Provided is a solid-phase photobioreactor for culturing photosynthetic organisms, such as cyanobacteria. Also provided is a method of assembling a photobioreactor and a method of producing a product using the photobioreactor.

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TITLE OF INVENTION

PHOTOBIOREACTOR FOR PHOTOSYNTHETIC ORGANISMS

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of U.S. Provisional Application Serial No. 61/883,451 filed 27 September 2013, and U.S. Provisional Application Serial No. 62/027,143 filed 21 July 2014, each of which is incorporated herein by reference in its entirety.

MATERIAL INCORPORATED-BY-REFERENCE

The Sequence Listing, which is a part of the present disclosure, includes a computer readable form comprising nucleotide and/or amino acid sequences of the present invention. The subject matter of the Sequence Listing is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

Conventional photobioreactors cultivate organisms in a liquid based culture medium. This submerged culture methodology has significant limitations when growing phototrophic organisms as the principle energy source is derived from photons. Photonic energy is sensitive to a line of sight pathway to photoreceptors maintained within phototrophic organisms. Unfortunately, high cell densities in liquid culture result in organism self shading. As a consequence, the vast majority of residence time within the liquid photobioreactor results in non-productive periods for each organism due to the inability to acquire light (photons).

A major issue with current photobioreactors concerns the limits of their deployment to production of value added products is the capital costs associated with photobioreactor construction. The deployment of photobioreactors for commodity chemical production requires a cost generally not to exceed $100,000 per acre. In addition, current photobioreactors limit the variables of carbon access to the concentration of CO\textsubscript{2} in the photobioreactor atmosphere.
and the mass transfer/active transport system found within the cultivated organism.

SUMMARY OF THE INVENTION

Among the various aspects of the present disclosure is the provision of a photobioreactor.

One aspect provides a photobioreactor for cultivating photosynthetic microorganisms. In some embodiments, the photobioreactor includes a shell, a growth panel assembly, a suspension system, an aerosol system, a collection trough, and an optional inoculation system.

In some embodiments, the shell includes a material that passes or substantially passes photosynthetically active radiation, where the material forms a physical barrier enclosing or substantially enclosing a growth panel assembly. In some embodiments, the shell includes a collection trough, where the collection trough is located on a bottom surface of the shell material and directs flow of a fluid product produced by the photosynthetic microorganisms. In some embodiments, the shell includes a resealable entry providing access from outside the bioreactor to inside the shell so as to access the growth panel assembly.

In some embodiments, the collection trough comprises two lateral walls separated so as to form trough extending along a longitudinal axis of the photobioreactor. In some embodiments, the collection trough is disposed under a concentrated drip zone of the growth panel assembly such that a fluid product drips into the collection trough.

In some embodiments, the shell includes a product discharge port disposed to collect fluid product from the collection trough and discharge it through the shell. In some embodiments, the shell includes at least two condensate channels flanking the collection trough. In some embodiments, the condensate channels collecting condensate flow from walls of the shell. In some embodiments, the shell includes at least one condensate discharge port.
disposed to collect condensate from the condensate channels and discharge it through the shell.

In some embodiments, the growth panel assembly includes a plurality of growth panels. In some embodiments, one or more growth panels include a growth panel hanger comprising an interface to the suspension system. In some embodiments, one or more growth panels include a non-gelatinous, solid cultivation support material suitable for providing nutrients and moisture to photosynthetic microorganisms on at least a portion of a surface thereof, wherein said portion of the surface has a topography that allows photosynthetic microorganisms to adhere thereto when said portion of the surface is oriented non-horizontally. In some embodiments, one or more growth panels include a concentrated drip zone at or near the bottom of the growth panel.

In some embodiments, the growth panel assembly includes about 10 to 100 growth panels. In some embodiments, the growth panel assembly includes about 20 to 80 growth panels. In some embodiments, the growth panel assembly includes about 30 to 60 growth panels. In some embodiments, the growth panel assembly includes about 35 to 55 growth panels. In some embodiments, the growth panel assembly includes about 40 to 50 growth panels. In some embodiments, the growth panel assembly includes about 45 growth panels. In some embodiments, the growth panel assembly includes 46 growth panels.

In some embodiments, the plurality of growth panels are connected in a zig-zag configuration. In some embodiments one or more of the plurality of growth panels has a surface area of about 1.5 m². In some embodiments, one or more of the plurality of growth panels has a laminate structure made up of one or more blended non-woven material. In some embodiments, the blended non-woven material is a rayon/polyester blended non-woven material.

In some embodiments, the growth panel hanger includes a grommet pass thru interface with a suspension cable. In some embodiments, the growth panel hanger includes a detachable hook interface with a suspension cable.

In some embodiments, the suspension system includes at least one suspension cable. In some embodiments, the suspension cable interfaces with a growth panel hanger to fully or partially support the growth panel assembly. In
some embodiments, the at least one suspension cable is tensioned between two points external to the shell of the photobioreactor. In some embodiments, the aerosol system includes a fluid source and a nebulizer sufficient to generate fog or mist inside the shell. In some embodiments, the shell comprises an aerosol system inlet and the nebulizer is operably connected to the aerosol system inlet.

In some embodiments, the photobioreactor includes a sterilization system. In some embodiments, the sterilization system uses hydrogen peroxide vapor.

In some embodiments, the inoculation system includes a drip emitter tube for inoculation of photosynthetic microorganisms on one more growth panels. In some embodiments, the drip emitter tube is attached to the growth panel hanger such that an orifice of the drip emitter tube is positioned to transfer inoculant to the growth panel connected to the growth panel hanger.

In some embodiments, the photobioreactor includes photosynthetic microorganisms. In some embodiments, photosynthetic microorganisms cultured in the photobioreactor include wild type cyanobacteria or genetically transformed cyanobacteria.

One aspect provides a method of installing a photobioreactor. In some embodiments, a photobioreactor described above is installed by placing the growth panel assembly inside the shell; connecting the suspension system to the growth panel assembly; and applying a positive air pressure to the inside of the shell so as to inflate the photobioreactor.

One aspect provides a method of producing a product from photosynthetic microorganisms. In some embodiments, photosynthetic microorganisms are cultured in a photobioreactor described above and a desired product is collected from the photosynthetic microorganisms. In some embodiments, photosynthetic microorganisms include a cyanobacteria genetically transformed to produce the product. In some embodiments, the product is a disaccharide sugar. In some embodiments, the product is sucrose or trehalose.

Other objects and features will be in part apparent and in part pointed out hereinafter.
DESCRIPTION OF THE DRAWINGS

Those of skill in the art will understand that the drawings, described below, are for illustrative purposes only. The drawings are not intended to limit the scope of the present teachings in any way.

FIG. 1 is a diagram of an isometric view of photobioreactor 100.

FIG. 2 is a diagram of the side view of photobioreactor 100.

FIG. 3 is a diagram of an front and top views of photobioreactor 100.

FIG. 4 is a diagram of the upstream end wall of the photobioreactor showing various ports.

FIG. 5 is a diagram of the downstream end wall of the photobioreactor showing various ports.

FIG. 6 is a diagram of a growth panel having a concentrated drip zone 125 at the base of the growth panel and a growth panel hanger at the top of the growth panel.

FIG. 7 is a series of photographs and a diagram showing product collection systems. FIG. 7A shows a product collection panel 210 connected to opposite shell walls with condensate runoff passages through the peripheral edges. FIG. 7B shows a product collection trough 220 with a product solution collected and directed towards a product discharge port 230. FIG. 7C shows a diagram of a product collection trough 220 having one product discharge port 230 (between the lateral walls) and two condensate discharge ports 240 (outside the lateral walls).

FIG. 8 is a pair of photographs showing growth panel hangers. FIG. 8A shows a grommet pass thru approach. FIG. 7B shows a detachable hanger approach.

FIG. 9 is a pair of photographs showing growth panel hangers. FIG. 9A shows a grommet pass thru approach. FIG. 9B shows a detachable hanger approach.

FIG. 10 is a photograph of a photobioreactor having a netting system
surrounding the film shell with a growth panel assembly of 46 growth panels inside the shell supported by grommet style growth panel hangers.

