/or to influence the exposure time of the algae to sunlight.

An alternative method of biomass production suitable for use on a large scale uses the plant illustrated in Figure 3. The plant comprises a pair of substantially transparent coiled tubes 20 and 22 arranged in parallel and each mounted on a suitable core structure (not shown). The coils may for example be of clear polyvinyl chloride tubing of 500 metres length and 30 mm diameter. A suitable core structure has been found to be a generally cylindrical white painted body, optionally also coated with reflective glass balls. It will be appreciated that, although two coils are shown, further coils may be employed. The synthesis mixture is fed to the coils 20 and 22 via lines 23 and 24 from a single line 25 which is supplied via flowmeter 26 with recirculating reactants pumped by pump device 27 (suitably a diaphragm pump). Before reaching line 25, the recirculating reactants pass through heat exchange unit 28 provided with immersion heater 29. Unit 28 serves to provide heat if necessary in cold weather, or alternatively to remove heat during hot ambient conditions. Carbon dioxide and air are also supplied to line 25 via suitable flowmeters (not shown) on lines 30 and 31 respectively.

At the top of the coils 20 and 22, the flowing synthesis mixtures join in line 32 for passage to header tank 33 with an overflow harvester device 34 which allows mixture to flow downwardly through return pipe 35 to a bag filter 36 in which product biomass (e.g. algae) is collected and periodically withdrawn. The bag is of a mesh which retains large mature algae while allowing smaller growing algae to pass through. Bag filter 36 is disposed in filter unit 37 supplied with make-up water on line 38 and nutrients on line 39 from a series of nutrient supply vessels 40. Filtrate in unit 37 with added water and nutrients is returned on line 41 to header tank 33 under the action of pump 42 which is responsive to level control valves 43.

Excess carbon dioxide (and/or other gaseous products) are withdrawn from header tank 33 on line 44. When necessary air is supplied to header tank 33 on air purge line 45. Circulating synthesis mixture not passing down overflow 34 returns to pump 27 on line 46.

Circulation in the system and harvesting of product are controlled by electronically operated pressure control values 47, which are brought into operation after start up once optimum synthesis conditions have been achieved (as determined for example by optical density measurement).

It will be noted that in the apparatus described above, the synthesis mixture is pumped up the coils and product flows downwardly under gravity through return pipe 35. Such an arrangement has the advantage that the carbon dioxide supply has a relatively long time to contact the growing algae for conversion before release into header tank 33. (If excess carbon dioxide remains in exit line 44, then the feed of carbon dioxide is reduced). Furthermore the straight and comparatively long down return pipe 35 to the filter bag 36 gives a high velocity which prevents clogging.

It will be appreciated that the bioreactors shown in the above Figures are easy to assemble and if wished can be constructed in modular form. Thus the tubular coil can readily be constructed in sections with valves and junctions allowing reaction products to be removed as needed and/or any necessary additional nutrient feed introduced. This is expecially useful for rapid reactions, such as certain fermentation reactions.

Although pump operation has been described above for providing the motive force necessary to give highly turbulent flow in the tubing, as is often desirable, in some reactions it is desirable to employ lower flow conditions, for example, where the product cells are of a delicate nature. In such cases it may be sufficient to employ air and/or other gaseous supply as the lift to sustain circulation. If need be a compressed gas venturi jet or a steam jet may be employed. Steam injection is particularly suitable where a certain amount of heat is required for growth.