DETAILED DESCRIPTION OF THE INVENTION

5 Described herein are various embodiments of a pod photobioreactor 100 that can provide basic systemic functions, including inoculating fabric growth panels 120 with cyanobacteria; introducing media feed stock or maintenance of growth or desired product (e.g., sucrose) formation over time; an environmentally survivable photobioreactor 100 capable of sustaining long duration deployment while exposed to harsh outdoor conditions; drip emitter systems 180 that can provide improved liquid dispersion uniformity of host organisms (e.g., cyanobacteria) or growth media to the fabric growth panels 120. Further improvements are also described.

Various embodiments of photobioreactors 100 described herein have optimized growth panel 120 orientations yielding 40% or more growth surface area while improving light exposure to the growth panel surfaces; tensioned cable support systems 150 that support growth panel assemblies 130, which reduce cost and improve photobioreactor 100 reliability; improved seam construction of the photobioreactor shell 110 to improve fielded durability; a drip emitter assembly 180 which reduces the amount of tubing by 60%; or resealable entries 170 (e.g., end cap zipper interfaces) to ease the cleaning, general maintenance, and growth panel 120 assembly change-out.

A photobioreactor 100 described herein can feature a mechanical suspension system 150 for the photobioreactor 100 including the shell 110 (e.g., netting system 160) or growth panel assemblies (e.g., suspension cable system 150 and growth panel hangers 140); provide reliable performance under high wind loads, while enhancing overall photobioreactor 100 access; provide repeatable internal shell 110 surface slope for liquid runoff; or provide for inexpensive sump concepts to collect any inadvertent residual liquid emanating from the photobioreactor shell 110.


A photobioreactor 100 described herein can include an outer shell 110, sometimes referred to as a barrier layer, enclosing a series of solid phase cultivation support materials, referred to as growth panels 120.

A plurality of growth panels 120 can be arranged as a growth panel assembly 130. A growth panel 120 can have a concentrated drip zone 125 at its base, which can direct product (e.g., sucrose) solution runoff to a selected position. A growth panel 120 or growth panel assembly 130 can be suspended by hangers 140. Growth panel hangers 140 can in turn be suspended independent, or substantially independent, of the shell 110 by way of a suspension system 150, such as a series of suspension cables 155.

The outer shell 110 can be covered or secured by a netting system 160 that surrounds all or part of the shell 110 and functions to secure the shell 110 or protect against environmental factors, such as wind. The outer shell 110 can have an integrated resealable entry 170 is formed from a fastener, such as a zipper fastener, at one or more distal ends of the photobioreactor 100.

A photobioreactor 100 can include a suspension system 150. Suspension cables 155 can be tensioned so as to be secured between two or more points, usually external to the photobioreactor 100 (e.g., one or more poles at or near longitudinal ends of the photobioreactor 100). Growth panel hangers 140 can interface with the tensioned suspension cables 155 so as to fully or partially support the growth panel assembly 130. Exemplary interfaces include, but are not limited to, a grommet pass thru growth panel hanger 142 or a detachable growth panel hanger 144.
A photobioreactor 100 can include an inoculant injection system or inoculant media feed manifold, such as a drip emitter tube system 180. A growth panel 120 or growth panel hanger 140 can be integrated with a drip emitter tube system 180. The drip emitter tube system 180 is usually configured to introduce inoculant containing photosynthetic organisms to growth panels 120 via orifices in the tubing. The drip emitter tube system 180 can also be configured to introduce water, nutrient media, or other fluids. The drip emitter tube system 180 can be gravity fed, pump assisted, or a combination thereof.

The photobioreactor 100 can contain an aerosol injection system 190. The aerosol injection system 190 can be integrated to the photobioreactor 100 via an aerosol injection inlet 192 and nebulizer interface 194. An aerosol injection system 190 can be used in conjunction with fluid supply lines and one or more pumps that generate a pressure sufficient for the nebulizer interface 194 to form a fog or mist. The nebulizer interface 194 can be located at or near the aerosol injection inlet 192 or at some other location within the shell 110. The aerosol injection system 190, aerosol injection inlet 192, and nebulizer interface 194 can be configured to as to directly or indirectly introduce a fog or mist inside the photobioreactor 100 (e.g., within the shell 110) so as to pre-wet, wet, or maintain wetness of a growth panel 120 or growth panel assembly 130.

Exemplary locations for the nebulizer interface 194 include the aerosol injection inlet 192 at or near an end wall of the photobioreactor 100 or at, near, on, or in a growth panel hanger 140.

A photobioreactor 100 can include a gas management system 200. The gas system 200 can include subsystems for gas input 202 and output 203. Gases, such as carbon dioxide, can be introduced to the interior of the photobioreactor 100 by way of pumps or compressors moving the gases from a gas supply through a gas supply line connected to a gas inlet 202 leading into the photobioreactor 100. The gas inlet 202 can be at various locations including at or near an end wall of the photobioreactor 100. Gases can be removed from the interior of the photobioreactor 100 by way of pumps or compressors moving the gases from the interior of the photobioreactor 100 through a gas outlet 204 connected to gas exhaust lines. Control of gas flow can be according to
computer control (e.g., based on maintaining a selected carbon dioxide concentration or a selected temperature).

A photobioreactor 100 can include a product collection system, such as a product collection panel 210 or product collection trough 220. A product collection trough 220 can be located at, near, or one the bottom surface of the shell 110, or can be an integrated part of the shell 110. A product collection trough 220 can have lateral walls or tubes forming a trough that guides product (e.g., sucrose) runoff from growth panels 120 via a damming effect to one or more product discharge ports 230. A product discharge port 230 can be located at various locations within the photobioreactor 100 including at or near an end wall of a lower end of the photobioreactor 100. One end of the photobioreactor 100 can be sufficiently lower than the other (by way of, e.g., alignment and positioning of suspension cables 155) so as to induce fluid flow. From the product discharge port 230, product can be directed to a product storage receptacle, such as a tank. Flow of product can be according to gravity flow, pump assisted, or a combination thereof. The product collection trough 220 can be configured to channel condensate from the walls of the photobioreactor 100 to flow along the bottom surface of the shell 110 outside the confines of the trough (i.e., separate from the of product) towards one or more condensate discharge ports 240. A condensate discharge port 240 can be located at various locations within the photobioreactor 100 including at or near an end wall of a lower end of the photobioreactor 100.

There are generally two feed streams into the photobioreactor. A carbon dioxide-enriched air stream typically containing between 1% and 10% carbon dioxide. At scale, approximately 90% of the delivered CO2 is consumed by the cyanobacteria. Carbon dioxide from fermentation off gas or flue gas are ideal carbon feed sources for the photobioreactor. Second, a dilute aqueous nutrient stream delivers water and nutrients to the photobioreactor via a drip irrigation system or an aerosol system. This stream can be trickled down or sprayed, misted or fogged onto growth panels. Water delivered to the cyanobacteria provides nutrients, participates in the sucrose synthesis reaction, and solubilizes product (e.g., sucrose) that is produced and secreted from the cyanobacteria.
Sucrose is a exemplary product output of a transgenic cyanobacteria. Only ppm levels of nutrients can be recovered in the solution, and none are known to inhibit fermentation. The produced sucrose stream can be concentrated to remove water or purified via evaporation as necessary for the biological or chemical production of fuels or fine chemicals.

**ORGANISM**

A photobioreactor 100, as described herein, can be used for cultivating photosynthetic organisms. Photosynthetic organisms that can be grown in the solid phase photobioreactor 100 include, but are not limited to, a naturally photosynthetic microorganism, such as a higher plant, an algae, a cyanobacterium, or an engineered photosynthetic microorganism, such as an artificially photosynthetic bacterium. Exemplary organisms that are either naturally photosynthetic or can be engineered to be photosynthetic include, but are not limited to, bacteria; fungi; archaea; protists; microscopic plants, such as a green algae; and animals such as plankton, planarian, and amoeba. Examples of naturally occurring photosynthetic microorganisms that can be grown in the photobioreactor 100 include, but are not limited to, *Spirulina* maximum, *Spirulina* platensis, *Dunaliella* salina, *Botryococcus* braunii, *Chlorella vulgaris*, *Chlorella* pyrenoidosa, *Serenastrum* capricomutum, *Scenedesmus* auadricauda, *Porphyridium* cruentum, *Scenedesmus* acutus, *Dunaliella* sp., *Scenedesmus obliquus*, *Anabaenopsis*, *Aulosira*, *Cylindrospermum*, *Synechoccus* sp., *Synechocystis* sp., or *Tolypothrix*.Photosynthetic organisms that can be cultivated in a photobioreactor 100 include photosynthetic organisms described in U.S. Pat. Pub. No. 2009/0181434. Density of photosynthetic organisms cultivated in a photobioreactor 100, including grams of dry biomass per liter equivalent, can be as described in U.S. Pat. Pub. No. 2009/0181434, incorporated herein by reference. In some embodiments, a higher plant, such as an orchid, can be grown in the photobioreactor 100, for example, from a tissue culture sample.

Culture and growth of photosynthetic microorganisms are known to those of ordinary skill in the art. Except as otherwise noted herein, therefore, culture...
and growth of photosynthetic microorganisms can be carried out in accordance with such known processes. One of ordinary can adapt methods of cultivation of photosynthetic organisms described in U.S. Pat. Pub. No. 2009/0181434, incorporated herein by reference, to a photobioreactor 100 described herein. A photobioreactor 100 can be used to cultivate a transgenic cyanobacteria engineered to accumulate a sugar, such as a disaccharide, as described in U.S. Pat. Pub. No. 2009/0181434, incorporated herein by reference. Accumulated sugar from a transgenic cyanobacteria or other photosynthetic organism can be harvested or collected from a product discharge port 230, a condensate discharge ports 240, a media outlet, collection panel 210, collection trough 220, media fabric, or a combination thereof, directly from the media or by harvesting the photosynthetic organisms and isolating the sugar therefrom. In some embodiments, a volatile product (e.g., ethanol) can be harvested or collected from any of the above or the condensate discharge port 240.

The balance of discussion refers to cyanobacteria but one of ordinary skill will understand such discussion can be adapted to other photosynthetic organisms.

**SHELL**

Various embodiments herein provide a photobioreactor 100 having an outer shell 110, otherwise known as a barrier layer. The term shell will be used in further discussion but one of ordinary skill will understand that descriptions of a barrier layer in, for example, references incorporated by reference can be applied herein in the context of the shell 100.

A shell 110 can include optimized interfaces for airflow inlets and outlets, cable pass thru fittings, or condensate flow distribution.

A photobioreactor shell 110 can include a film material. For example, a shell 110 can comprise Lumisol™ horticulture or greenhouse film material. A film material can control or help control light transmission, light diffusion, temperature, condensation (e.g., anti-condensation to form water film rather than droplets).
In some embodiments a shell 110 can have improved seam construction and reliability, revised port locations, and interfaces to the tensioned support system. A heat sealed construction of the shell 110 can improve the reliability of the heat sealed photobioreactor joints, including the longitudinal seams, or seam construction for introduction of gas inlet 202 or outlet 204 ports, zippers, or support cable interfaces. Port locations can provide for incorporation of an aerosol generation system 190, or an integrated collection trough 220 to direct product (e.g., sucrose) solution from the growth panels 120 to the outlet port.

In some embodiments, the shell 110 can comprise a coating with optical modification properties, such as wave-length filtering (e.g., filter out infrared radiation or non-photosynthetically active radiation), anti-reflective (e.g., to avoid photon loss and maximize entry of photons into the system), and internally reflectivity (e.g., to maximize photon retention in the system).

In some embodiments, a film material (e.g., Lumisol™) can use a "pinch seam" thermal weld construction (i.e., thermally welded pinch seal about perpendicular to film surface). While a film material with pinch seams was functional, intermittent seam failures were observed at the welded joints, which can require patching in the field.

In some embodiments, a film material can use a "lap seam" (i.e., thermally welded lap seal about parallel to film surface. Studies showed that a film lap seam provided a significant improvement in seam reliability. Studies also verified the film lap seam long term reliability via load testing of the representative seams under temperature extremes.

In some embodiments, a photobioreactor shell 110 comprising a film
material can eliminate some or all longitudinal seam construction of the photobioreactor shell 110. A photobioreactor shell 110 can include a homogenous tube produced using a film blowing process.

In some embodiments, a photobioreactor shell 110 comprises a seamless construction.

**GROWTH SURFACE AND ORIENTATION**

Various embodiments herein provide a photobioreactor 100 having a fabric orientation or design. The fabric orientation or design can be a transverse "Z" fold design providing for a collapsible fabric insert. The fabric orientation or design can be a curved bottom, which can afford product drip into a narrow area. The fabric orientation or design can allow for separation of wall condensate from product with a fold over ridge, which can eliminate or reduce a need for a product trough.

Greater surface area within photobioreactor 100 can provide advantages to photosynthetic cultivation processes. Light entering a photobioreactor 100 is often wasted in the sense that photons have a significant probability to strike non-photosynthetic surfaces or be reflected out of the system without being harvested by organisms. Arranging growing organisms in multiple orientations can provide more efficient capture of photon energy. Many photosynthetic organisms are sensitive to direct intense sunlight. In liquid based photobioreactors, organisms reside in a water column of defined pond depth. As the organisms grow within the media they self shade each other and reduce the overall direct light exposure. In a solid state photobioreactor, the growing surface generally affords a thin film of growing organisms on the surface, which prevents substantial self shading as found in liquid based systems. Arranging growing surfaces in high density, complex geometries can provide a mechanism to effectively reduce the overall light exposure to each organism by creating multiple surfaces that afford greater surface area per two dimensional surface thereby reducing the effective photon flux per unit area.

Biomass density can be an important factors driving overall productivity.
Photosynthetic organisms are generally difficult to grow to high cell densities in liquid photobioreactors necessary for cost effective bioprocesses. Solid state photobioreactors can position organisms in thin films on high surface area designs, which enable greater biomass accumulation and consequently more efficient, productive photobioreactors. The growth panel 120 configuration described herein can be altered to increase overall growth surface area that can also provide complex surface orientation to distribute light energy more effectively through the photobioreactor 100.

Various embodiments herein provide a photobioreactor 100 having highly angled growth surfaces. Highly angled growth surfaces can limit direct solar irradiation, prevent photobleaching, or improve packing density for the growth surface. Growth panel 120 orientation can include a multifold continuous growth panel 120 with equally spaced hanger 140 systems and integrated drip emitter tubes 180. Such an arrangement has been shown to yield approximately 40% more growth surface area while improving light transmission exposure and scattering for fielded deployment.

Various embodiments herein provide a photobioreactor 100 having an improved growth surface area to reactor volume. An improved growth surface area to reactor volume can provide a higher percentage of usable light captured on surfaces.

Fabric selection can provide improved dispersion and distribution of both cyanobacteria and growth media. A desirable growth fabric can provide high rates of liquid adsorption or rapid transmittance through the fabric structure; durability or capability of multiple re-use, withstanding sterilization processes, or good UV stability; ability to process in high volume production processes, including thermal welding, sewing, or die or water jet cutting; or low cost and easy processing from commercial off-the-shelf materials.

In some embodiments, a growth panel 120 includes a lofted non-woven material. For example, a growth panel 120 can includes a wood pulp-derived lofted non-woven material, such as Fitesa MBAL Airlaid. Such materials are conventionally used in feminine care and diaper products.
In some embodiments, a growth panel 120 includes a non-woven material. For example, a growth panel 120 can include a rayon/polyester blended non-woven material (e.g., Lyocell). For example, a growth panel 120 can include Alternative Laminate Using Dupont™ Sontara® 8646, which studies showed exhibited exceptional adsorption and wicking capability. As another example, a growth panel 120 can include Sontara® 8646, Sontara® 8868, or Sontara® 8801, or similar materials, or combinations thereof.