When using tubular modules, provision may be made for intermediate pumps, and/or air or steam injection so as to control the flow rates through the tubing even for long flow passages. This is particularly valuable when the reaction medium has a tendency to become viscous, for example in certain fermentation processes. Figure 4 schematically

illustrates a modified reactor which embodies provisions to overcome problems of pressure drop (and also possible elongation of the tubing when warm, e.g. at 35°C). Thus a coil 50 is arranged in sections on core 51. Synthesis mixture is pumped up the coil via the recycle pump and heat exchanger unit 52 but, instead of being all introduced at the bottom of the coil, it is introduced therealong on-a series on inlet lines 53. Air and CO_2 are also introduced to each line 53 via a feed main 57 having valve entries 58 to each line 53. Similarly outlet lines 54 lead from each coil section to header tank 55 via rising main 56. It is advantageous to construct rising main 56 so that it can move on the side of the coil to cater for expansion of the tubing. Thus the main may be flexible or may be rigid but provided with a flexible mounting. The lengths of tube in each coil section will vary according to flow rate, tubing bore and tower height etc. but approximately eight sub units with lengths of about 300 metres and 20 mm tubing bore have been found to be suitable.

The method and apparatus described above are applicable to a wide range of biomass production processes. If desired, the feed system to the reactor can be controlled to introduce small amounts of one or more trace elements such as selenium, cobalt, copper, zinc, gallium and germanium under varying conditions to alter trace element amounts. It will be seen that the process allows the production of single strain pure biomass from, for example, algae and seaweed under controlled conditions to give a pure and consistent product. Dependent on the ancillary processing employed, the concentration of certain valuable products in the biomass can be increased. It has been found that algae and other simple organisms can form solubilised complexes, usually proteins, which are beneficial or even essential to human and animal well being. For example, a high concentration of lipid containing gamma linolenic acid (GLA) can be obtained from Spirulina. Alternatively high grade agar may be produced from Gracilaria or beta-carotene from Dunaliella. If the process being carried out results in an increase in colour density in the reactor (due to increased quantities of water soluble natural pigments), pigment removal means (such as chromatographic separation, or solvent extraction, possibly employing a Graesser contactor as described above) may be incorporated, suitably associated with pigment recovery means. The build-up of excessive pigmentation which adversely affects light penetration is thus preserved. Such pigments include chlorophylls, carotenes, phycocyanins and phycoerythins.

It will be appreciated that considerable variation is possible in the nutrients supplied to the bioreactor and the operating conditions.

It has been found of value to use ammonia gas as one of the nitrogen sources, or as the sole nitrogen source. Controlled injection of ammonia gas, while promoting the growth of an organism such as Spirulina, inhibits the growth of unwanted microscopic life such as bacteria, amoeba and rotifers. This is of considerable commercial importance as the growth of such microscopic species has been a major problem in previously proposed methods for biomass production. Other gases which inhibit bacterial growth, such as carbon monoxide, may be employed.

As an alternative, or in addition, bacterial invasion problems may be at least partially alleviated by the use of ultraviolet irradiation of sections of the tubing. This may, for example, be accomplished by winding an ultraviolet emitting coil around one or more portions of the tubings and/or by the inclusion of an ultraviolet emitting tube withing the tubing itself, suitably in a specially widened tubing section.

The reactor described above is suitable for use for both aerobic and anaerobic biomass production processes. Thus gases such as carbon dioxide or air may be used, for example for Spirulina and Chlorella production, while air/oxygen mixtures or oxygen alone may be employed for certain processes such as yeast growth. Anaerobic processes may be carried out, such as the cultivation of Rhodopseudomonas Palustris using as nutrient high BOD (biological oxygen demand) carbohydrate waste, a reaction which produces carbon dioxide. Alternative processes include the growth of Norcadia, Candida and other Pseudomonas organisms for degradation of hydrocarbons to carbon dioxide.

According to a useful further embodiment of the invention, two bioreactors, or banks of bioreactors, may be joined in series, the first being used for an anaerobic reaction, such as the growth of Rhodopseudomonas Palustris or Acidophila which produces CO_2, while the second reactor utilises the CO_2 in the cultivation of CO_2 - utilising, oxygen-producing algae such as Chlorella or Spirulina. Such a system is illustrated in Figure 5.

In the flow diagram of Figure 5, a high BOD effluent liquor is passed on line 60 to a first bank of reactors 61 as nutrient for the cultivation of a carbon dioxide-producing organism such as Rhodopseudomonas acidophila. Carbon dioxide produced in reactors 61 is withdrawn on line 62. Liquor from reactors 61 is withdrawn on line 63 to filter unit 64, where solid biomass is withdrawn. The carbon dioxide stream in line 62 is combined with the liquor from filter 64 in line 65 for passage as nutrient to a second bank of reactors 66 for the cultivation of a carbon dioxide-consuming, oxygen-producing organism such as Spirulina. Oxygen is

withdrawn on line 67 for any suitable purpose, while the liquor withdrawn on line 68 is filtered in unit 69 to give a solid biomass product. The remaining effluent on line 70 has a considerably reduced BOD value.

Of course further stages may be added and any desired number of reactors may be used in each bank. Any other gases produced in the first reactors may be used in subsequent bioreactors or for other purposes. The use of a plurality of reactors can also prove useful when the first reactor is used for example for the growth of a water splitting algae such as Chalydamonas Reinhardtii which produces hydrogen and oxygen as gaseous products, which are separated and the oxygen used in the second reactor for an oxygen consuming substance.

The provision of a continuously operable process with recycling of the mixture keeps the consumption of gases and nutrients as low as possible with minimum wastage. Product oxygen can be used in any adjacent chemical plant. Any heat produced can be employed in heat exchange. High biomass densities can be obtained, of up to 7, or even 40, times the densities obtainable in open channel photosynthesis processes. Even derelict and uneven land can be utilised and the size of the installation can readily be expanded to fill growing needs. The use of angled units maxmimises light usage and even diffuse light can be effectively utilised. Thus the possible latitude ranges for biomass production are comparatively wide and even the light of an overcast English winter day is found to be sufficient for algae or seaweed growth. Only low grade heat at most is required even in a severe winter to keep a temperature minimum of approximately 10°C. In severe weather, it has been found advantageous to insulate the tubing with an outer curtain of transparent polyethylene sheeting. Cooling in summer is desirable to maintain a maximum temperature of approximately 35°C. The use of turbulent conditions enables long running periods before the need for cleaning, so that shut down periods are kept to a minimum. In any case cleaning of the tubing is a comparatively straightforward operation and can be effected by forcing a cleaning "bullet" through the tubing. This in contrast to the problems encountered in cleaning conventional fermentation tanks where contamination often has to be scraped from the walls.

It will be seen that the system described above lends itself to automatic control and the whole arrangement of modules can be computer controlled, thereby saving labour. A further advantage is that part of such a multi-module system can be switched, if required, from producing one type of product to another, without the need for major plant modifications.

Claims

1. A photobioreactor comprising:
an upstanding core structure (2);
a substantially transparent tube (6) supported on the core structure so that, in use, the exterior of the tube is exposed to natural light;
means (12) for causing a synthesis mixture comprising living plant matter together with essential nutrients for growth of the plant matter to flow under turbulent conditions through the transparent tube; and
means (20) for withdrawing a biomass synthesis product from the mixture;
characterised in that the core structure (2) is of substantially cylindrical form, the transparent tube (6) is wound helically on the outside of the core structure, and light is encouraged to penetrate into the tube in the region of contact between the tube and the core structure.

2. A photobioreactor as claimed in claim 1, characterised in that the support structure is hollow and comprises a wall of cylindrical form and which is of open construction providing openings to permit light to pass through the openings and so penetrate into the tube.

3. A photobioreactor as claimed in claim 2, characterised in that the tube is wound at an angle to the horizontal of about 3° and adjacent turns of the tube are separated by a distance equal to at least one quarter of the diameter of the tube.

4. A photobioreactor as claimed in claim 1, characterised in the provision of light reflecting means (4) located between the tube and the outside of the support structure.