In some embodiments, a growth panel 120 includes a non-woven, converted laminate material. For example, a non-woven material (e.g., Sontara® 8646) can be converted into laminate form by sandwiching it between two layers of other materials (e.g., "baseline" Sontara® 8868). Studies showed that as a center layer of laminate construction, Sontara® 8646 exhibited exceptionally improved performance in transmission of liquid across a growth panel 120 face in comparison to a baseline Sontara® 8801 core layer. Further studies showed that a center core of Sontara® 8646 when combined with a drip emitter tube 180 provided exceptional improvement in uniform wetting and dispersion of liquids compared to some other materials in combination with a drip emitter tube 180.

**GROWTH PANELS**

In some embodiments, a photobioreactor 100 includes multiple (e.g., about five) growth panels 120, which can have about 10 square meters of growth surface area (or about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50 or more square meters of growth surface area). A growth panel 120 can be spaced (e.g., at approximately 6 inch gaps) between each panel. A growth panel 120 can also have a drip emitter tube 180 assembled (e.g., permanently assembled) into a top of the panel.

In some embodiments, a photobioreactor 100 includes multiple growth panels 120 (e.g., about 10 to 100 panels; about 20 to 80 panels; about 30 to 60 panels; about 35 to 55 panels; about 40 to 50 panels; about 45 panels; or 46 panels). As used herein, a growth panel assembly 130 can refer to a plurality of growth panels 120 arranged as described herein.
A growth panel 120 can have about 1.5 m\(^2\) of surface area (e.g., front and back faces of the panel), resulting in a total growth panel 120 exposed surface area of about 70 m\(^2\).

A growth panel 120 can have a concentrated drip zone 125 at the base of each growth panel 120. A concentrated drip zone 125 can direct product (e.g., sucrose) solution runoff to a selected position. An exemplary growth panel 120 featuring a concentrated drip zone 125 is shown in FIG. 6.

A photobioreactor 100 can have a growth panel hanger 140, optionally incorporated directly in or on the growth panel 120 of FIG. 6 also shows a panel hanger 140 (e.g., a low density polyethylene (LDPE) panel hanger), or stiffener assembly, that can be used with a growth panel 120 with or without a concentrated drip zone 125. A growth panel hanger 140 can be attached to the top of a fabric panel to structurally support the suspended weight when fully wetted with liquid (see e.g., FIG. 6). A growth panel hanger 140 can also be used for drip emitter tubing 180 interfaces or to support the photobioreactor 100. A growth panel hanger 140 can provide effective structural support of wetted growth fabric, while maintaining a desired flatness for each panel to facilitate direct exposure to sunlight.

In some embodiments, a growth panel hanger 140 can have one or more (e.g., 1, 2, 3, 4, or more; preferably 3) integrated pass thru (e.g., grommets), through which a suspension cable(s) can be inserted (i.e., a grommet pass thru hanger 142 approach) (see e.g., FIG. 8A). A drip emitter tube 180 can be interlaced through each hanger 140 in the grommet pass thru hanger 142 approach.

For a grommet pass thru hanger 142 approach, suspension cables 155 can be passed through grommets in a packed growth panel assembly 130 during installation. The growth panel assembly 130 can be placed inside the photobioreactor shell 110, with suspension cables 155 passed through the top of each hanger 140 at the top of a growth panel 120. The suspension cables 155 can then be reattached to a supporting structure and re-tensioned.

In some embodiments, a growth panel hanger 140 can be mounted to a
suspension cable(s) in similar fashion to a “coat-hanger” (i.e., a detachable hanger 144 approach), where the hooks can be permanently incorporated into growth panel hanger 140 geometry (see e.g., FIG. 8B). One advantage of a detachable hanger 144 is the ability to remove the growth panel assembly 130 from the cables 155 for quick retrofit, without having to detach the cable terminations. A drip emitter tube 180 can be interlaced through each detachable hanger 144.

For a detachable hanger 144 approach, suspension cables 155 can remain tensioned throughout the installation sequence, which is significantly less effort. FIG. 8B shows exemplary suspension cable interfaces and details the packed growth panel assembly 130 integration using the detachable hanger 144 configuration.

In some embodiments, a growth panel assembly 130 can be in two configurations, fully extended or in a compressed packed condition. Unfurling (i.e., fully extending from compressed packed condition) of the growth panel assembly 130 pack can occur with either the grommet pass thru hanger 142 approach or the detachable hanger 144 approach. Unfurling a growth panel assembly 130 on detachable growth panel hangers 144 can result in relatively less friction as compared to a grommet pass thru approach. The detachable growth panel hanger 144 exhibited very low levels of friction, and slid unobstructed along the tensioned cables 155.

Studies showed that both pass thru grommet hangers 142 and detachable hangers 144 provided uniformity of growth panel 120 geometry once deployed. Both pass thru grommet hangers 142 and detachable hangers 144 provided uniform spacing of the hangers 140, and good separation and stability of the growth panels 120 inside the photobioreactor shell 110. FIG. 9A and FIG. 9B show sections of both pass thru grommet hangers 142 and detachable hangers 144 configurations with the photobioreactor shell 110 removed for clarity.

**PRODUCT COLLECTION.**

A photobioreactor 100 described herein can have a product collection
system.

In some embodiments, a product (e.g., sucrose) collection panel 210 collects product solution run-off from the growth panels 120, guiding the liquid to a discharge port. A product collection panel 210 can be attached to each side of the shell 110 and run longitudinally down the length of the photobioreactor 100. A product collection panel 210 can be configured to allow residual condensate from the photobioreactor 100 interior to drip through the edge interfaces of the collection panel 210, thus ensuring that no or substantially no condensate would mix or contaminate the product solution runoff. While a product collection panel 210 can provide the desired separation of product solution from condensate, it can be relatively complex to assemble to the photobioreactor shell 110 walls, and can suffered from geometric interface issues which tends to "pool" sucrose solution near the downstream end of the photobioreactor 100.

In some embodiments, a product (e.g., sucrose) collection trough 220 placed on the bottom interior surface of the photobioreactor shell 110. A collection trough 220 can alleviate the need for a large collection panel 210. A product collection trough 220 can have a pair of lateral walls forming a trough there between. A product collection trough 220 can be constructed using two plastic walls or tubes spaced at a predetermined distance apart (e.g., about 2, 3, 4, 5, 6, or more inches apart; preferably about 4 inches apart), which attached (e.g., sealed, such as thermally sealed) to the bottom interior surface of the photobioreactor shell 110 (see e.g., FIG. 7). The walls or tubes can provide a damming effect, guiding the product (e.g., sucrose) solution runoff to one or more product discharge ports 230. Condensate can be captured on the outer sides of the trough 220, and can be directed to one or more (e.g., 1, 2, 3, 4, or more; preferably 2) condensate discharge ports 240 near or at the end of the photobioreactor 100. FIG. 7 shows a product collection trough 220 and discharge port configuration. A product collection trough 220 can eliminate the need for a collection panel 210 attached from side to side of the shell 110, which can significantly simplify construction, installation, and operation of the photobioreactor 100.

In some embodiments, a product collection trough 220 can be
implemented via plastic extrusions or similar structures that can reduce the amount of labor to install the device. An extruded trough material can reduce required welding, while still providing runoff or product-from-condensate separation performance.

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STRUCTURAL SUPPORT

A photobioreactor 100 described herein can have growth panels 120 connected directly the shell 110 or independent of the shell via a suspension system 150.

Various embodiments herein provide a photobioreactor 100 having growth panels 120 connected directly to a shell 110 of the photobioreactor 100. Growth panels 120 can be attached to the photobioreactor 100. Growth panels 120 can be attached to the photobioreactor 100 according to permanent panel heat sealed interfaces; hanger 140 supports welded to the interior of the pod shell 110, or zipper interfaces.

While studies showed that zipper interfaces were useful for attaching growth panels 120 to the photobioreactor 100 via the shell 110, a zipper interface can require additional manufacturing labor for zipper incorporation; structural support of the growth panel assemblies via shell 110 element stiffness, e.g., as applied to the pod during inflation; or relatively high internal pod pressures (e.g., 2 to 3 inches water gauge pressure) to support the growth panels 120 while also providing support against high wind loads. As an alternative, one can support the growth panel assembly 130 independently from the inflated shell 110 using a series of tensioned cables 155 supported external to the photobioreactor 100 while passing through the shell 110 itself at each end cap of the photobioreactor 100.

Various embodiments herein provide a photobioreactor 100 having a suspension system 150. A suspension system 150 can include a tensioned rope, cord, line, string, twine, cable, wire, or wire rope, where the tensioned support suspends the growth panels 120, optionally independent from the photobioreactor shell 110. The balance of discussion will refer to a support
"cable" but one of ordinary skill will understand such discussion to apply to each of rope, cord, line, string, twine, wire, or wire rope, or other similar structures, unless specified otherwise.

In some embodiments, a growth panel assembly 130 can be supported from multiple tensioned support cables 155 (e.g., 2, 3, 4, 5, 6, 7, 8, 9, 10, or more). Multiple support cables 155 (e.g., 3) can be tensioned between two supports (e.g., end poles) at each end of a photobioreactor 100. The support cables 155 can provide full or partial support of a growth panel assembly 130, while also orienting the shell 110 of the photobioreactor 100 such that interface fittings are aligned or substantially aligned with outside piping or tubing connections or other systems described herein.

A suspension system 150 can eliminate some or all structural interfaces or stresses between a growth panel assembly 130 and the shell 110 of the photobioreactor 100, and significantly simplifies photobioreactor 100 fabrication. A suspension system 150 can reduce (e.g., significantly reduce) fabrication costs.

A suspension system 150 can fully or partially support a growth panel assembly 130, eliminating all, most or some heat sealed interfaces, reducing skin stresses in photobioreactor shell 110, or significantly simplifying the photobioreactor 100 fabrication or photobioreactor shell 110 fabrication. A suspension system 150 can provide accurate and repeatable alignment of the shell 110, given that cables 155 can pass through the end caps at precise locations. A suspension system 150 can allow easy deployment of a growth panel assembly 130 during installation, which can be critical to facilitate field change-out or cleaning of the growth panels 120. A suspension system 150 can have cable terminations accurately located to ensure proper photobioreactor 100 slope for liquid runoff or drainage. A suspension system 150 can provide simplified installation, optionally using standardized cable couplings or sealed fittings on the end caps.

A suspension system 150 featuring a support cable can facilitate rapid deployment of growth panels 120 from a packaged (e.g., compressed) state.
within the photobioreactor shell 110, without necessarily relying on the shell 110 for structural support of the panels. Support of the growth panels 120 independently from the shell 110 using support cables 155 can provide the benefit of reducing the complexity of the photobioreactor 100 construction, such as by eliminating welded joint interfaces to the growth panel assembly 130. A photobioreactor 100 can include a growth panel hanger 140 to interface with support cables 155 (e.g., a series of tensioned support cable).

In some embodiments, the photobioreactor 100 includes a growth panel 120 with a growth panel hanger 140 and pass thru (e.g., grommets) to allow for cable suspension of the panels.

Various embodiments herein provide a photobioreactor 100 having a wire suspension system 150. A suspension system 150 can support the reactor or growth fabric. A growth fabric can include an integrated stiffening rib held (e.g., by wire) to spread the fabric in place. A suspension system 150 can allow a collapsible growth fabric cartridge to minimize labor or provide for cleaning or servicing in place of operation. A suspension system can support growth panels 120 internal to the photobioreactor 100, allowing for rapid field deployment or change-out of growth panel assemblies while simplifying the photobioreactor shell 110.

In some embodiments, the photobioreactor 100 includes a netting system 160 surrounding the outside of the shell 110 (see e.g., FIG. 10). In some embodiments, the photobioreactor 100 does not includes a netting system 160 surrounding the outside of the shell 110.

In some embodiments, the photobioreactor 100 can be suspended or conveyed as described in U.S. Pat. Pub. No. 2009/0181434, incorporated herein by reference. For example, the photobioreactor 100 can be part of a system including a conveyance system that moves the photobioreactor 100 so as to optimize position of the growth fabric for receiving light. As another example, the photobioreactor 100 can be part of a system including a plurality of growth fabrics radiating outward from a central point, or a plurality of photobioreactors radiating outward from a central point. As another example, the photobioreactor
100 can be part of a system including a conveyance system that moves a plurality of growth fabrics around the central point so as to optimize position of one or more growth fabric for receiving light.

5

RESEALABLE ENTRY

Various embodiments herein provide a photobioreactor 100 having resealable entry 170 (e.g., zipper access) at one or more locations of the photobioreactor 100, which can allow easy access for maintenance and cleaning. For example, a resealable entry 170 can be present at one or both longitudinal ends of the photobioreactor 100.

In some embodiments, the resealable entry 170 is formed from excess shell 110 material, which can be located at a distal end of the photobioreactor 100, rolled over to form an airtight or substantially airtight seal. In such configurations, access can be via unrolling the distal end shell 110 material. In some embodiments, the resealable entry 170 is formed from excess shell 110 material, which can be located at a distal end of the photobioreactor 100, sealed (e.g., thermally welded) to form an airtight or substantially airtight seal. In such configurations, access can be via cutting away an amount of shell 110 material so as to remove or substantially remove the seal; the shell 110 can be resealed by then making a new seal in the excess shell 110 fabric. In such configurations, the excess shell 110 material can form a nose-like extension, where material in the extended portion is alternately sealed and cut away until the extension is exhausted.

In some embodiments, the resealable entry 170 is formed from a fastener integrated with the shell 110 material. The resealable entry 170 can be located at a distal end of the photobioreactor 100. A faster can be, for example, a zipper, button, buckle, clamp, clasp, clip, cleko, clutch, flange, frog, grommet, hook-and-eye closure, hook and loop fastener, latch, snap, strap, tag, tie, batten, anchor, bolt, nut, screw, nail, peg, pin, rubber band, or captive fastener.

Preferably, the resealable entry 170 is formed from a zipper fastener integrated
with the shell 110 material at one or more distal ends of the photobioreactor 100.

Various embodiments herein provide a photobioreactor 100 having an overall design that allows a low cost "roll to roll" manufacturing process.

**AEROSOL SYSTEM**

Various embodiments herein provide a photobioreactor 100 having an aerosol injection system 190. An aerosol injection system 190 can provide for pre-wetting of growth panels 120 in preparation for cyanobacteria inoculation, or supply intermittent or continual water or growth media. An aerosol injection system 190 can produce a fog or mist that can create an internal weather pattern preventing runaway temperature increases. A fog or mist can help to more evenly scatter light within the reactor. A nutrient media in the fog or mist can prevent "streaking" or patterning on growth surface. "Streaking" or patterning on growth surface can result in less biomass wash off from a gravity pumped liquid feed.

In some embodiments, a photobioreactor 100 can include an aerosol injection system 190 and a drip emitter tube 180. In some embodiments, a photobioreactor 100 can include an aerosol injection system 190 but not contain a drip emitter tube 180. In some embodiments, a photobioreactor 100 can include drip emitter tube 180 but not an aerosol injection system 190.

**DRIP Emitter TUBE SYSTEMS**

Various embodiments herein provide a photobioreactor 100 having a drip emitter tube 180. An optimized drip emitter tubing 180 configuration can reduce the required tubing by up to about 60%. A drip emitter tube 180 can provide for introduction of cyanobacteria inoculant, water, or nutrient media to the growth panels 120.

In some embodiments, a photobioreactor 100 can include an aerosol injection system 190 and a drip emitter tube 180. In some embodiments, a photobioreactor 100 can include an aerosol injection system 190 but not contain a drip emitter tube 180. In some embodiments, a photobioreactor 100 can
include drip emitter tube 180 but not an aerosol injection system 190.

Desirable features of drop emitter tube 180 include a high level of flexibility or resilience; good UV or chemical resistance; low cost of the tubing; consistently introduce cyanobacteria to each growth panel 120 simultaneously or substantially simultaneously; introduce nutrient medias to growth panels 120 for cyanobacteria sustainment; or significantly reduce the amount of drip emitter tubing in the design. Tubing can be punctured in a variety of ways to provide for fluid drip (e.g., inoculant or feedstock liquids) under various pressures and flow rates. A desirable material for a drip emitter tube 180 can have reduced propensity of orifice clogging, reduced effects of elevation change on tubing or manifolds, increased insoluble solids filtering, or orifice spacing for flow optimization.