5. A photobioreactor as claimed in any preceding claim, characterised in the provision of a header tank (18) mounted on top of the support structure with the upper end of the transparent tube connected to the header tank, a pipe (16) having a cross-section greater than that of the helically wound tube extending from the header tank to the bottom of the support structure, said pipe (16) at the bottom of the support structure being connected to the lower end of the transparent tube and wherein means are provided for withdrawing the biomass synthesis product from the header tank.

6. A photobioreactor as claimed in claim 1, characterised in that the tube is wound in a plurality of sections one above the other on the

withdrawn on line 67 for any suitable purpose, while the liquor withdrawn on line 68 is filtered in unit 69 to give a solid biomass product. The remaining effluent on line 70 has a considerably reduced BOD value.

Of course further stages may be added and any desired number of reactors may be used in each bank. Any other gases produced in the first reactors may be used in subsequent bioreactors or for other purposes. The use of a plurality of reactors can also prove useful when the first reactor is used for example for the growth of a water splitting algae such as Chalydamonas Reinhardtii which produces hydrogen and oxygen as gaseous products, which are separated and the oxygen used in the second reactor for an oxygen consuming substance.

The provision of a continuously operable process with recycling of the mixture keeps the consumption of gases and nutrients as low as possible with minimum wastage. Product oxygen can be used in any adjacent chemical plant. Any heat produced can be employed in heat exchange. High biomass densities can be obtained, of up to 7, or even 40, times the densities obtainable in open channel photosynthesis processes. Even derelict and uneven land can be utilised and the size of the installation can readily be expanded to fill growing needs. The use of angled units maxmimises light usage and even diffuse light can be effectively utilised. Thus the possible latitude ranges for biomass production are comparatively wide and even the light of an overcast English winter day is found to be sufficient for algae or seaweed growth. Only low grade heat at most is required even in a severe winter to keep a temperature minimum of approximately 10°C. In severe weather, it has been found advantageous to insulate the tubing with an outer curtain of transparent polyethylene sheeting. Cooling in summer is desirable to maintain a maximum temperature of approximately 35°C. The use of turbulent conditions enables long running periods before the need for cleaning, so that shut down periods are kept to a minimum. In any case cleaning of the tubing is a comparatively straightforward operation and can be effected by forcing a cleaning "bullet" through the tubing. This in contrast to the problems encountered in cleaning conventional fermentation tanks where contamination often has to be scraped from the walls.

It will be seen that the system described above lends itself to automatic control and the whole arrangement of modules can be computer controlled, thereby saving labour. A further advantage is that part of such a multi-module system can be switched, if required, from producing one type of product to another, without the need for major plant modifications.

Claims

1. A photobioreactor comprising:
   an upstanding core structure (2);
   a substantially transparent tube (6) supported on the core structure so that, in use, the exterior of the tube is exposed to natural light;
   means (12) for causing a synthesis mixture comprising living plant matter together with essential nutrients for growth of the plant matter to flow under turbulent conditions through the transparent tube; and
   means (20) for withdrawing a biomass synthesis product from the mixture;
   characterised in that the core structure (2) is of substantially cylindrical form, the transparent tube (6) is wound helically on the outside of the core structure, and light is encouraged to penetrate into the tube in the region of contact between the tube and the core structure.

2. A photobioreactor as claimed in claim 1, characterised in that the support structure is hollow and comprises a wall of cylindrical form and which is of open construction providing openings to permit light to pass through the openings and so penetrate into the tube.

3. A photobioreactor as claimed in claim 2, characterised in that the tube is wound at an angle to the horizontal of about 3° and adjacent turns of the tube are separated by a distance equal to at least one quarter of the diameter of the tube.

4. A photobioreactor as claimed in claim 1, characterised in the provision of light reflecting means (4) located between the tube and the outside of the support structure.

5. A photobioreactor as claimed in any preceding claim, characterised in the provision of a header tank (18) mounted on top of the support structure with the upper end of the transparent tube connected to the header tank, a pipe (16) having a cross-section greater than that of the helically wound tube extending from the header tank to the bottom of the support structure, said pipe (16) at the bottom of the support structure being connected to the lower end of the transparent tube and wherein means are provided for withdrawing the biomass synthesis product from the header tank.

6. A photobioreactor as claimed in claim 1, characterised in that the tube is wound in a plurality of sections one above the other on the

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support structure, each section having an inlet end and an outlet end, said inlet ends being connected together and the synthesis mixture is caused to flow through said sections of tube in parallel.

7. A photobioreactor as claimed in any preceding claim, characterised in that the tube is of polyethylene or polyvinyl chloride.

8. A method of biomass production comprising:
causing a synthesis mixture comprising living plant matter together with essential nutrients for growth of the plant matter to flow under turbulent conditions through a substantially transparent tube supported on an upstanding core structure;
exposing the exterior of the wound tube to natural light and withdrawing a biomass synthesis product from the mixture;
characterised in that the synthesis mixture is caused to flow upwardly along the tube which is wound helically on the outside of the core structure and light is encouraged to penetrate into the tube in the region of contact between the tube and the core structure.

9. A method as claimed in claim 8, characterised in that the tube is wound in a plurality of sections one above the other on the support structure and the synthesis mixture is caused to flow through said sections of tube in parallel.

10. A method according to claim 8 or 9, wherein the plant matter comprises algae.

11. A method according to claim 8 or 9, wherein the essential nutrients for growth comprise carbon dioxide and a source of nitrogen.

12. A method according to claim 11, wherein ammonia gas is used as a source of nitrogen.

13. A method according to any one of claims 8 to 12, wherein an anaerobic synthesis is carried out in the said tube and, after withdrawal of a first biomass synthesis product, the synthesis mixture is passed through a second tube in which an aerobic reaction is carried out using carbon dioxide evolved in said anaerobic synthesis and a second biomass synthesis product is withdrawn after passage through said second tube.

Patentansprüche

1. Photobioreaktor mit
einer aufrecht stehenden Kernstruktur (2);
einem im wesentlichen durchsichtigen transparenten Rohr (6), welches so an der Kernstruktur abgestützt ist, daß das Äußere des Rohrs im Betrieb natürlichem Licht ausgesetzt ist;
einer Einrichtung (12) zum Herstellen eines Synthesegemisches, welches lebendes Pflanzenmaterial zusammen mit essentiellen Nährstoffen für das Wachstum des Pflanzenmaterials enthält, welches unter turbulenten Bedingungen durch das transparente Rohr fließen soll; und
einer Einrichtung (20) zum Abziehen eines Biomassen-Syntheseprodukts aus dem Gemisch:
dadurch gekennzeichnet, daß
die Kernstruktur (2) von im wesentlichen zylindrischer Form ist, das transparente Rohr (6) wendelartig auf die Außenseite der Kernstruktur aufgewickelt ist und Licht zum Eindringen in das Rohr im Kontaktbereich zwischen dem Rohr und der Kernstruktur gebracht wird.

2. Photobioreaktor nach Anspruch 1, dadurch gekennzeichnet, daß die Stützstruktur hohl ist und eine Wand von zylindrischer Form aufweist und eine offene Konstruktion mit Öffnungen darstellt, damit Licht durch die Öffnungen durchtreten und in das Rohr eintreten kann.

3. Photobioreaktor nach Anspruch 2, dadurch gekennzeichnet, daß das Rohr unter einem Winkel von etwa 3 ° gegen die Horizontale gewikkelt ist und benachbarte Windungen des Rohrs voneinander durch eine Entfernung beabstandet sind, die mindestens ein Viertel des Rohrdurchmessers beträgt.

4. Photobioreaktor nach Anspruch 1, gekennzeichnet durch lichtreflektierende Mittel (4), die zwischen dem Rohr und der Außenseite der Stützstruktur angeordnet sind.