In some embodiments, a drip emitter tube 180 and corresponding orifice can be incorporated or integrated into or onto to a growth panel hanger 140.

A drip emitter tube 180 can comprise a thermoplastic polymer (e.g., Santoprene® Thermoplastic Elastomer resin). A drip emitter tube 180 can comprise PVC (e.g., PVC food grade tubing from, e.g., Hudson extrusions). A drip emitter tube 180 can comprise Tygon® E-1000 Laboratory Tubing. In some embodiments, a photobioreactor 100 can contain multiple growth media surfaces (e.g., 5 curtains of growth media) aligned in parallel along the length of the photobioreactor 100. One or more growth media curtain (e.g., all) can include a drip emitter tube 180 (e.g., Santoprene®) integrated (e.g., directly integrated) to the top of the growth panel 120. An exemplary photobioreactor 100 can include a shell 110 (e.g., a polyethylene isolation bag having a DuraFilm green house film); a multilayered (e.g., a three layered) laminated growth fabric (e.g., polyester/wood pulp growth fabric); integral feed tube connections; intermediate condensate drain panel; webbing support system (e.g., polypropylene webbing); carbon dioxide inlets or outlets; and drip emitter tubing (e.g., Santoprene® Drip Emitter Tubing).

A drip emitter tube 180 can comprise PVC (e.g., PVC food grade tubing from, e.g., Hudson extrusions). A drip emitter tube 180 can comprise Tygon® E-
In some embodiments, a drip emitter tube 180 can interface with growth panels 120 using multiple drip emitter tubes 180 (e.g., 2, 3, 4, 5, 6, 7, 8, 9, 10, or more) that can pass through all growth panels 120 in a straight tube length lying in the axial direction of the photobioreactor 100. Studies have shown that two drip emitter tubes 180 can sufficiently wet the growth panel 120 material (e.g., fabric) during periods (e.g., sustained periods) of media introduction. Studies have also shown that a single drip emitter tube 180 approach can sufficiently inoculate cyanobacteria onto each growth panel 120 where used in combination with an aerosol injection system 190 to pre-wet or wet growth panels 120.

In some embodiments, a collection cone can be thermally formed into a growth panel hanger 140 with integrated grommets to suspend the growth panels 120 inside the photobioreactor 100. A drip emitter tube 180 (e.g., Tygon® E-1000 tubing) with integrated orifices can be passed through each growth panel hanger 140, locating each individual orifice on the interior of the collection cone. During injection of liquids, the orifice can drip directly into the interior of the cone, distributing the liquid droplets directly to the attached growth panel 120.

In some embodiments, a drip emitter tube 180 can be passed or clamped through a growth panel hanger 140 (e.g., an LDPE detachable growth panel hanger), such that droplets from the tubing directly impact the growth fabric adjacent to the growth panel hanger 140.

In some embodiments, a photobioreactor 100 does not include drip emitter tubing system. In such embodiments, the aerosol wetting system 190 combined with gross application approaches for cyanobacteria can eliminate the need for a drip emitter approach.

**INTEGRATED PORTS.**

A photobioreactor 100 described herein can have a plurality of integrated ports.

In some embodiments, a photobioreactor 100 can have one or more of a
gas inlet 202 or outlet 204, aerosol injection inlet 192, inoculant injection inlet, product discharge outlet, condensate discharge port 240, or cable pass thru.

A gas inlet 202 or outlet 204 can provide gas injection or exit locations for carbon dioxide laden air, or circulatory photobioreactor ventilation. An aerosol injection inlet 192 can provide a nebulizer interface 194. An inoculant injection inlet can provide cyanobacteria delivery to growth panels 120. A product discharge outlet can provide run-off of product, such as sucrose, solution from growth panels 120. A condensate discharge port 240 can provide run-off of residual condensation from photobioreactor 100 interior. A cable pass thru can provide pass thru of tensioned support cables 155 through the photobioreactor shell 110, where number of ports can correspond to number of cables 155 at each end of photobioreactor 100.

FIG. 4 and FIG. 5 shows exemplary locations and fitting types for photobioreactor 100 end walls.

Carbon dioxide is the principle carbon source for metabolism in photosynthetic organisms operating photoautotrophically. Under ambient temperatures, pressures and environmental conditions, CO₂ is present nominally at about 380ppm as a gas dispersed in the natural atmosphere. This relatively low level of carbon can limit the rate at which photosynthetic organisms uptake the material for growth. In addition, the solubility of carbon dioxide in aqueous solution is approximately 40 mM at room temperature and atmospheric pressure, which can be 1/10th or lower than when compared to carbon feedstocks generally associated with submerged cultures such as glucose, sucrose, or glycerol. Taken together, the available carbon delivered from atmospheric gas flow and the solubility of CO₂ in aqueous solution combined with the mass transfer concerns of partitioning solutes from a gas to a liquid phase can create a low available carbon concentration to maintain the active cultivation of photosynthetic organisms.

Direct exposure of organisms into atmospheric CO₂ can optimize the growth rate based upon carbon feedstock. Access to carbon feedstock can be of increasing importance as the cell density increases. In one embodiment,
atmospheric C\textsubscript{02} is introduced to the photobioreactor 100 by the gas inlet 202 unit and is exhausted through the gas outlet 204 unit. The gas inlet 202 unit can include a filter that removes any contaminants in the atmospheric C\textsubscript{02}. In one embodiment, the gas inlet 202 unit acts as a one way valve allowing atmospheric C\textsubscript{02}, or other gas, to move into the photobioreactor 100 without allowing the atmospheric C\textsubscript{02}, or other gas, to move out of the photobioreactor 100. In another embodiment, the C\textsubscript{02}, or other gas, is introduced to the photobioreactor 100 under pressure from a pressure generating device such as, but not limited to, a pump.

Additional C\textsubscript{02}, or another gas, can be injected into the photobioreactor 100 from an external source. In one embodiment, the additional C\textsubscript{02} is mixed with the atmospheric C\textsubscript{02} before entering the photobioreactor 100. In another embodiment, the additional C\textsubscript{02} is injected into the photobioreactor 100 separate from the atmospheric C\textsubscript{02}.

A computer system can monitor the C\textsubscript{02} concentration in the photobioreactor 100 and inject or exhausts C\textsubscript{02} to maintain a constant C\textsubscript{02} concentration in the photobioreactor 100. The computer system can include a memory, a processor, a plurality of ports for connecting sensors configured to convert environmental measurements into an electrical signal, a plurality of switches capable of controlling the supply of power to electrical devices such as actuators and signal generators capable generating analog signals. The environmental measurements include, but are not limited to, pressure, temperature, gas concentration, strain, gas flow or any other measurable force or environmental condition.

The computer system can execute programs on the processor that monitors forces and environmental conditions in the photobioreactor 100 and that toggle switches or generate analog signals to control devices to control the environment in the photobioreactor 100. As an illustrative example, the computer system measures the amount atmospheric C\textsubscript{02} flowing into and out of the photobioreactor 100 and sends an analog signal to an actuator coupled to a valve on a gas inlet 202 unit to increase or decrease the amount of atmospheric C\textsubscript{02} injected into the system to maintain a desired atmospheric C\textsubscript{02} setpoint in
the photobioreactor 100.

Direct exposure of organisms in the photobioreactor 100 to atmospheric CO$_2$ optimizes the growth rate based upon carbon feedstock availability in the current invention over submerged culture photobioreactors. In addition, the photobioreactor 100 allows for better control of CO$_2$ concentrations available to cultivated cells. The reactor atmosphere can be supplemented with CO$_2$ gas that provides higher concentrations of feedstock carbon to growing cells. While atmospheric CO$_2$ and CO$_2$ have been used to describe gases injected into the photobioreactor 100, any gas or mixture of gases can be injected into the photobioreactor 100.

**STERILIZATION SYSTEM**

Sanitizing modules described herein can be integrated into a photobioreactor or multi-photobioreactor array and can achieve <100 CFU/ml. This integrated sanitizing process is low-cost, scalable, non-toxic, and does no damage to components of the array.