5. Photobioreaktor nach einem der vorhergehenden Ansprüche, gekennzeichnet durch
einen Kopftank (18), der an der Oberseite der Stützstruktur angebracht ist, wobei das obere Ende des transparenten Rohrs mit dem Kopftank verbunden ist,
eine Leitung (16), die einen Querschnitt größer als den des wendelartig gewundenen Rohrs aufweist und sich vom Kopftank bis zum Boden der Stützstruktur erstreckt, wobei die Leitung (16) am Boden der Stützstruktur mit dem unteren Ende des transparenten Rohrs verbunden ist,
und wobei Mittel vorgesehen sind zum Abziehen des Biomassen-Syntheseprodukts aus dem Kopftank.

6. Photobioreaktor nach Anspruch 1, dadurch gekennzeichnet, daß das Rohr in mehreren Bereichen übereinander auf die Stützstruktur aufgewickelt ist, wobei jeder Bereich ein Einlaßende und ein Auslaßende hat, wobei die Einlaßenden miteinander verbunden sind, und wobei das Synthesegemisch zum parallelen Fließen durch diese Rohrbereiche gebracht wird.

7. Photobioreaktor nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß das Rohr aus Polyethylen oder Polyvinylchlorid besteht.

8. Verfahren zum Herstellen von Biomasse, bei dem man ein Synthesegemisch, welches lebendes Pflanzenmaterial zusammen mit essentiellen Nährstoffen für das Wachstum des Pflanzenmaterials enthält, unter turbulenten Bedingungen durch ein im wesentlichen transparentes Rohr zum Fließen bringt, welches an einer aufrecht stehenden Kernstruktur abgestützt ist;
das Äußere des gewickelten Rohrs natürlichem Licht aussetzt und ein Biomassen-Syntheseprodukt aus dem Gemisch abzieht;
dadurch gekennzeichnet,
daß man das Synthesegemisch aufwärts entlang des Rohrs fließen läßt, welches wendelartig auf der Außenseite der Kernstruktur aufgewickelt ist, und das Licht zum Eindringen in das Rohr in dem Kontaktbereich zwischen dem Rohr und der Kernstruktur gebracht wird.

9. Verfahren nach Anspruch 8, dadurch gekennzeichnet, daß das Rohr in mehreren Bereichen übereinander auf die Stützstruktur aufgewickelt ist, und das Synthesegemisch zum parallelen Fließen durch diese Rohrbereiche gebracht wird.

10. Verfahren nach Anspruch 8 oder 9, wobei das Pflanzenmaterial Algen enthält.

11. Verfahren nach Anspruch 8 oder 9, wobei die essentiellen Nährstoffe für das Wachstum Kohlendioxid und eine Stickstoffquelle enthalten.

12. Verfahren nach Anspruch 11, wobei man als Stickstoffquelle Ammoniakgas verwendet.

13. Verfahren nach einem der Ansprüche 8 bis 12, wobei man in dem Rohr eine anaerobe Synthese ausführt und nach Abziehen eines ersten Biomassen-Syntheseprodukts das Synthesegemisch durch ein zweites Rohr leitet, in dem eine aerobe Reaktion durchgeführt wird, wobei das bei der anaeroben Synthese entstehende Kohlendioxid und ein zweites Biomassen-Syntheseprodukt nach Durchlaufen des zweiten Rohrs abgezogen werden.

Revendications

1. Photobioréacteur qui comprend :
une structure creuse pratiquement verticale;
un tube pratiquement transparent (6) supporté sur ladite structure de façon que, pendant l'utilisation, l'extérieur du tube soit exposé à la lumière naturelle;
des moyens (12) pour faire en sorte qu'un mélange de synthèse comprenant des matières végétales vivantes, ainsi que des substances nutritives essentielles pour la croissance des matières végétales, circule dans des conditions turbulentes dans le tube transparent; et
des moyens (20) pour retirer du mélange la biomasse de synthèse produite,
caractérisé en ce que la structure creuse (2) comprend une forme pratiquement cylindrique, tandis que le tube transparent (6) est enroulé hélicoïdalement autour de la face extérieure de la structure creuse, tandis que la lumière est encouragée à pénétrer à l'intérieur du tube dans la région de contact entre ce dernier et la structure creuse.

2. Photobioréacteur selon la revendication 1, caractérisé en ce que la structure de support est creuse et comporte une paroi de forme cylindrique et qui présente une structure comportant des ouvertures livrant passage à la lumière qui peut ainsi pénétrer à l'intérieur du tube.

3. Photobioréacteur selon la revendication 2, caractérisé en ce que le tube s'enroule suivant un angle d'environ 3° par rapport à l'horizontale, et en ce que les spires adjacentes du tube sont séparées par une distance égale, au moins, à un quart du diamètre dudit tube.

4. Photobioréacteur selon la revendication 1, caractérisé par la présence de moyens (4) réfléchissant la lumière, entre le tube et la face extérieure de la structure de support.

5. Photobioréacteur selon l'une quelconque des revendications précédentes, caractérisé par la présence d'un réservoir collecteur (18) monté au sommet de la structure de support et en ce que l'extrémité supérieure du tube transparent est raccordée à cette cuve collectrice, un tuyau (16), dont la section est plus grande que celle du tube enroulé hélicoïdalement s'éten-

dant de la cuve collectrice jusqu'à la base de la structure de support, ledit tuyau (16) étant relié à l'extrémité inférieure du tube transparent, et en ce que des moyens sont prévus pour retirer, de la cuve collectrice, la biomasse de synthèse produite.

6. Photobioréacteur selon la revendication 1, caractérisé en ce que le tube s'enroule autour de la structure de support en formant un certain nombre de spires superposées, chaque spire possédant une extrémité d'entrée et une extrémité de sortie, lesdites extrémités d'entrée étant reliées ensemble, ce qui oblige le mélange de synthèse de circuler en parallèle dans les différentes spires dudit tube.

7. Photobioréacteur selon l'une quelconque des revendications précédentes, caractérisé en ce que ledit tube est en polyéthylène ou en chlorure de polyvinyle.

8. Procédé pour produire une biomasse qui consiste :

à faire circuler dans des conditions turbulentes, un mélange de synthèse comprenant des matières végétales vivantes, ainsi que des substances nutritives essentielles pour la croissance des végétaux, dans un tube transparent supporté par une structure centrale verticale;

à exposer l'extérieur du tube enroulé à la lumière naturelle et à retirer du mélange la biomasse de synthèse produite, caractérisé en ce qu'on oblige le mélange de synthèse de circuler en s'élevant le long du tube qui est enroulé en hélice, autour de la face extérieure de la structure de support, et on favorise la pénétration de la lumière à l'intérieur du tube, dans la région de contact entre le tube et ladite structure.

9. Procédé selon la revendication 8, caractérisé en ce que le tube s'enroule en formant un certain nombre de spires superposées sur la structure de supporrt et en ce qu'on fait circuler le mélange de synthèse en parallèle à travers lesdites spires.

10. Procédé selon la revendication 8 ou 9, caractérisé en ce que la matière végétale comprend des algues.

11. Procédé selon la revendication 8 ou 9, caractérisé en ce que les substances nutritives essentielles pour la croissance comprennent du bioxyde de carbone et une source d'azote.

12. Procédé selon la revendication 11, caractérisé en ce que l'on utilise du gaz ammoniac comme source d'azote.

13. Procédé selon l'une quelconque des revendications 8 à 12, caractérisé en ce qu'on effectue une synthèse anaérobie dans ledit tube et en ce que, après avoir retiré une première biomasse de synthèse produite, on fait passer le mélange de synthèse dans un second tube, dans lequel s'effectue une réaction aérobie utilisant le bioxyde de carbone dégagé au cours de ladite synthèse anaérobie, et en ce qu'on recouvre une seconde biomasse de synthèse produite après le passage dans ledit second tube.