At commercial-scale operation of the system, operations staff can take sub-arrays of photobioreactors off-line at approximately six-month intervals for cleaning, sanitization, and re-inoculation. Takedown, servicing, and re-inoculation back to production phase can take approximately two weeks. When photobioreactors are taken off line, an operator can open each photobioreactor to remove the growth panel assemblies, wash off existing cyanobacteria biomass film, and replaces them into the photobioreactor (or install a new growth panel assembly). The photobioreactors can be re-installed, sanitized or re-inoculated. The expected lifetime of a photobioreactor is five years owing to constant exposure of direct and diffused sunlight and other environmental conditions.

An array of photobioreactors can vulnerable to contamination at three key points: the photobioreactor and hardware, the liquid feed stream, and the gas feed stream. These entry points may reveal two key vulnerabilities in the operation of the array. First, the product (e.g., sucrose) in the effluent stream is a
ready carbon source for potential contaminants. Unlike other submerged culture systems that produce primarily oils or biocrude, the production of sucrose creates an environment wherein contamination at inoculation and in operation is a key consideration, even at the one photobioreactor scale. Second, the low-cost photobioreactor design and process is sensitive to typical state-of-the-art decontamination processes.

The system of photobioreactor arrays is not amenable to traditional chemical agents, as these treatments can cause degradation of the photobioreactor or mechanical failure of the array. As a result, toxic byproducts and residues from many of these sanitizing processes cannot be removed easily from the system. Their residual nature threatens the viability of the cyanobacteria, as well as the fidelity of the low-cost photobioreactor and array.

Described herein is a method by which photobioreactors individually or in arrays can be sanitized prior to inoculation and perform sufficiently. Specifically, the disclosed technology can maintain a minimal level of microbial contamination during the entire active phase of process, while facilitating development of an economic startup clean-in place method that does not negatively impact growth or productivity during operations. Some benefits of such technology yield high productivity, cost-efficiency, and scalability.

Photobioreactors and arrays described herein can be used in combination with commercial-off-the-shelf (COTS) hydrogen peroxide vapor systems. A hydrogen peroxide passivating vapor sterilization system was developed as a clean in place system for decontamination of its conversion platform (HP CIP system). Hydrogen peroxide vapor systems currently in use for pharmaceutical applications are applied to small surface area steel or plastic systems indoors. A low-cost HP CIP system that does not degrade the low-cost materials utilized in the photobioreactor and array components is important to preserve a sanitary system and ensure the stable cyanobacteria growth necessary for high sucrose productivity.

Compositions and methods described herein utilizing molecular biology protocols can be according to a variety of standard techniques known to the art.


Definitions and methods described herein are provided to better define the present disclosure and to guide those of ordinary skill in the art in the practice of the present disclosure. Unless otherwise noted, terms are to be understood according to conventional usage by those of ordinary skill in the relevant art.

In some embodiments, numbers expressing quantities of ingredients, properties such as molecular weight, reaction conditions, and so forth, used to describe and claim certain embodiments of the present disclosure are to be understood as being modified in some instances by the term "about." In some embodiments, the term "about" is used to indicate that a value includes the standard deviation of the mean for the device or method being employed to determine the value. In some embodiments, the numerical parameters set forth in the written description and attached claims are approximations that can vary depending upon the desired properties sought to be obtained by a particular embodiment. In some embodiments, the numerical parameters should be construed in light of the number of reported significant digits and by applying ordinary rounding techniques. Notwithstanding that the numerical ranges and parameters setting forth the broad scope of some embodiments of the present disclosure are approximations, the numerical values set forth in the specific examples are reported as precisely as practicable. The numerical values
presented in some embodiments of the present disclosure may contain certain errors necessarily resulting from the standard deviation found in their respective testing measurements. The recitation of ranges of values herein is merely intended to serve as a shorthand method of referring individually to each separate value falling within the range. Unless otherwise indicated herein, each individual value is incorporated into the specification as if it were individually recited herein.

In some embodiments, the terms "a" and "an" and "the" and similar references used in the context of describing a particular embodiment (especially in the context of certain of the following claims) can be construed to cover both the singular and the plural, unless specifically noted otherwise. In some embodiments, the term "or" as used herein, including the claims, is used to mean "and/or" unless explicitly indicated to refer to alternatives only or the alternatives are mutually exclusive.

The terms "comprise," "have" and "include" are open-ended linking verbs. Any forms or tenses of one or more of these verbs, such as "comprises," "comprising," "has," "having," "includes" and "including," are also open-ended. For example, any method that "comprises," "has" or "includes" one or more steps is not limited to possessing only those one or more steps and can also cover other unlisted steps. Similarly, any composition or device that "comprises," "has" or "includes" one or more features is not limited to possessing only those one or more features and can cover other unlisted features.

All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g. "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the present disclosure and does not pose a limitation on the scope of the present disclosure otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the present disclosure.

Groupings of alternative elements or embodiments of the present
disclosure disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any combination with other members of the group or other elements found herein. One or more members of a group can be included in, or deleted from, a group for reasons of convenience or patentability. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified thus fulfilling the written description of all Markush groups used in the appended claims.

Citation of a reference herein shall not be construed as an admission that such is prior art to the present disclosure.

Having described the present disclosure in detail, it will be apparent that modifications, variations, and equivalent embodiments are possible without departing the scope of the present disclosure defined in the appended claims. Furthermore, it should be appreciated that all examples in the present disclosure are provided as non-limiting examples.

EXAMPLES

The following non-limiting examples are provided to further illustrate the present disclosure. It should be appreciated by those of skill in the art that the techniques disclosed in the examples that follow represent approaches the inventors have found function well in the practice of the present disclosure, and thus can be considered to constitute examples of modes for its practice. However, those of skill in the art should, in light of the present disclosure, appreciate that many changes can be made in the specific embodiments that are disclosed and still obtain a like or similar result without departing from the spirit and scope of the present disclosure.

EXAMPLE 1: SELECTION OF CABLE AND ANALYSIS

An important feature of a tensioned cable approach is to provide sufficient structural support from the cables to suspend the growth panel assembly of the photobioreactor without excessive downward deflection. It was determined that a maximum catenary deflection of the cable of less than about 1.5 inches can provide adequate support of a full wetted growth panel assembly.
To accomplish this level of deflection, calculations were completed to verify the required pretensioning required in each of the three cables to support the fully wetted growth panel assembly weight. Standard catenary curve equations were used to determine the anticipated cable sag in each of the three cables, assuming the use of a specific cable and optimal tension:

\[
\begin{align*}
q &= w \cdot g, \\
a &= n / q, \\
h &= a(\cosh(l/(2a)) - 1), \\
s &= 2 \cdot a \cdot \sinh(l/(2a))
\end{align*}
\]

Where:
- \( q \) = cable weight per unit length,
- \( w \) = cable mass per unit length,
- \( g \) = force perpendicular to cable length,
- \( a \) = angle between x axis and cable sector,
- \( n \) = cable tension,
- \( l \) = straight line distance,
- \( h \) = cable sag, and
- \( s \) = cable length.

For this effort, 3/16" stainless steel 7 x 19 strand wire rope were selected as well suited, with a breaking strength of approximately 3800 lb.

Where:
- \( q = 1.65 \text{ lb/ft} \) (assumes weight of cable plus 33 lbs of full wetted growth fabric assy per cable*),
- \( l = 22.0 \text{ ft} \),
- \( n = 840 \text{ lb} \) (20% of breaking strength), and
- \( s = 22.0 \text{ ft} \).

*based on actual weighed growth panel material.
Calculating for h (sag) results in a maximum of 1.43 inches at mid-span, which was deemed to be acceptable for this application. Thus, the 3/16" stainless steel cable was established for a baseline photobioreactor configuration.

**EXAMPLE 2: VERIFICATION OF GROWTH PANEL WETTING**

The following example shows testing of a grommet pass thru growth panel hanger and a detachable growth panel hanger. Both growth panel hanger configurations were successfully validated during wetting trials, using conventional pressure-pot interfaces to pod manifolds, operating at liquid injection pressures of 3.0 to 4.0 psig. Sontara 8646/8868 material laminate was used for both configurations of growth panel assemblies. All 46 panels in the grommet pass thru and detachable hanger configurations were found to wet uniformly, despite the fact that the detachable cable configuration only utilized a single drip emitter tube. It is believed that the Sontara® laminate contributed significantly to the improved consistency and uniformity of growth panel wetting.

**EXAMPLE 3: PHOTOBIOREACTOR SHELL INFLATION STABILITY AND NETTING SUPPORT**

As validation of the photobioreactor structural interface integrity with a cable suspension system, a photobioreactor shell with full growth panel fabric assemblies (containing 46 growth panels) was mounted into operating position. The system was maintained for three continuous days under inflation. During this period, daytime wind gusts in the range of 25 to 30 mph occurred, with no visible impact to the photobioreactor shell, cable pass thru interfaces, or netting system. All welded seams of the pod shell remained completely sealed and zipper end cap access ports remained accessible slope orientation for proper liquid drainage was maintained.
CLAIMS

What is claimed is:

Claim 1. A photobioreactor for cultivating photosynthetic microorganisms, the photobioreactor comprising:
   a shell;
   a growth panel assembly;
   a suspension system;
   an aerosol system;
   a collection trough; and
   an optional inoculation system.

Claim 2. The photobioreactor of claim 1, wherein the shell comprises:
   (i) a material that passes or substantially passes photosynthetically active radiation, where the material forms a physical barrier enclosing or substantially enclosing a growth panel assembly;
   (ii) the collection trough, wherein the collection trough is located on a bottom surface of the shell material and the collection trough directs flow of a fluid product produced by the photosynthetic microorganisms; or
   (ii) a resealable entry providing access from outside the bioreactor to inside the shell so as to access the growth panel assembly.

Claim 3. The photobioreactor of claim 2, wherein
   the collection trough comprises two lateral walls separated so as to form trough extending along a longitudinal axis of the photobioreactor; and
   the collection trough is disposed under a concentrated drip zone of the growth panel assembly such that a fluid product drips into the collection trough.

Claim 4. The photobioreactor of any one of claims 2-3, wherein the shell comprises a product discharge port disposed to collect fluid product from the collection trough and discharge it through the shell.
Claim 5. The photobioreactor of any one of claims 3-4, wherein:
the shell comprises at least two condensate channels flanking the collection trough;
the condensate channels collecting condensate flow from walls of the shell;
the shell comprises at least one condensate discharge port disposed to collect condensate from the condensate channels and discharge it through the shell.

Claim 6. The photobioreactor of any one of claims 1-5, wherein the growth panel assembly comprises a plurality of growth panels, each growth panel comprising:
(i) a growth panel hanger comprising an interface to the suspension system,
(ii) a non-gelatinous, solid cultivation support material suitable for providing nutrients and moisture to photosynthetic microorganisms on at least a portion of a surface thereof, wherein said portion of the surface has a topography that allows photosynthetic microorganisms to adhere thereto when said portion of the surface is oriented non-horizontally, and
(iii) a concentrated drip zone at or near the bottom of the growth panel.

Claim 7. The photobioreactor of claim 6, wherein the growth panel assembly comprises about 10 to 100 growth panels; about 20 to 80 growth panels; about 30 to 60 growth panels; about 35 to 55 growth panels; about 40 to 50 growth panels; about 45 growth panels; or 46 growth panels.

Claim 8. The photobioreactor of any one of claims 6-7, wherein the plurality of growth panels are connected in a zig-zag configuration.

Claim 9. The photobioreactor of any one of claims 6-8, wherein each growth panel comprises a surface area of about 1.5 m².
Claim 10. The photobioreactor of any one of claims 6-9, wherein each growth panel comprises a laminate structure comprising one or more blended non-woven material, optionally a rayon/polyester blended non-woven material.

Claim 11. The photobioreactor of any one of claims 6-10, wherein the growth panel hanger comprises (i) a grommet pass thru interface with a suspension cable or (ii) a detachable hook interface with a suspension cable.

Claim 12. The photobioreactor of any one of claims 1-11, wherein the suspension system comprises at least one suspension cable, the suspension cable interfacing with a growth panel hanger to fully or partially support the growth panel assembly.

Claim 13. The photobioreactor of claim 12, wherein the at least one suspension cable is tensioned between two points external to the shell of the photobioreactor.

Claim 14. The photobioreactor of any one of claims 1-13, wherein:

- the aerosol system comprises a fluid source and a nebulizer sufficient to generate fog or mist inside the shell; or
- the shell comprises an aerosol system inlet and the nebulizer is operably connected to the aerosol system inlet.

Claim 15. The photobioreactor of any one of claims 1-13, further comprising a sterilization system, the sterilization system comprising hydrogen peroxide vapor.

Claim 16. The photobioreactor of any one of claims 1-15, wherein the inoculation system comprises a drip emitter tube for inoculation of photosynthetic microorganisms on the plurality of growth panels.

Claim 17. The photobioreactor of claim 6, wherein the drip emitter tube is attached to the growth panel hanger such that an orifice of the drip emitter tube
is positioned to transfer inoculant to the growth panel connected to the growth panel hanger.

Claim 18. The photobioreactor of any one of claims 1-17, further comprising photosynthetic microorganisms, the photosynthetic microorganisms comprising wild type cyanobacteria or genetically transformed cyanobacteria.

Claim 19. A method of installing a photobioreactor of any one of claims 1-18, comprising:
placing the growth panel assembly inside the shell;
connecting the suspension system to the growth panel assembly; and
applying a positive air pressure to the inside of the shell so as to inflate the photobioreactor.

Claim 20. A method of producing a product from photosynthetic microorganisms comprising:
culturing photosynthetic microorganisms in the photobioreactor of any one of claims 1-18; and
collecting a product from the photosynthetic microorganisms;
wherein,
the photosynthetic microorganisms comprise a cyanobacteria genetically transformed to produce the product; and
the product is a disaccharide sugar.
A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - C12M 1/00; C12M 3/00 (2014.01)

CPC - C12M 21/02; C12M 31/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

CPC: C12M 21/02; C12M 31/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

CPC: C12M 21/02; C12M 31/02 (text search)

USPC: 435/292, 1; 435/1 62.3 (text search)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Electronic data bases: PatBase; Google Scholar; Google Patents; Google Web

Search terms: photobioreactor (PBR), protective translucent shell, growth panels, vertical plate PBR, suspension cable for hanging panels, aerosol system for fog or mist, collection trough, photosynthetic organism, cyanobacteria

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>US 20130115689 A1 (AIKENS et al.) 9 May 2013 (09.05.2013). Especially para [0020], [0112], [0114], [0130], [0132], [0188], [0191], [0195], sheet 10 figs 12A, 12B.</td>
<td>1-4</td>
</tr>
<tr>
<td>A</td>
<td>US 201000028976 A1 (HU et al.) 4 February 2010 (04.02.2010). Especially para [0011-0033], sheet 1 fig 1, sheet 2 fig 2.</td>
<td>1-4</td>
</tr>
<tr>
<td>A</td>
<td>US 20120309090 A1 (AIKENS et al.) 6 December 2012 (06.12.2012). Especially sheet 5 fig 5, para [0021-0031], sheet 2 fig 2, sheet 3 fig 3</td>
<td>1-4</td>
</tr>
</tbody>
</table>

Further documents are listed in the continuation of Box C.

* Special categories of cited documents:
  "A" document defining the general state of the art which is not considered to be of particular relevance
  "E" earlier application or patent but published on or after the international filing date
  "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
  "O" document referring to an oral disclosure, use, exhibition or other means
  "P" document published prior to the international filing date but later than the priority date claimed

T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

& document member of the same patent family

Date of the actual completion of the international search
4 December 2014 (04.12.2014)

Date of mailing of the international search report
02 JAN 2015

Name and mailing address of the ISA/US
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450
Facsimile No. 571-273-3201

Authorized officer:
Lee W. Young

PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774
This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. Claims Nos.: because they relate to subject matter not required to be searched by this Authority, namely:

2. Claims Nos.: because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. Claims Nos.: 5-20 because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

This International Searching Authority found multiple inventions in this international application, as follows:

1. As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: