

V-Trough Photobioreactor System and Method of Use**CROSS REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims the benefit of U.S. Patent Application No. 13/149,463, filed May 31, 2011 and U.S. Patent Application No. 13/249,426, filed September 30, 2011, the entire contents of which are hereby incorporated by reference herein in their entireties.

FIELD OF THE INVENTION

[0002] Disclosed herein are photobioreactor systems for high productivity aquaculture or aquafarming for growing of algae or other organisms in an aquatic environment featuring aspects that favor improved growth rates by achieving efficient mixing rates, control over the contents of the growth medium, including carbon source, nitrogen source, and essential trace elements necessary for growth.

BACKGROUND

[0003] Algae have gained significant importance in recent years given their advantage in solving several critical global issues such as the production of renewable fuels and animal feedstock, reducing global climate change via carbon dioxide remediation, wastewater treatment, and sustainability. Algae farming is also used for the production of food, feed, nutraceuticals, chemicals, biofuels, pharmaceuticals, and other products that can be extracted from algae.

[0004] Algae's superiority as a biofuel feedstock arises from a number of factors such as high per-acre productivity when compared to typical terrestrial oil crop plants, non-food based feedstock resources, and its ability to be cultivated on otherwise non-productive, non-arable land.

[0005] Several thousand species of algae have been screened and studied for lipid production worldwide over the past several decades, of which about 300 species rich in lipid production have been identified. The lipids produced by algae are similar in composition when compared to other contemporary oil sources such as oil seeds, cereals, and nuts.

[0006] As the United States has already consumed over 80% of its proven oil reserves, it currently imports more than 60% of its oil. It is anticipated that within 20 years the United States will be importing in the range of 80-90% of its oil. Much of this imported oil is supplied by nations in politically volatile regions of the world, a fact which poses a constant threat to a stable oil supply for the United States. Although the United States can continue to increasingly

import foreign oil, global oil supplies are not infinite and importation continues to increase the United States trade deficit and create an increasing burden on the economy.

[0007] Commercial cultivation of lipid-producing algae provides a solution to the growing problem of oil shortages and increases in cost of importation. Algae oil can be used to replace petroleum-based products. Algae can be used to generate oil of varying lipid profiles for use in a variety of applications, including, but not limited to, the generation of diesel, gasoline, kerosene, and jet fuel.

[0008] Algae farming typically uses photobioreactors (PBRs), such as flat panel PBRs and tubular PBRs, which are small in volume in order to improve the amount of light utilized by the algae. These devices have high productivity, but not high enough to make up for the loss in volume. Other PBR systems, such as ponds, raceways or troughs are used to provide larger scale production, but these systems suffer from low productivity. Current PBR systems are typically designed with flat bottoms where solids settle out, and over time potentially lead to bacterial and fungal growth. Such unwanted growth potentially decreases the productivity and growth of algae. Additionally, pond systems are large systems (half acre, acre, or hectare size) with minimal mixing. Mixing in these systems is often accomplished by way of paddle wheels or air lines, which are not optimal for algae growth, and do not develop a systematic pattern of mixing within the system to keep solids from settling out. Optimal mixing of such systems require large amounts of energy, reducing overall cost efficiency. Pond or raceway systems also require maintenance such as draining, harvesting, and cleaning to maintain optimal productivity levels for algae growth. This results in downtime of the system, labor to clean, and large amounts of water to refill these systems.

[0009] The present disclosure provides V-shaped PBR systems designed for optimal productivity at large volumes in order to deliver a high yield per acre. These systems produces large volumes of algae in a highly productive and cost efficient manner.

BRIEF SUMMARY OF THE INVENTION

[0010] In one aspect, a photobioreactor is disclosed which comprises a cavity defined by: a substantially V-shaped base comprising: two base walls, the base walls meeting proximate to an axis defining an interior angle, each base wall comprising: a sloped portion and a substantially vertical portion, a proximal end and a distal end, and a length extending along the axis and a width extending perpendicular to the axis; the cavity being further defined by: a proximal side wall adjacent to the proximal end, and a distal side wall adjacent to the distal end; and the photobioreactor system further comprising: at least one gas delivery system

disposed within the cavity and extending parallel to the axis, and at least one carbon dioxide delivery system disposed within the cavity and extending parallel to the axis.

[0011] In another aspect, a photobioreactor is disclosed which comprises a cavity defined by: a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel, the contoured base comprising: a first substantially vertical portion; a first sloped portion; a second sloped portion; a third sloped portion; a fourth sloped portion; a second substantially vertical portion; wherein the first sloped portion and the second sloped portion meet proximate to a first axis defining a first interior angle; wherein the first sloped portion and the second sloped portion define a first substantially V-shaped feature defining a first depth; wherein the third sloped portion and the fourth sloped portion meet proximate to a second axis defining a second interior angle; and wherein the third sloped portion and the fourth sloped portion define a second substantially V-shaped feature defining a second depth; the contoured base further comprising a proximal end and a distal end; and a length extending along the axes and a width extending perpendicular to the axes; the cavity further defined by a proximal side wall adjacent to the proximal end; and a distal side wall adjacent to the distal end.

[0012] In another aspect, a kit for assembling a photobioreactor is disclosed which comprises two base walls, a proximal side wall, a distal side wall and a first liner capable of being folded, collapsed, or rolled up, which, when assembled into a photobioreactor, comprises a cavity defined by: a substantially V-shaped base comprising: the base walls, the base walls meeting proximate to an axis defining an interior angle, each base wall comprising: a sloped portion and a substantially vertical portion, a proximal end and a distal end, and a length extending along the axis and a width extending perpendicular to the axis; and the cavity being further defined by: the proximal side wall, disposed adjacent to the proximal end, and the distal side wall, disposed adjacent to the distal end.

[0013] In another aspect, a kit for assembling a photobioreactor is disclosed which comprises a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel; a proximal side wall; a distal side wall; and a first liner capable of being folded, collapsed, or rolled up; which, when assembled into a photobioreactor, comprises a cavity defined by: the contoured base, the contoured base comprising: a first substantially vertical portion; a first sloped portion; a second sloped portion; a third sloped portion; a fourth sloped portion; a second substantially vertical portion; wherein the first sloped portion and the second sloped portion meet proximate to a first axis defining a first interior angle; wherein the first sloped portion and the second sloped portion define a first

substantially V-shaped feature defining a first depth; wherein the third sloped portion and the fourth sloped portion meet proximate to a second axis defining a second interior angle; and wherein the third sloped portion and the fourth sloped portion define a second substantially V-shaped feature defining a second depth; the contoured base further comprising a length extending along the axes and a width extending perpendicular to the axes; the cavity further defined by the proximal side wall, disposed adjacent to the proximal end; and the distal side wall, disposed adjacent to the distal end.

[0014] In another aspect, a method of producing a biomass is disclosed which comprises dispensing a biomass culture medium in a photobioreactor, the photobioreactor comprising: a cavity defined by: a substantially V-shaped base comprising: two base walls, the base walls meeting proximate to an axis defining an interior angle, each base wall comprising: a sloped portion and a substantially vertical portion, a proximal end and a distal end, and a length extending along the axis and a width extending perpendicular to the axis; the cavity being further defined by: a proximal side wall adjacent to the proximal end, and a distal side wall adjacent to the distal end; the photobioreactor system further comprising: at least one gas delivery system disposed within the cavity and extending parallel to the axis, and at least one carbon dioxide delivery system disposed within the cavity and extending parallel to the axis; and the method further comprising supplying a gas through the gas delivery system, producing bubbles having diameters between about 1 and about 3 mm, and supplying carbon dioxide through the carbon dioxide delivery system, producing bubbles having diameters between about 0.001 and about 500 microns.

[0015] In another aspect, a method of producing a biomass is disclosed which comprises dispensing a biomass culture medium in a photobioreactor, the photobioreactor comprising: a cavity defined by: a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel, the contoured base comprising: a first substantially vertical portion; a first sloped portion; a second sloped portion; a third sloped portion; a fourth sloped portion; a second substantially vertical portion; wherein the first sloped portion and the second sloped portion meet proximate to a first axis defining a first interior angle; wherein the first sloped portion and the second sloped portion define a first substantially V-shaped feature defining a first depth; wherein the third sloped portion and the fourth sloped portion meet proximate to a second axis defining a second interior angle; and wherein the third sloped portion and the fourth sloped portion define a second substantially V-shaped feature defining a second depth; the contoured base further comprising a proximal end and a distal end; and a length extending along the axes and a width extending perpendicular to the axes; the

cavity further defined by a proximal side wall adjacent to the proximal end; and a distal side wall adjacent to the distal end; the photobioreactor further comprising at least one gas delivery system disposed within the cavity and extending parallel to at least one of the first axis and the second axis; and at least one carbon dioxide delivery system disposed within the cavity and extending parallel to at least one of the first axis and the second axis; the method further comprising supplying a gas through the gas delivery system, producing bubbles having diameters between about 1 and about 3 mm; and supplying carbon dioxide through the carbon dioxide delivery system, producing bubbles having diameters between about 0.001 and about 500 microns.

[0016] The V-trough PBR systems disclosed herein concentrate settleable material at an axis, and apply gas at the same point for mixing and keeping materials and algae in suspension. This system of agitation also serves to bring algae to the surface, where light penetration may be focused for increased productivity. The geometric shape of the V defines the axis where solids would otherwise concentrate. These V-trough PBR systems are more efficient and require less energy for mixing because the culture medium is concentrated along the axis at the bottom of the V, creating a specific location where application of agitation is most efficient. This allows the system to be run in a semi-continuous or continuous mode, which decreases downtime, labor and energy that would otherwise be required to keep the system running efficiently, and thus resulting in improved total annual productivity.

Glossary

[0017] As used herein, the term “productivity” refers to a standing biomass concentration for a batch harvest, or the daily biomass generated per given volume for a semi-continuously or continuously operated PBR. Productivity is a function of the amount of light, carbon dioxide, and nutrients that the biomaterials receive.

[0018] As used herein, the term “light” generally refers to photosynthetically active radiation (PAR), which can come in the form of unseparated wavelengths of light (such as sunlight), or selected wavelengths of light. Light can be natural or supplied by other means, such as light emitting diodes (LEDs) or micro-LEDs. In some embodiments, light is separated into selected wavelengths by coatings, coverings or films on or incorporated in PBR covers, tubing, or pipes. In some embodiments, light is applied in varying intensities and photoperiods, such as in timed pattern or duty cycle caused by flashing the light source or passing the algae culture past light transmissive and light blocking materials. A duty cycle is the time that an organism spends in an active state as a fraction of the total time under consideration.

BRIEF DESCRIPTION OF THE FIGURES

- [0019] Like numerals indicate like features in the Figures included herein.
- [0020] Fig. 1 shows a perspective view schematic of an illustrative embodiment of the V-trough PBR systems disclosed herein.
- [0021] Fig. 2 shows a bird's eye view of an additional illustrative embodiment of the V-trough PBR systems disclosed herein.
- [0022] Fig. 3 shows an end-on view of the proximal side wall of an illustrative embodiment of the V-trough PBR systems disclosed herein.
- [0023] Fig. 4 shows an end-on view of the distal side wall of an illustrative embodiment of the V-trough PBR systems disclosed herein.
- [0024] Fig. 5 shows a flowchart of an illustrative embodiment of the method for growing a biomass using the V-trough PBR systems disclosed herein.
- [0025] Fig. 6 shows an end-on view of the proximal side wall of an illustrative embodiment of the V-trough PBR systems disclosed herein.
- [0026] Fig. 7 shows an exploded aspected view of an illustrative embodiment of the V-trough PBR systems disclosed herein, where the system is disassembled.
- [0027] Fig. 8 shows a perspective view schematic of an illustrative embodiment of the V-trough PBR systems disclosed herein.
- [0028] Fig. 9 shows a chart of the absorption spectrum of chlorophyll *a*.
- [0029] Fig. 10 shows a chart of the absorption spectra of chlorophyll *a* and chlorophyll *b*.
- [0030] Fig. 11 shows a perspective view schematic of an illustrative embodiment of the V-trough PBR systems disclosed herein.
- [0031] Fig. 12 shows a perspective view schematic of an illustrative embodiment of the V-trough PBR systems disclosed herein.

DETAILED DESCRIPTION

[0032] In one aspect, a photobioreactor is disclosed which comprises a cavity defined by: a substantially V-shaped base comprising: two base walls, the base walls meeting proximate to an axis defining an interior angle, each base wall comprising: a sloped portion and a substantially vertical portion, a proximal end and a distal end, and a length extending along the axis and a width extending perpendicular to the axis; the cavity being further defined by: a proximal side wall adjacent to the proximal end, and a distal side wall adjacent to the distal end; and the photobioreactor system further comprising: at least one gas delivery system

disposed within the cavity and extending parallel to the axis, and at least one carbon dioxide delivery system disposed within the cavity and extending parallel to the axis.

[0033] In some embodiments, the base walls comprise a curved transition between the sloped portion and the substantially vertical portion.

[0034] In some embodiments, the interior angle is between about 60 and about 140 degrees.

[0035] In another aspect, a photobioreactor is disclosed which comprises a cavity defined by: a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel, the contoured base comprising: a first substantially vertical portion; a first sloped portion; a second sloped portion; a third sloped portion; a fourth sloped portion; a second substantially vertical portion; wherein the first sloped portion and the second sloped portion meet proximate to a first axis defining a first interior angle; wherein the first sloped portion and the second sloped portion define a first substantially V-shaped feature defining a first depth; wherein the third sloped portion and the fourth sloped portion meet proximate to a second axis defining a second interior angle; and wherein the third sloped portion and the fourth sloped portion define a second substantially V-shaped feature defining a second depth; the contoured base further comprising a proximal end and a distal end; and a length extending along the axes and a width extending perpendicular to the axes; the cavity further defined by a proximal side wall adjacent to the proximal end; and a distal side wall adjacent to the distal end.

[0036] In some embodiments, the photobioreactor further comprises a fifth sloped portion and a sixth sloped portion, wherein the fifth portion and the sixth sloped portion meet proximate to a third axis defining a third interior angle; and wherein the fifth sloped portion and the sixth sloped portion define a third substantially V-shaped feature defining a third depth.

[0037] In some embodiments, the contoured base further comprises at least one additional substantially V-shaped feature.

[0038] In some embodiments, the first interior angle and the second interior angle are each independently between about 60 and about 140 degrees. In some embodiments, the first interior angle and the second interior angle are the same. In some embodiments, the first interior angle and the second interior angle are different.

[0039] In some embodiments, the first depth of the first substantially V-shaped feature is the same as the depth of the second substantially V-shaped feature. In some embodiments, the first depth of the first substantially V-shaped feature is different from the depth of the second substantially V-shaped feature.

[0040] In some embodiments, the first interior angle, the second interior angle and the third interior angle are each independently between about 60 and about 140 degrees. In some embodiments, at least two of the first interior angle, the second interior angle and the third interior angle are the same. In some embodiments, at least two of the first interior angle, the second interior angle and the third interior angle are different.

[0041] In some embodiments, at least two of the first depth of the first substantially V-shaped feature, the second depth of the second substantially V-shaped feature and the third depth of the third substantially V-shaped feature are the same. In some embodiments, at least two of the first depth of the first substantially V-shaped feature, the second depth of the second substantially V-shaped feature and the third depth of the third substantially V-shaped feature are different.

[0042] In some embodiments, the substantially V-shaped feature most proximate to the first substantially vertical portion and the substantially V-shaped feature most proximate to the second substantially vertical portion define depths greater than at least one of the other substantially V-shaped features. In further embodiments, the substantially V-shaped feature most proximate to the first substantially vertical portion and the substantially V-shaped feature most proximate to the second substantially vertical portion define interior angles smaller than at least one of the other substantially V-shaped features.

[0043] In some embodiments, the photobioreactor further comprises at least one gas delivery system disposed within the cavity and extending parallel to at least one of the first axis and the second axis.

[0044] In some embodiments, the photobioreactor further comprises at least one carbon dioxide delivery system disposed within the cavity and extending parallel to at least one of the first axis and the second axis.

[0045] In some embodiments, the photobioreactor further comprises a liner disposed within the cavity.

[0046] In some embodiments, the photobioreactor further comprises a harvesting aperture through at least a portion of the proximal side wall.

[0047] In some embodiments, the photobioreactor further comprises a nutrient injection system.

[0048] In some embodiments, the gas delivery system comprises a line comprising a plurality of disposed orifices along its length to provide congruent pressure for even gas dispersion. In some embodiments, the gas delivery system comprises a line comprising a

plurality of orifices disposed along its length, the orifices comprising a major dimension ranging between about 1 mm and about 5 mm.

[0049] In some embodiments, the carbon dioxide delivery system comprises a line comprising a plurality of orifices disposed along its length, the orifices comprising a major dimension ranging between about 0.001 microns and about 1 mm.

[0050] In some embodiments, the orifices comprise at least one of perforations, pores, injection points, or apertures.

[0051] In some embodiments, the photobioreactor further comprises a slope from the proximal end to the distal end.

[0052] In some embodiments, the photobioreactor further comprises a cover.

[0053] In some embodiments, the photobioreactor further comprises a support structure, wherein at least a portion of the base is disposed on top of the support structure.

[0054] In some embodiments, the photobioreactor further comprises a culture medium comprising biomaterials disposed within the cavity.

[0055] In some embodiments, the cover further comprises a glazing material fabricated from a material selected from the group consisting of polyethylene, lexan, polycarbonate, clear vinyl, clear polyvinyl chloride, glass, or a combination thereof.

[0056] In some embodiments, the support structure comprises HDPE. In some embodiments, the support structure comprises foam.

[0057] In some embodiments, the support structure is capable of disassembly and stacking.

[0058] In some embodiments, the photobioreactor further comprises foam insulation disposed adjacent to at least a portion of the on a side opposite the cavity. In some embodiments, the foam insulation comprises the support structure.

[0059] In some embodiments, the support structure is installed in the ground.

[0060] In some embodiments, the culture medium has a stable pH. In some embodiments, the gas and carbon dioxide delivery systems are used in conjunction with pH buffers for stabilizing the pH of the culture medium.

[0061] In some embodiments, the biomaterials are harvested from the culture medium via a gravity line.

[0062] In some embodiments, a flow of gas exiting the gas delivery system provides for a mixing rate of the culture medium. In some embodiments, the culture medium is driven from the proximal end to the distal end. In some embodiments, the photobioreactor further comprises a slope from the proximal end to the distal end, wherein the slope and the mixing rate drive the culture medium in a direction from the proximal end to the distal end.

[0063] In some embodiments, the photobioreactor further comprises at least one of a fluid pumping system and an agitation system for mixing and/or circulating the culture medium.

[0064] In some embodiments, at least two of the gas delivery system, fluid pumping system and agitation systems operate to create a strategic mixing pattern.

[0065] In some embodiments, the photobioreactor further comprises a return structure for recirculating harvested fluid back to the cavity. In some embodiments, the return structure comprises at least one of piping, tubing and channels. In some embodiments, the return structure is disposed outside the cavity. In some embodiments, the return structure is disposed within the cavity.

[0066] In some embodiments, at least one of the piping, tubing and channels are transparent.

[0067] In some embodiments, light is applied to at least one of piping, tubing and channels. In some embodiments, the light is applied to at least one side of the at least one of piping, tubing and channels. In some embodiments, the light is applied to more than one side of the at least one of piping, tubing and channels.

[0068] In some embodiments, the photobioreactor further comprises a light source directed into the cavity. In some embodiments, the light source comprises LEDs or micro-LEDs. In some embodiments, the light is provided by a light source selected from at least one of LEDs and micro-LEDs. In some embodiments, the light source comprises light bars.

[0069] In some embodiments, the light is applied continuously. In some embodiments, the light is applied non-continuously.

[0070] In some embodiments, the light comprises light having wavelengths in the range of at least one of: about 600 nm to about 700 nm, about 650 nm to about 700 nm, about 620 nm to about 650 nm and about 680 nm to about 700 nm. In some embodiments, the light comprises light having wavelengths in the range of at least one of: about 400 nm to about 550 nm, about 450 nm to about 550 nm and about 400 nm to about 500 nm. In some embodiments, the light comprises light having wavelengths of at least one of about 430 nm, about 453 nm, about 643 nm, about 662 nm, 680 nm and about 700 nm.

[0071] In some embodiments, at least one of carbon dioxide, air and ozone are introduced into at least one of the piping, tubing and channels.

[0072] In some embodiments, the photobioreactor further comprises at least one of a coating, covering or film which separates light into selected wavelengths. In some embodiments, at least one of the coating, covering or film is incorporated into at least one of a cover, tubing and piping.

[0073] In another aspect, a kit for assembling a photobioreactor is disclosed which comprises two base walls, a proximal side wall, a distal side wall and a first liner capable of being folded, collapsed, or rolled up, which, when assembled into a photobioreactor, comprises a cavity defined by: a substantially V-shaped base comprising: the base walls, the base walls meeting proximate to an axis defining an interior angle, each base wall comprising: a sloped portion and a substantially vertical portion, a proximal end and a distal end, and a length extending along the axis and a width extending perpendicular to the axis; and the cavity being further defined by: the proximal side wall, disposed adjacent to the proximal end, and the distal side wall, disposed adjacent to the distal end.

[0074] In some embodiments, the base walls and the side walls comprise foam blocks.

[0075] In some embodiments, the kit further comprises a second liner which, when assembled, at least partially contains the base walls and the side walls.

[0076] In another aspect, a kit for assembling a photobioreactor is disclosed which comprises a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel; a proximal side wall; a distal side wall; and a first liner capable of being folded, collapsed, or rolled up; which, when assembled into a photobioreactor, comprises a cavity defined by: the contoured base, the contoured base comprising: a first substantially vertical portion; a first sloped portion; a second sloped portion; a third sloped portion; a fourth sloped portion; a second substantially vertical portion; wherein the first sloped portion and the second sloped portion meet proximate to a first axis defining a first interior angle; wherein the first sloped portion and the second sloped portion define a first substantially V-shaped feature defining a first depth; wherein the third sloped portion and the fourth sloped portion meet proximate to a second axis defining a second interior angle; and wherein the third sloped portion and the fourth sloped portion define a second substantially V-shaped feature defining a second depth; the contoured base further comprising a length extending along the axes and a width extending perpendicular to the axes; the cavity further defined by the proximal side wall, disposed adjacent to the proximal end; and the distal side wall, disposed adjacent to the distal end.

[0077] In some embodiments, the kit further comprises: a fifth sloped portion; and a sixth sloped portion; wherein the first fifth portion and the sixth sloped portion meet proximate to a third axis defining a third interior angle; and wherein the fifth sloped portion and the sixth sloped portion define a third substantially V-shaped feature defining a third depth.

[0078] In some embodiments, the contoured base further comprises at least one additional substantially V-shaped feature.

[0079] In some embodiments, the contoured base and the side walls comprise foam blocks.

[0080] In some embodiments, the kit further comprises a second liner which, when assembled, at least partially contains the contoured base and the side walls.

[0081] In some embodiments, the first and the second liners are folded, collapsed, or rolled up, and the support structure is disassembled.

[0082] In some embodiments, the first and the second liners are secured to one another.

[0083] In another aspect, a method of producing a biomass is disclosed which comprises dispensing a biomass culture medium in a photobioreactor, the photobioreactor comprising: a cavity defined by: a substantially V-shaped base comprising: two base walls, the base walls meeting proximate to an axis defining an interior angle, each base wall comprising: a sloped portion and a substantially vertical portion, a proximal end and a distal end, and a length extending along the axis and a width extending perpendicular to the axis; the cavity being further defined by: a proximal side wall adjacent to the proximal end, and a distal side wall adjacent to the distal end; the photobioreactor system further comprising: at least one gas delivery system disposed within the cavity and extending parallel to the axis, and at least one carbon dioxide delivery system disposed within the cavity and extending parallel to the axis; and the method further comprising supplying a gas through the gas delivery system, producing bubbles having diameters between about 1 and about 3 mm, and supplying carbon dioxide through the carbon dioxide delivery system, producing bubbles having diameters between about 0.001 and about 500 microns.

[0084] In another aspect, a method of producing a biomass is disclosed which comprises dispensing a biomass culture medium in a photobioreactor, the photobioreactor comprising: a cavity defined by: a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel, the contoured base comprising: a first substantially vertical portion; a first sloped portion; a second sloped portion; a third sloped portion; a fourth sloped portion; a second substantially vertical portion; wherein the first sloped portion and the second sloped portion meet proximate to a first axis defining a first interior angle; wherein the first sloped portion and the second sloped portion define a first substantially V-shaped feature defining a first depth; wherein the third sloped portion and the fourth sloped portion meet proximate to a second axis defining a second interior angle; and wherein the third sloped portion and the fourth sloped portion define a second substantially V-shaped feature defining a second depth; the contoured base further comprising a proximal end and a distal end; and a length extending along the axes and a width extending perpendicular to the axes; the cavity further defined by a proximal side wall adjacent to the proximal end; and a distal side

wall adjacent to the distal end; the photobioreactor further comprising at least one gas delivery system disposed within the cavity and extending parallel to at least one of the first axis and the second axis; and at least one carbon dioxide delivery system disposed within the cavity and extending parallel to at least one of the first axis and the second axis; the method further comprising supplying a gas through the gas delivery system, producing bubbles having diameters between about 1 and about 3 mm; and supplying carbon dioxide through the carbon dioxide delivery system, producing bubbles having diameters between about 0.001 and about 500 microns.

[0085] In some embodiments, the contoured base further comprises: a fifth sloped portion; and a sixth sloped portion; wherein the first fifth portion and the sixth sloped portion meet proximate to a third axis defining a third interior angle; wherein the fifth sloped portion and the sixth sloped portion define a third substantially V-shaped feature defining a third depth; wherein the at least one gas delivery system is disposed within the cavity and extending parallel to at least one of the first axis, the second axis and the third axis; and wherein the at least one carbon dioxide delivery system is disposed within the cavity and extending parallel to at least one of the first axis, the second axis and the third axis.

[0086] In some embodiments, the contoured base further comprises at least one additional substantially V-shaped feature.

[0087] In some embodiments, solids are substantially prevented from settling by flow of gas exiting the gas delivery system.

[0088] In some embodiments, the method further comprises operating an ozone sensor and control system such that ozone levels in the culture medium are maintained between about 0.5 and about 1 mg/mL.

Shape of the V-Trough

[0089] The V-shaped base of the V-trough PBR systems disclosed herein comprises an inner dimension that tapers substantially to a V at the bottom. In some embodiments, the bottom of the trough is a point (*i.e.* meeting of two flat elements). In further embodiments, the bottom of the trough is rounded. This property results in reduced dead space as compared to a flat-bottomed tank, allows for increased mixing rate of the culture medium, improved turnover of the medium and biomass within the PBRs and overall high volume, high productivity PBR systems. Absent this V-shaped base, the propensity of solids to settle at the bottom of the PBR is increased.

[0090] In further embodiments, the base of the V-trough PBR system comprises multiple tapering inner dimensions, forming a contoured base of multiple substantially V-shaped features in parallel. In some embodiments, the multiple V-shaped features define the same interior angle and depth. In some embodiments, at least one of the multiple V-shaped features defines different interior angles and/or depths as compared to other V-shaped features in the PBR system. By varying the interior angles and/or depths of the V-shaped features in the PBR system, the mixing, concentration, and/or settling of the culture disposed in the PBR system is manipulated for various purposes or strategies, such as strategic mixing patterns (*e.g.*, comprising both horizontal and vertical mixing), nutrient distribution, light availability, or contamination control. In some embodiments, the outermost V-shaped features of the PBR system are deeper and define a narrower angle than the other V-shaped features, enabling the culture to have volume harvested out of the deeper outer V-shaped features while the shallower middle V-shaped features hold a portion of the culture for mixing with new medium that is added after harvesting is concluded.

[0091] The V-shaped base defines an interior angle less than about 180° and more than about 45°. In some embodiments, the angle is between about 34° and about 140°. In some embodiments, the angle is between about 60° and about 140°. In some embodiments, the angle is between about 34° and about 120°. In some embodiments, the angle is between about 60° and about 120°. In some embodiments, the angle is between about 80° and about 112°. In some embodiments, the angle is between about 800° and about 100°. The angle depends on light source, geographic location of the PBR, the targeted biological materials, standing biomaterial concentration, and desired productivity. As the angle decreases, the total volume of the PBR decreases, assuming all other dimensions are held constant. The substantially vertical portions of the base walls can extend vertically to compensate for loss in volume as the angle decreases. In some embodiments, the vertical portions of the base walls extend a range of heights in combination with the range of interior angles to create embodiments of a plurality of different volumes.

[0092] Side walls extend upward from the V-shaped base to increase the total volume of the PBR. As the side walls extend, the volume of the PBR increases while maintaining the same footprint, given that all other dimensions are held constant. In some embodiments, the side walls extend vertically upwards. In some embodiments, the side walls extend upwards at an angle. In some embodiments, the side walls range in thickness from between about 2 to about 10 inches. In further embodiments, the side walls range in thickness from between about 4 to about 6 inches. In some embodiments, the side walls are straight. In further embodiments,

the side walls are curved. In some embodiments, the side walls and V-shaped base curve such that they form a single wall, with no discernible separation. In some embodiments, the cavity is a single formed unit.

[0093] The desired length and volume of the V-trough PBR systems disclosed herein is determined by the efficiency of heating and/or cooling capacity, and retention time of the biomaterials. The volumes of the systems are designed to harvest biomaterials before growth and productivity drop off as a function of cell longevity and cell vigor. Cell longevity and cell vigor is a function of the nature of the biomaterials, contamination in the culture, environmental parameters applied to the culture, and water chemistry parameters. In some embodiments, the V-trough PBR system is between about 15 feet and about 100 feet long. In further embodiments, the system is over 100 feet long.

[0094] The volume of the V-trough PBR systems disclosed herein are determined by a number of factors, including the angle of the V-shaped base, the dimensions of the side walls, and the overall length and width of the V-trough. Generally, for light-dependent biomaterials, productivity is increased as the volume of the PBR system decreases, due to increased mixing and exposure of the biomaterials to light. The V-trough is designed to mitigate the loss in productivity that occurs when the volume of a vessel is increased. The surface area to volume ratio of the V-trough is such that the biomaterials have a greater exposure to light, as biomaterials circulating through the PBR system will receive differing amounts of light depending on whether they are proximate to an illuminated surface or distal from it (in a “dark zone”) during circulation.

[0095] The reduction of settleable solids in the V-trough PBR systems disclosed herein provides a significant advantage over existing devices. First, the systems disclosed herein can be run in a continuous or semi-continuous mode, while existing devices require downtime and maintenance costs to remove settled solids. Further, because the system does not need to be stopped periodically, or with the frequency of existing systems, the biomass shows an improved probability of surviving at the desired productivity for a longer period of time than existing devices.

Gas Delivery System

[0096] The gas delivery systems of the V-trough PBR systems disclosed herein can be used, *inter alia*, for efficient mixing of the culture medium. The gas delivery systems are placed strategically along or near the axis defined by the bottom of the V to keep solids in suspension, and to provide improved mixing of the culture medium. Mixing rate of the culture

medium can be controlled by the gas delivery system alone, or in combination with other agitation means. In some embodiments, a fluid pumping system is used alone or in combination with the gas delivery system to mix and/or circulate the culture medium. In some embodiments, utilizing the gas delivery system, a fluid pumping system, or a combination of agitation means to mix and/or circulate the culture medium, creates a strategic mixing pattern within the V-trough PBR system to maintain and/or modify the conditions of the culture medium. Control of mixing rate and retention time of the culture medium is important so that these parameters can be varied depending on the concentration of the medium. Rate of gas injection, gas injection aperture size, gas injection aperture shape, number of gas injection apertures, placement of gas injection apertures, flow rate of pumped fluid, direction of pumped fluid, placement of pumped fluid inflow, and/or placement of pumped fluid outflow, combined with the V-shaped design drives the mixing efficiency of the system. In some embodiments, the fluid is pumped in more than one direction, which prevents the biomass in the culture medium from settling. In some embodiments, fluid is pumped in more than one direction by alternating the inlet and outlet flow. In some embodiments, alternating the inlet and outlet flow is achieved through cycling solenoid valves or a switching circuit to reverse pump rotation. In some embodiments, the fluid comprises water. In some embodiments, the fluid comprises the culture medium. Generally, for light-dependent biomaterials, a higher rate of mixing is desired to increase the amount of biomaterials coming into contact with the light, resulting in greater productivity. In some embodiments, the gas comprises air. In further embodiments, the gas comprises ozone.

[0097] The gas delivery systems disclosed herein can produce gas bubbles of varying size. Bubble size affects several factors relevant to the V-trough PBR systems disclosed herein. First, larger bubbles result in more efficient mixing, while smaller bubbles mix the culture medium less efficiently. Second, larger bubbles have reduced surface area compared to smaller bubbles, resulting in less gas exchange with the culture medium. Larger bubbles thus can have less of an effect on the pH of the system, while smaller bubbles can be utilized for more efficient gas diffusion into the system. In some embodiments, bubble size is controlled by the type of gas delivery system, the pressure of the gas applied, the density of the gas being introduced into the system, and the perforation, pore, injection point, aperture or orifice size through which the gas is introduced into the culture medium. In some embodiments, the bubbles are between about 1 and about 3 mm in diameter. In some embodiments, the bubbles are between about 1 and about 3 mm in diameter, and are used primarily for mixing the culture medium. In further embodiments, the bubbles are less than about 1 mm in diameter (*i.e.* micro

bubbles). In some embodiments, the bubbles are less than about 1 mm in diameter and are used primarily for gas diffusion into the culture medium. In still further embodiments, the bubbles are between about 0.001 and about 500 microns in diameter. In some embodiments, the gas delivery systems operate at a pressure between about 1 and about 50 psi, and generate bubble size of between about 1 and about 3 mm in diameter. In some embodiments, air is applied at a bubble size of about 1 to about 3 mm to aid in mixing the medium.

[0098] In some embodiments, the culture medium in the V-trough photobioreactor systems disclosed herein is mixed and/or circulated by the gas delivery system in a strategic mixing pattern. In some embodiments, the culture medium in the V-trough photobioreactor systems disclosed herein is mixed and/or circulated in a strategic mixing pattern by a fluid pumping system comprising at least one fluid pump, at least one inflow for the pumped fluid in the V-trough, and at least one outflow for the pumped fluid in the V-trough. In some embodiments, the culture medium in the V-trough photobioreactor systems disclosed herein is mixed and/or circulated in a strategic mixing pattern by a combination of the gas delivery system and a fluid pumping system. In some embodiments, the gas exiting from the gas delivery system, the fluid flowing from a fluid pumping system, or a combination of gas and fluid, generates an upward movement of biomass and liquid phase from the axis towards the top of the system. In some embodiments, the biomass is exposed to light near the top of the circulation or mixing path. In some embodiments, the medium then circulates outwards towards the substantially vertical portions of the base walls, which in some embodiments provides for additional exposure to light. In some embodiments, the culture medium then moves down the base walls and back towards the axis, where the process is repeated continuously or semi-continuously. Further description of this type of circulation is found in U.S. Patent No. 5,846,816 to Forth, the contents of which is incorporated herein by reference in its entirety. By creating strategic mixing patterns both horizontally and vertically within the V-trough, the benefits to the biomass in the culture medium include: an increase in frequency of times the biomass is circulated into portions of the V-trough where light is available for photosynthetic activity; an increase in the amount of biomass maintained in suspension where more light, nutrients, and gases are available; and a decrease in biomass settling on surfaces of the V-trough where less light, nutrients, and gases are available.

[0099] In some embodiments, the gas delivery system uses positive pressure to prevent infiltration of water and other components into the gas delivery system. In further embodiments, perforation, pore, injection point, aperture or orifice size is selected to prevent

infiltration of molecules, such as proteins, having molecular weights less than about 30,000 Daltons.

[0100] The gas delivery systems are made of any suitable materials. In some embodiments, the gas delivery systems comprise ceramic, stainless steel, rubber, glass, or polyethylene. In some embodiments, the gas delivery system comprises a line running along the axis of the V-shaped base, perforated with perforations, pores, injection points, apertures or orifices along its length. In some embodiments, the gas delivery system comprises a gas sparging line. In some embodiments, bubbles are sparged into the medium through stainless steel, membrane and other materials having the desired perforation, pore, injection point, aperture or orifice size range. In some embodiments, the gas delivery system comprises a Graver Technologies, Glasgow, DE sintered metal filter with a 1 micron pore size that is adapted to sparging carbon dioxide into growth medium. In some embodiments, the perforations, pores, injection points, apertures or orifices comprise holes and/or slots. In some embodiments, the holes and/or slots are oriented vertically. In further embodiments, the holes and/or slots are oriented at an angle to improve mixing of the medium. In some embodiments, the holes and/or slots are arranged uniformly along the gas delivery system. In further embodiments, the holes and/or slots are arranged randomly along the gas delivery system. In some embodiments, holes and/or slots are oriented both vertically and at an angle. In some embodiments, the line or lines comprise perforations, pores, injection points, apertures or orifices strategically placed along their length to achieve consistent and congruent pressure along the line for even gas dispersion. In some embodiments, the gas delivery systems comprise micro-pore diffusers. In some embodiments, the perforations, pores, injection points, apertures or orifices comprise gas injection ports.

[0101] In some embodiments, a single gas delivery system is present in each V-trough PBR system. In some embodiments, the system comprises a single line perforated with perforations, pores, injection points, apertures or orifices. In further embodiments, the V-trough PBR systems disclosed herein comprise multiple gas delivery systems. In some embodiments, the system comprises an array of lines perforated with perforations, pores, injection points, apertures or orifices. In some embodiments, the gas delivery system comprises at least one terminal through at least a portion of one of the side walls defining the cavity of the V-trough PBR systems disclosed herein.

[0102] In some embodiments where ozone is delivered to the V-trough PBR systems disclosed herein, ozone is provided at levels that do not harm the biomass, but kill or inhibit the growth of contaminants or predators. In some embodiments, ozone is delivered by a separate

line than other gases. In some embodiments, ozone is delivered by the same line as other gases. In some embodiments, ozone is applied constantly. In further embodiments, ozone is applied prophylactically, to prevent contamination rates reaching detrimental levels in the culture. The amount and timing of the ozone application for sterilization of the culture is determined by the contaminant in question. In some embodiments, ozone is applied at levels between about 0.5 and about 1 mg/L for sterilizing viable cultures without effecting the targeted biomass.

Carbon Dioxide Delivery System

[0103] The carbon dioxide delivery systems of the V-trough PBR systems disclosed herein are separated from the gas delivery systems. Carbon dioxide is required for the growth of many culture media, such as algae, and thus serves as a carbon source. The separation of carbon dioxide and gas delivery systems have the advantage over, *e.g.*, a single system which delivers carbon dioxide-enriched air, by being able to optimize mixing and carbon source separately.

[0104] The carbon dioxide delivery systems disclosed herein can produce carbon dioxide bubbles of varying size. As with other gasses, carbon dioxide bubble size affects several factors relevant to the V-trough PBR systems disclosed herein. First, carbon dioxide bubbles can contribute to mixing of the system, and, as with other gasses, larger bubbles result in more efficient mixing, while smaller bubbles mix the culture medium less efficiently. Second, smaller carbon dioxide bubbles have increased surface area compared to larger bubbles, resulting in more gas exchange with the culture medium and more efficient delivery of the carbon source to the culture medium. This can also affect the pH of the system. In some embodiments, bubble size is controlled by the type of gas delivery system, the pressure of the gas applied, the density of the gas being introduced into the system, and the perforation, pore, injection point, aperture or orifice size of the through which the gas is introduced into the culture medium. In some embodiments, the bubbles are between about 1 and about 3 mm in diameter. In some embodiments, the bubbles are between about 1 and about 3 mm in diameter, and are used primarily for mixing the culture medium. In further embodiments, the bubbles are less than about 1 mm in diameter (*i.e.* micro bubbles). In some embodiments, the bubbles are less than about 1 mm in diameter and are used primarily for gas diffusion into the culture medium. In still further embodiments, the bubbles are between about 0.001 and about 500 microns in diameter for high efficiency gas exchange. In some embodiments, the gas delivery

systems operate at a pressure between about 1 and about 50 psi, and generate bubble size of between about 1 and about 3 mm in diameter.

[0105] In some embodiments, carbon dioxide is applied at a bubble size of less than about 1 mm for efficient gas exchange for enhancing photosynthesis. In some embodiments, carbon dioxide bubbles are presented in the micron to sub-micron range. For example, the surface area of ten 100 micron diameter bubbles is 1,000 times the surface area of a bubble having a diameter of 1 mm. The result is an exponential increase in dissolved carbon dioxide into the surrounding liquid medium as bubble size reduces.

[0106] In some embodiments, carbon dioxide is applied at a rate and bubble size, relative to the concentration of carbon dioxide-consuming biomaterials in the system. In these embodiments, carbon dioxide is supplied relative to the biomass concentration in the system for maximum efficiency. In some embodiments, as the standing biomass concentration increases, the amount of carbon dioxide required for beneficial growth also increases.

[0107] In some embodiments, the carbon dioxide delivery systems are disposed adjacent to the gas delivery systems. In further embodiments, the carbon dioxide delivery systems are disposed at a different location. In some embodiments, the carbon dioxide delivery systems are disposed away from the axis to provide additional mixing along the side walls.

[0108] In some embodiments, the carbon dioxide delivery system uses positive pressure to prevent infiltration of water and other components into the carbon dioxide delivery system. In further embodiments, perforation, pore, injection point, aperture or orifice size is selected to prevent infiltration of molecules, such as proteins, having molecular weights less than about 30,000 Daltons.

[0109] The carbon dioxide delivery systems are made of any suitable materials. In some embodiments, the carbon dioxide delivery system comprises a line running along the axis of the V-shaped base, perforated with perforations, pores, injection points, apertures or orifices distributed along its length. In some embodiments, the gas delivery system comprises a gas sparging line. In some embodiments, bubbles are sparged into the medium through stainless steel, membrane and other materials having the desired perforation, pore, injection point, aperture or orifice size range. In some embodiments, the gas delivery system comprises a Graver Technologies, Glasgow, DE sintered metal filter with a 1 micron pore size that is adapted to sparging carbon dioxide into growth medium. In some embodiments, the perforations, pores, injection points, apertures or orifices comprise holes and/or slots. In some embodiments, the holes and/or slots are oriented vertically. In further embodiments, the holes and/or slots are oriented at an angle to improve mixing of the medium or more efficient gas

dissolution. In some embodiments, the holes and/or slots are arranged uniformly along the carbon dioxide delivery system. In further embodiments, the holes and/or slots are arranged randomly along the carbon dioxide delivery system. In some embodiments, holes and/or slots are oriented both vertically and at an angle. In some embodiments, the line or lines comprise perforations, pores, injection points, apertures or orifices strategically placed along their length to achieve consistent and congruent pressure along the line for even gas dispersion. In some embodiments, the carbon dioxide delivery systems comprise micro-pore diffusers.

[0110] In some embodiments, a single carbon dioxide delivery system is present in each V-trough PBR system. In some embodiments, the system comprises a single line perforated with holes and/or slots. In further embodiments, the V-trough PBR systems disclosed herein comprise multiple sources of carbon dioxide for injection into the culture medium. In some embodiments, the carbon dioxide delivery system comprises one line perforated with holes and/or slots on either side of the gas delivery system. In some embodiments, the system comprises an array of lines perforated with holes and/or slots. In some embodiments, the carbon dioxide delivery system comprises at least one terminal through at least a portion of one of the side walls defining the cavity of the V-trough PBR systems disclosed herein.

[0111] The ability to independently change the bubble size of the gas and carbon dioxide delivery systems in the V-trough PBR systems disclosed herein allows for beneficial productivity of the biomass, and represents a significant advantage over existing systems.

pH Stabilizers

[0112] As disclosed above, gas and carbon dioxide affect the pH of the system. To customize and stabilize the pH of the system, pH buffers are used. The use of pH stabilizers allows gas to be used at a constant and beneficial flow rate and bubble size for maximum efficiency in mixing, while carbon dioxide is used at a constant and beneficial flow rate and bubble size to provide maximum efficiency in supplying a carbon source to the system, without the need to vary these parameters to affect the pH.

[0113] In some embodiments, the biomaterials in the V-trough PBR systems disclosed herein undergo photosynthesis, consuming carbon dioxide and producing oxygen as a byproduct, consequently affecting the pH of the system. pH stabilizers serve to stabilize the pH of the system such that the effects on pH of changing carbon dioxide and oxygen concentrations are reduced or eliminated. Exemplary pH stabilizers include calcium carbonate, magnesium, dolomite Ag, Baker's Lime, limestone, magnesium carbonate, potassium hydroxide, sodium hydroxide.

[0114] One advantage of the V-trough PBR systems disclosed herein is that there are multiple methods to control the pH of the system, including carbon dioxide flow rate and bubble size, mixing gas flow rate and bubble size, and pH buffers. This allows for an increase in, for example, carbon dioxide flow rate to provide additional carbon source to the biomass to improve productivity without the risk of a detrimental change in pH, since control of pH stabilizers allows precise control of the pH of the system. Likewise, mixing rate of the culture medium can be optimized by adjusting the flow rate and/or bubble size of the gas delivery system without the risk of a detrimental change in pH as discussed above.

Harvesting Aperture

[0115] In some embodiments, the V-trough PBR systems disclosed herein further comprise a harvesting aperture for removal of all or a portion of the biomass from the cavity. In some embodiments, the harvesting aperture is located through at least a portion of the distal side wall.

[0116] In some embodiments, harvesting is accomplished by automated injection of nutrients, trace elements, pH stabilizers and/or water into the system by the nutrient injection system described below. In some embodiments, harvesting is accomplished by gravity drainage. In further embodiments, harvesting is accomplished by a pumping system. In some embodiments, the pumping system further comprises pumping into a protein skimmer for further harvesting, washing, contamination removal, and/or dewatering in a continuous or semi-continuous system.

[0117] In some embodiments, the biomass removed from the V-trough PBR system through the harvest aperture and/or the biomass which has had contamination removed by a protein skimmer recirculates to the culture in the V-trough PBR system through a return structure. In some embodiments, the return structure is configured to recirculate the biomass culture medium. In some embodiments, the return structure comprises piping, tubing, and/or channels. In some embodiments, the return structure comprises a single pipe, tube or channel. In some embodiments, the return structure comprises multiple pipes, tubes, and/or channels. In some embodiments, the return structure is disposed outside the cavity defined by the PBR. In some embodiments, the return structure is disposed within the cavity defined by the PBR. In some embodiments, the return structure is disposed within the cavity defined by the PBR and proximate to the center of a fluid flow pattern within the PBR. In some embodiments, the return structure runs at least a portion of the length of the PBR. In some embodiments the return structure runs at least a portion of circumference of the PBR.

[0118] In some embodiments, the return structure further comprises at least one pipe configured to include an artificial lighting source along the length of the at least one pipe. In some embodiments, the artificial lighting source produces PAR. In some embodiments, the artificial lighting source comprises LEDs or micro-LEDs. In some embodiments, the artificial lighting source is run continuously. In some embodiments, the artificial lighting source is run non-continuously. In some embodiments, the artificial light source applies light at a predetermined duty cycle. In some embodiments, the return structure comprises an LED light source providing PAR disposed on the interior of the piping structure to apply PAR to the biomass culture medium within the piping structure. In some embodiments, applying PAR to the interior of the piping structure allows the biomass to engage in photosynthetic activity while returning to the PBR and to arrive at the PBR in a condition optimal to continue at a desired growth rate. In some embodiments, the piping structure disposed within the PBR further comprises an LED light source providing PAR disposed on the exterior of the piping structure to apply PAR to the biomass culture medium within the PBR. In some embodiments, the PAR emitted from the exterior of the pipe reaches biomass that is beyond the penetration depth of the ambient sunlight or other light source providing light to the PBR, and promotes photosynthetic activity within the PBR. In some embodiments, the pipe comprises a transparent material and a single LED light source providing PAR, disposed either on the interior of the pipe, the exterior of the pipe, or between two pipe walls. In some embodiments, this single LED light source provides PAR to both the biomass within the pipe and biomass within the PBR.

[0119] In some embodiments, the return structure comprises at least one pipe configured to include a device to introduce a gas into the biomass culture medium in the at least one pipe. In some embodiments, the gas is selected from the group consisting of air, carbon dioxide, and ozone. In some embodiments, at least one sensor monitoring carbon dioxide concentration and/or pH is disposed within the return structure. In some embodiments, the size of carbon dioxide bubbles and rate of producing carbon dioxide bubbles introduced into the at least one pipe is determined by feedback from at least one sensor which monitors the carbon dioxide concentration within with the biomass culture medium and/or the pH of the biomass culture medium.

Nutrient Injection System

[0120] In some embodiments, the V-trough PBR systems disclosed herein further comprise injection pumps for the addition of water, nutrients, pH stabilizers, trace elements, pH

stabilizers, and/or other components into the system. In illustrative implementations, the nutrient injection system comprises a dosing pump, a tank for supplying nutrients, and an inlet port supplied on one of the walls of the PBR. In some embodiments, the inlet port is supplied through at least a portion of the proximal side wall. In some embodiments, the nutrients are supplied via gravity flow into the V-Trough. In some embodiments where the V-trough system is in the ground, the nutrient holding containers are at ground level and gravity feed into the V-trough. In some embodiments where the V-trough system is above ground, the nutrient holding containers are placed above the level of the V-Trough for gravity feeding nutrients.

[0121] In some embodiments, the nutrient injection system provides a means for introducing nutrients, trace elements, water, pH stabilizers, and/or other components into the system. One skilled in the art is familiar with these techniques. In some embodiments, macro and micro nutrients are added to the system at rates determined by the biomass concentration of the system and the available light. Exemplary macronutrients are known to those skilled in the art, and include, but are not limited to, nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. Exemplary micronutrients are also known to those skilled in the art, and include, but are not limited to, boron, copper, iron, chlorine, manganese, molybdenum, and zinc. Exemplary trace elements include, but are not limited to, iron, magnesium, and manganese. In some embodiments, the nutrient injection system feeds from a source containing a mixture of water, nutrients, pH stabilizers and/or trace elements customized to the particular biomass being grown. In further embodiments, the nutrient injection system feeds from multiple sources containing multiple different mixtures. This allows for the separation of elements which might demonstrate undesired reactivity or physical properties, such as chemical reactions, coagulation, and/or precipitation. In some embodiments, the nutrient injection system is controlled such that the addition of water or other liquid, nutrients, pH stabilizers, trace elements, and/or other components can be independently controlled to improve the productivity of the biomass.

[0122] In some embodiments, the nutrient injection provides a carbon source to the culture for mixotrophic or heterotrophic culture growth. A mixotroph is a microorganism that can use a mix of different sources of energy and carbon, while a heterotroph is an organism that cannot fix carbon and instead uses organic carbon for growth. In some embodiments, adding a carbon source to the V-trough PBR system with a mixotrophic culture enables the algae to use the light source during the light available portions of the mixing cycle and the carbon source during the light deficient portions of the mixing cycle. In some embodiments, the carbon source added by the nutrient injection system also stabilizes the pH of the culture.

[0123] In some embodiments, the nutrient injection system comprises an aperture in at least a portion of the proximal side wall. In some embodiments, the nutrient injection system comprises a line comprising perforations, pores, injection points, apertures or orifices. In some embodiments, the nutrient injection system does not extend to the distal side wall. In some embodiments, the nutrient injection system extends less than about half the length of the cavity. In embodiments where the nutrient injection system extends less than about half the length of the cavity and comprises an aperture in at least a portion of the proximal side wall, harvesting through a distally-located harvesting aperture reduces the removal of newly or recently injected nutrients, water or pH buffers during harvest compared to harvesting through a proximally-located harvesting aperture.

Light Source

[0124] Many biomaterials used in the V-trough PBR systems disclosed herein require light to grow and produce the desired product. For light-dependent biomaterials, the amount of light received is a function of the surface area of the medium exposed to light, volume of the PBR system, and mixing of the medium within the PBR system. Consequently, a smaller angle of the V-shaped base may result in a greater exposure to light, due to decreased volume and increased mixing. However, a larger angle of the V-shaped base may also result in greater exposure to light due to increased surface area. The fluid dynamics in the V-trough PBR system creates a mixing of the medium so that the biomaterials are brought to the light for growth.

[0125] In some embodiments of the presently disclosed V-trough PBR systems, the light source is LED lights. In some embodiments, the LED lights are light bars.

[0126] In some embodiments, fluid from the V-trough is pumped through a tube or multiple tubes which are irradiated by light bars. In some embodiments, the light bars are positioned on one side of the tubes. In further embodiments, the light bars are positioned on more than one side of the tubes. In some embodiments, the light bars are positioned in pairs on opposite side of the tubes. In still further embodiments, the light bars surround the tubes.

[0127] In some embodiments, the light source emits light in the range of about 600 nm to about 700 nm. In some embodiments, the light source emits light in the range of about 650 nm to about 700 nm. In some embodiments, the light source emits light in the range of about 620 nm to about 650 nm. In further embodiments, the light source emits light in the range of about 680 nm to about 700 nm. In still further embodiments, the light source emits light in the range of about 400 nm to about 550 nm. In still further embodiments, the light source emits light in

the range of about 450 nm to about 550 nm. In some embodiments, the light source emits light in the range of about 400 nm to about 500 nm.

[0128] In some embodiments, the light source emits light over more than one of the preceding ranges or wavelengths. In some embodiments, the light source emits light at about 680 nm and about 700 nm. In some embodiments, the light source emits light at about 430 nm and about 662 nm. In further embodiments, the light source emits light at about 453 nm and about 643 nm.

[0129] In some embodiments, the ranges or wavelengths of light emitted by the light source are tailored to particular components present in the culture medium. In some embodiments, the components are carotenoids, phycobilins, phycobiliproteins, chlorophyll *a*, chlorophyll *b*, or other light absorbing molecules. In some embodiments, the carotenoid is lutein.

Materials

[0130] The V-trough PBR systems disclosed herein can be made from any suitable materials, of any appropriate thickness. Materials and thickness can depend on the desired application, particular biomaterials, growing medium, location and geographic area for production. In some embodiments, the V-trough PBR systems disclosed herein comprise plastic liners. In some embodiments, the plastic liner is high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinyl chloride (PVC), or ethylene propylene diene monomer (EPDM). In some embodiments, the plastic liner is between about 5 to about 60 mm in thickness. In some embodiments, the liners are semi-rigid. In further embodiments, the liners are completely rigid. In still further embodiments, the liners are flexible. In some embodiments, the liners are capable of being folded, collapsed, or rolled up. In some embodiments, the liners are formed in a desired shape and have resiliency to form that molded shape, but still exhibit overall flexibility.

[0131] In some embodiments, the V-trough PBR systems disclosed herein further comprise foam insulation adhered to the outside of the PBR. In some embodiments, the foam insulation provides structural support. In further embodiments, the foam insulation provides insulation which aids in the maintenance of optimum and consistent temperatures required for desired productivity of the biomass. In further embodiments, the V-trough PBR systems disclosed herein are structurally supported by metal, wood, or earth.

[0132] In some embodiments, the V-trough PBR systems disclosed herein comprise containers at least partially transparent to light, and/or which are translucent. In further

embodiments, the V-trough PBR systems disclosed herein comprise PBRs with open tops to allow light to enter.

Covered V-Trough PBR System

[0133] In some embodiments, the V-trough PBR systems disclosed herein further comprise a cover for the cavity. In some embodiments, the cover comprises a greenhouse manifold. In further embodiments, the greenhouse manifold further comprise glazing material. In some embodiments, the glazing material is fabricated from polyethylene, lexan, polycarbonate, clear vinyl, clear polyvinyl chloride, glass or any other material used for covering greenhouses and/or growth chambers, which are known to those skilled in the art. In some embodiments, the cover is affixed to the cavity. In further embodiments, the cover is held to the cavity by gravity. In some embodiments, the cover is made of a flexible material, such that gas evolution can at least partially inflate the cover, creating a positive pressure system.

[0134] In some embodiments, the cover defines an air volume present in the system. In these embodiments, the air volume affects the amount of solar irradiance, relative and absolute humidities, and ambient temperature of the air in the system. Air volume will depend on several factors, including, but not limited to, geographic location and elevation of the system. The air volume is also dependent on the relationship between the volume of water mass within the covered system, the water temperature, the air temperature outside the covered system and the air temperature inside the covered system. The air volume can be manipulated by altering the height of the covered system to meet the thermal demands of the targeted biomass to be grown, or by adjusting the flexibility of the cover.

[0135] In some embodiments, the cover comprises a flexible sheet, corrugated rigid panels, corrugated rigid multi-panels, multi-layer flexible sheets, a combination of corrugated rigid sheets and flexible films, a combination of flexible and/or rigid glazing materials that can be used for covering greenhouse and/or growth, and/or a mixture of the above. In some embodiments, the cover comprises a single layer glazing material and/or a double layer glazing material. In some embodiments, the space between the double layer glazing material comprises air or water which serves as a means of thermal insulation. In some embodiments, the space between the double layer glazing material comprises a chemical constituent that is manipulated via electrical or chemical means to change the insulation and light transmission properties of the cover.

[0136] In some embodiments, the cover comprises infrared reflective, infrared absorptive, infrared transmitting materials, and/or a combination of the foregoing for managing heat

generated from thermal stress. In further embodiments, the cover comprises wavelength-selective reflective, absorptive, transmitting materials and/or a combination of the foregoing for manipulation of the wavelengths of light that enter the system. The selection of the covering material is dependent on, *inter alia*, the targeted biomass and geographic location of the system.

[0137] In some embodiments, the cover comprises the shape of a loop, A-frame or any other version of greenhouse structures known to those skilled in the art.

[0138] In some embodiments, the covered V-trough PBR systems disclosed herein have improved capability to maintain temperature, pH, and concentrations of nutrients, trace elements and/or other components of the system.

[0139] In some embodiments, the cover comprises at least one opening or vent.

[0140] In some embodiments, the covered V-trough PBR systems disclosed herein provide improved biosecurity by isolating the biomass production system from potential vectors of contamination, such as those that can occur from the exposure to the natural elements. In embodiments where the covered PBR system is a positive pressure system, contaminants such as dust are preventing from entering the system through apertures or vents.

Other Features

[0141] In some embodiments, the V-trough PBR systems disclosed herein further comprise a harvesting aperture. In some embodiments, the harvesting aperture is disposed through at least a portion of the distal side wall.

[0142] In some embodiments, the V-trough PBR systems disclosed herein are level along their lengths, *i.e.* having a slope of 0. In further embodiments, the systems are off-level or sloped along their lengths to increase the ease of harvesting the desired product at the low end, to drive biomass from one end to a harvesting end, to assure mixing and turnover within the system, to skim the top of the culture out of the system, or to allow spill over for ease of harvesting. In some embodiments, the slope or leveling of the system is modified by grading of the land on which the system sits, or by modifying the dimensions of the structural support on which the system sits. In some embodiments, the offset of one end of the system to the other is between about 0.5 and about 6 inches. In some embodiments, a system comprising a cavity length of about 15 feet comprises an offset of about 0.5 inches. In further embodiments, a system comprising a cavity length of about 10 feet comprises an offset of about 4 to about 6 inches.

[0143] In some embodiments, the V-trough PBR systems disclosed herein further comprise temperature and/or pH sensors.

[0144] In some embodiments, the V-trough PBR systems disclosed herein further comprise controls to add water, nutrients, pH stabilizers, and further biomass to the system. In some embodiments, these controls are automated in conjunction with sensors such that productivity is optimized and held roughly constant.

[0145] In some embodiments, the V-trough PBR systems disclosed herein further comprise cooling and/or heating means. In some embodiments, the cooling and/or heating means comprise at least one heat exchanger. In further embodiments, the cooling and/or heating means comprise pan and fan evaporative cooling systems. Such systems are known to those of skill in the art, and are described in Bucklin, et al., *Fan and Pad Greenhouse Evaporative Cooling Systems*, Univ. of Fla. Dept. of Agric. and Biological Eng'g, Fla. Coop. Extension Serv., Inst. of Food and Agric. Sci. Circular 1135, Dec. 1993, *available at* <http://edis.ifas.ufl.edu/ae069> or <http://edis.ifas.ufl.edu/pdf/ae/AE06900.pdf>, which is incorporated herein by reference in its entirety. In some embodiments, the cooling and/or heating means comprise cooling by water mist sprayed to cool the air surrounding the systems. In some embodiments where the V-trough PBR systems disclosed herein are in an enclosed structure, such as a greenhouse or the covered V-trough PBR systems disclosed herein, further cooling is achieved by natural or mechanical ventilation of the structure. In some embodiments, use of the preceding heating and/or cooling means improves and reduces the operational costs of maintaining the temperature of the culture medium in the systems disclosed herein. In some embodiments, the cooling and/or heating means comprise heating systems and/or covering materials which retain heat loss via black body radiation. In further embodiments, the V cooling and/or heating means comprise geothermal heating and/or cooling, subterranean heating and/or cooling, gas burners, air conditioners, waste heating and/or cooling from industrial sources, and/or a combination of the foregoing. In some embodiments, a combination of foam structural insulation and covering materials is utilized for maintaining diurnal temperature fluctuation.

[0146] In some embodiments, the V-trough PBR systems disclosed herein are stand-alone units. In further embodiments, the systems are dug into the ground for added stability and improved insulation for maintaining optimum and consistent temperatures required for desired productivity of the biomass.

[0147] In some embodiments, the V-trough PBR systems disclosed herein further comprise a drain for harvesting biomaterials. In some embodiments, the drain is opposite controls such

that as water, nutrients, pH stabilizers and biomass are added to the system, water is forced out of the drain. In some embodiments, the drain is on the proximal wall, while the controls are on the distal wall. In further embodiments, the drain is on the distal wall, while the controls are on the proximal wall.

[0148] In some embodiments, airlift technology is used to pump water into or out of the system via the gas and carbon dioxide delivery systems. In further embodiments, airlift technology is used to pump water into or out of the system via a separate system. In some embodiments, airlift technology is used to mix and/or circulate the culture medium within the V-trough PBR system via a fluid pumping system. As known by those skilled in the art, airlift technology is a process used in aquaculture for moving water via air. The concept behind the process is to inject air into water at a point in a pipe and/or vessel where the buoyancy of the bubble lifts the water to the desired area. The rate of flow is determined by the air flow into the vessel, the density of the air or gas used, the density of the water, and the diameter or size of the vessel. Air lift pumping can be more energy efficient and economical when compared to conventional means of pumping such as by centrifugal pumps.

[0149] In some embodiments, the V-trough PBR systems disclosed herein breaks down into small pieces for efficient shipping. In some embodiments, the system is a turnkey system that can be delivered to a site, set up, and retrofitted with necessary components. In some embodiments, the V-trough PBR systems disclosed herein comprise a structural support, and a first liner disposed on top of the structural support which comprises the cavity of the system. In some embodiments, the support structure is foam. In some embodiments, the support structure comprises stackable pieces which can be broken down to facilitate shipment. In some embodiments, the support structure comprises foam blocks. In further embodiments, the system further comprises a second liner which at least partially contains the support structure. In some embodiments, the second liner helps maintain the shape of the support structure. In some embodiments, the first and second liners are secured to one another. In some embodiments, the liners are secured by friction. In further embodiments, the liners are secured by mechanical means. In still further embodiments, the liners are secured by chemical means. In some embodiments, the liners are secured by clamps or adhesives. In some embodiments, the liners are secured by heating. In some embodiments, the support structure is broken down and stacked, and the first and/or second liners are folded, collapsed, or rolled up to facilitate shipment. The ability to break down and fold, collapse or roll up the separate components of the V-trough PBR systems disclosed herein facilitates more efficient shipment by conventional means, where the structural support can be assembled onsite, either by itself or at least partially

contained within the unrolled, uncollapsed or unfolded second liner to help maintain its shape, and the first liner placed on the support to form the cavity.

[0150] In some embodiments, the V-trough PBR systems disclosed herein further comprise light reflecting means which increase the amount of light directed into the system.

[0151] In some embodiments, the V-trough PBR systems disclosed herein further comprise gravity lines. In some embodiments, the gravity lines are used for harvesting biomass or introducing water, nutrients, trace elements and/or pH stabilizers without the use of a pump. In the foregoing embodiments, biomass can be harvested from, or water, nutrients, trace elements pH stabilizers and/or other components can be introduced into the culture medium by varying the elevation of the gravity line and/or fluid source with respect to the PBR system.

Automated Sensor and Control Systems

[0152] Some embodiments of the V-trough PBR systems disclosed herein further comprise a sensor and control system for maintaining and modifying conditions within the V-trough PBR system. Such systems are known by those skilled in the art. In some embodiments, the sensor and control system monitors the conditions in the PBR system and controls various components of the PBR system via computer, data logger, programmable logic control, any other type of real time monitoring and control system, or any combination thereof. In some embodiments, the sensor and control systems disclosed herein comprise at least one sensor and/or at least one control.

[0153] In some embodiments, the sensor and control system comprises a data logging system that is equipped with sensors and controls which monitor and control various aspects of the V-trough PBR systems disclosed herein. In some embodiments, the data logging system comprises a National Instruments, Campbell Scientific, and/or Allen-Bradley product, or a combination of the foregoing.

[0154] In some embodiments of the V-trough PBR systems disclosed herein, the sensors disclosed herein comprise temperature, carbon dioxide, ozone, dissolved oxygen, light, relative humidity, air speed, pH, chlorophyll *a*, phycobilins, turbidity, optical density and/or electrical conductivity sensors, or any combination of the foregoing. In some embodiments, the sensors comprise Campbell Scientific, Honeywell, YSI, National Instruments, and/or Hanna Instruments products, or a combination of the foregoing. In some embodiments, real-time feedback from the sensors is analyzed by software uploaded to the data logger equipment. In some embodiments, real-time feedback from the sensors is processed and control systems are adjusted according to set points and applications set forth in the software program. In some

embodiments, environmental set points are determined with reference for favorable growing conditions of the targeted biomass. In some embodiments, the sensor systems are wireless systems, reducing the need for wires and other materials.

[0155] In some embodiments, the sensor and control system is run in a continuous or semi-continuous mode. In further embodiments, the sensor and control system is run to adjust and maintain selected parameters within predetermined limits to provide a beneficial environment for the selected biomass. In some embodiments, the sensor and control system controls the amount of light and standing biomass concentration in the system to improve the productivity of the system.

[0156] In some embodiments, the sensors disclosed herein monitor air temperature and humidity and the controls disclosed herein adjust these properties using cooling and/or heating means. In some embodiments, the sensors disclosed herein monitor the temperature of the culture medium and the controls disclosed herein control the heating and/or cooling system to maintain and/or control the temperature.

[0157] In some embodiments where the V-trough PBR system is covered, the sensors disclosed herein monitor the carbon dioxide and dissolved oxygen in the air space to determine the amount of gas that leaves the system.

[0158] In some embodiments, the sensors disclosed herein monitor the pH of the culture medium and the controls disclosed herein maintain and/or adjust desired pH thresholds of the culture medium for the targeted biomass. In some embodiments, the controls disclosed herein maintain or adjust desired pH thresholds by stabilizing or adjusting the pH of the culture medium by adjusting or maintaining a combination of the flow rate and bubble size of gas and carbon dioxide introduced into the system, the addition of pH stabilizers, and/or other factors, or a combination of the foregoing.

[0159] In some embodiments, the sensors disclosed herein monitor chlorophyll *a* and/or phycobilin concentration in the culture medium to determine the amount of biomass in the system. Chlorophyll *a* and phycobilins are photo-harvesting pigments in algae and cyanobacteria. If cyanobacteria is not the biomass that is targeted for production, then the phycobilin concentration can be used to determine the amount of cyanobacteria contamination within the system.

[0160] In some embodiments, the sensors disclosed herein monitor the amount of light entering the PBR system, and the controls disclosed herein adjust or maintain the harvest rate to compensate for the amount of light that is entering the system. In some embodiments, light

sensors and controls enable the operation of the PBR system at a desired productivity as determined by the light level.

[0161] In some embodiments, the sensors disclosed herein comprise one or more turbidity sensors, chlorophyll *a* sensors and/or optical density sensors. In these embodiments, the foregoing sensors are utilized individually or in conjunction with one another to measure real-time biomass concentrations in the system. In some embodiments, the controls disclosed herein utilize the real-time biomass concentration measurements determined by the sensors disclosed herein to control the harvest rate, nutrient injection rate, contamination rate, or a combination of the foregoing. In these embodiments, the controls disclosed herein initiate nutrient injection and/or harvesting depending on the productivity in the system. In some embodiments, electrical conductivity sensors measure the salt content of the water, and the controls disclosed herein provide salinity and fertilizer salts in the system to adjust to the desired concentration. In some embodiments, the controls disclosed herein maintain or adjust the nutrient injection rate based on electrical conductivity measurements made by the sensors disclosed herein. In these embodiments, a desired or target electrical conductivity level is determined relative to the targeted biomass for production.

[0162] In some embodiments, sensors disclosed herein measure contamination of the medium by the productivity rate of the PBR system and the difference between the turbidity and chlorophyll *a* concentration in the system. In some embodiments, contamination is monitored by one or more phycobilin sensors, where the targeted biomass is not a cyanobacteria. In some embodiments, the controls disclosed herein apply contamination treatments the PBR system to maintain desired productivity by killing, inhibiting or reducing the concentration of potential contaminants that inhibit or effect biomass productivity. In some embodiments, ozone is applied to the system to prevent contamination. In further embodiments, ozone is applied prophylactically, to prevent contamination rates reaching detrimental levels in the culture. The amount and timing of the ozone application for sterilization of the culture is determined by the contaminant in question. In some embodiments, ozone is applied at levels between about 0.5 and about 1 mg/L for sterilizing viable cultures without effecting the targeted biomass. In some embodiments, the sensor and control system comprises an ozone sensor and control for ozone application, wherein ozone is adjusted and maintained within a predetermined range to prevent contamination rates from reaching detrimental levels in the culture. In some embodiments, ozone is adjusted and maintained between about 0.5 and about 1 mg/L of culture. In some embodiments, ozone

levels between about 0.5 and about 1 mg/L are sufficient to kill or prevent the growth of contaminants, but will not harm biomaterials such as *Nannochloropsis*.

[0163] The Figures that follow demonstrate how the full spectrum of solar radiation can be used by splitting the full spectrum into selected and non-selected wavelengths of radiation.

[0164] Fig. 1 shows an illustrative embodiment of the V-trough PBR systems disclosed herein, where substantially V-shaped base **100** (comprising two base walls **125** with sloped portions **135** and substantially vertical portions **140**), proximal side wall **130** and distal side wall **160** define cavity **145**. Fig. 1 also shows sloped portions **135** of base walls **125** meeting proximate to axis **190**, along which gas delivery system **170** lies, which base walls further define interior angle **195**. Fig. 1 further shows two carbon dioxide delivery systems **150** disposed parallel to axis **190** and gas delivery system **170**. Fig. 1 still further shows carbon dioxide delivery systems **150** comprising carbon dioxide terminals **120** through proximal side wall **130**, and gas delivery system **170** comprising gas delivery terminal **110** also through proximal side wall **130**. Fig. 1 also shows that the system further comprises apertures **180** through proximal side wall **130**, which may be apertures for a nutrient injection system.

[0165] Fig. 2 shows another illustrative embodiment of the V-trough PBR systems disclosed herein, where nutrient injection system **260** feeds from nutrient solutions **200** and **210**, as well as pH stabilizer **220** to inject these components through proximal side wall **130**. Fig. 2 shows that the system further comprises gas delivery system **170**, carbon dioxide delivery systems **150**, sensors **230** (distributed at three different positions along base wall **125**), and a harvesting aperture **240** through distal side wall **160**, feeding to harvesting receptacle **250**.

[0166] Fig. 3 shows another illustrative embodiment of the V-trough PBR systems disclosed herein, looking end on at proximal side wall **130**, where sloped portions **135** and substantially vertical portions **140** of base walls **125**, proximal side wall **130** and the distal side wall (not pictured) define cavity **145**. Fig. 3 also shows sloped portions **135** of base walls **125**, which define interior angle **195**, cover **300**, and culture medium **310**. Fig. 3 also shows carbon dioxide delivery systems **150**, separated from gas delivery system **170**, and nutrient injection apertures **180** through proximal side wall **130**. Further, Fig. 3 shows support structure **320**.

[0167] Fig. 4 shows another illustrative embodiment of the V-trough PBR systems disclosed herein, looking end on at distal side wall **160**, where sloped portions **135** and substantially vertical portions **140** of base walls **125**, the proximal side wall (not pictured) and distal side wall **160** define cavity **145**. Fig. 4 further shows sloped portions **135** of base walls **125** defining interior angle **195**, and also shows harvesting aperture **240** through distal side wall **160**. Further, Fig. 4 shows support structure **320**.

[0168] Fig. 5 shows a flowchart of an illustrative embodiment of the method for growing a biomass using the V-trough PBR systems disclosed herein wherein biomass is dispensed into a PBR **500**, gas is supplied for mixing **510** via a gas delivery system, carbon dioxide is supplied **520** through a carbon dioxide delivery system, light is delivered **530** for biomass growth, and the biomass is harvested **540**. Fluid may also be supplied for mixing via a fluid pumping system (not shown).

[0169] Fig. 6 shows an end-on view of the proximal side wall of an illustrative embodiment of the V-trough PBR systems disclosed herein which illustrates the circulation pattern **620** on one side of the system (circulation pattern on the other side not shown). Fig. 6 shows gas bubbles **610** as the major contributor to circulation, with carbon dioxide bubbles **600** additionally contributing, but less significantly.

[0170] Fig. 7 shows an exploded aspected view of an illustrative embodiment of the V-trough PBR systems disclosed herein, where disassembled system comprises a molded liner **700** defining cavity **145**, which is ready for assembly with proximal side wall **130**, distal side wall **160** and base walls **125**.

[0171] Fig. 8 shows an illustrative embodiment of the V-trough PBR systems disclosed herein, where pump **810** is configured to pump a liquid (*e.g.*, culture medium) from V-shaped cavity **145**, to outlets **821** and **822**. In one embodiment, pump **810** pulls a liquid out of cavity **145** through suction piping **840**, through tubes **820** to one or more of outlets **821** and **822** and back into V-shaped cavity **145**. In other embodiments, pump **810** is configured to pump a liquid from inlet **821** to outlet **822**, or vice versa, back into cavity **145**. In still further embodiments, pump **810** is configured to pump a liquid from one or more of inlets **821** and **822** through suction piping **840** and back into cavity **145**. Light bars **830** and **831** emit light at selected wavelengths to irradiate the liquid as it passes through tubes **820**. In the depicted embodiment, two sets of light bars **831** and **832** are in place, on opposite sides of tubes **820**.

[0172] Fig. 9 shows a chart of the absorption spectrum of chlorophyll *a*, where the approximate absorbance maxima are at about 430 nm and about 662 nm.

[0173] Fig. 10 shows a chart of the absorption spectra of chlorophyll *a* and chlorophyll *b*, where the approximate absorbance maxima of chlorophyll *a* are at about 430 nm and about 662 nm, and the approximate absorbance maxima of chlorophyll *b* are at about 453 nm and about 642 nm.

[0174] Fig. 11 shows an illustrative embodiment of the V-trough PBR systems disclosed herein, where base **100** (comprising two base walls **125** with a multitude of sloped portions **1100** defining a contoured base of multiple substantially V-shaped features **1130** in parallel and

substantially vertical portions **140**), proximal side wall **130**, distal side wall **160** define cavity **145**. Fig. 11 also shows sloped portions **1100** of base walls **125** meeting proximate to axes **1110**, which sloped portions further define interior angles **1120**, which in the depicted embodiment are all equal to 60 °.

[0175] Fig. 12 shows an illustrative embodiment of the V-trough PBR systems disclosed herein, where base **100** (comprising two base walls **125** with a multitude of sloped portions **1200** defining a contoured base of multiple substantially V-shaped features **1230** in parallel and substantially vertical portions **140**), proximal side wall **130**, distal side wall **160** define cavity **145**. Fig. 11 also shows sloped portions **1200** of base walls **125** meeting proximate to axes **1210**, which sloped portions further define interior angles **1220**, which in the depicted embodiment are all equal to 80 °.

EQUIVALENTS

[0176] Those skilled in the art will recognize, or be able to ascertain, using no more than routine experimentation, numerous equivalents to the specific embodiments described specifically herein. Such equivalents are intended to be encompassed in the scope of the following claims.

[0177] What is claimed is:

CLAIMS

1. A photobioreactor, comprising:
 - a) a cavity defined by:
 - i) a substantially V-shaped base comprising two base walls, said base walls meeting proximate to an axis defining an interior angle, each base wall comprising:
 - 1) a sloped portion and a substantially vertical portion;
 - 2) a proximal end and a distal end; and
 - 3) a length extending along said axis and a width extending perpendicular to said axis;
 - ii) a proximal side wall adjacent to said proximal end; and
 - iii) a distal side wall adjacent to said distal end;
 - b) at least one gas delivery system disposed within said cavity and extending parallel to said axis; and
 - c) at least one carbon dioxide delivery system disposed within said cavity and extending parallel to said axis.
2. The photobioreactor of claim 1, wherein said base walls comprise a curved transition between said sloped portion and said substantially vertical portion.
3. The photobioreactor of claim 1, wherein said interior angle is between about 60 and about 140 degrees.
4. A photobioreactor, comprising:
 - a) a cavity defined by:
 - i) a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel, the contoured base comprising:
 - 1) a first substantially vertical portion;
 - 2) a first sloped portion;

- 3) a second sloped portion;
- 4) a third sloped portion;
- 5) a fourth sloped portion;
- 6) a second substantially vertical portion;

wherein said first sloped portion and said second sloped portion meet proximate to a first axis defining a first interior angle;

wherein said first sloped portion and said second sloped portion define a first substantially V-shaped feature defining a first depth;

wherein said third sloped portion and said fourth sloped portion meet proximate to a second axis defining a second interior angle; and

wherein said third sloped portion and said fourth sloped portion define a second substantially V-shaped feature defining a second depth;

- 7) a proximal end and a distal end; and
 - 8) a length extending along said axes and a width extending perpendicular to said axes;
- ii) a proximal side wall adjacent to said proximal end; and
 - iii) a distal side wall adjacent to said distal end.

5. The photobioreactor of claim 4, further comprising:

- 1) a fifth sloped portion; and
- 2) a sixth sloped portion;

wherein said fifth portion and said sixth sloped portion meet proximate to a third axis defining a third interior angle; and

wherein said fifth sloped portion and said sixth sloped portion define a third substantially V-shaped feature defining a third depth.

6. The photobioreactor of any one of claims 4-5, said contoured base further comprising at least one additional substantially V-shaped feature.

7. The photobioreactor of claim 4, wherein said first interior angle and said second interior angle are each independently between about 60 and about 140 degrees.
8. The photobioreactor of any one of claims 4 or 7, wherein said first interior angle and said second interior angle are the same.
9. The photobioreactor of any one of claims 4 or 7, wherein said first interior angle and said second interior angle are different.
10. The photobioreactor of any one of claims 4 or 7-9, wherein said first depth of said first substantially V-shaped feature is the same as the second depth of said second substantially V-shaped feature.
11. The photobioreactor of any one of claims 4 or 7-9, wherein said first depth of said first substantially V-shaped feature is different from the second depth of said second substantially V-shaped feature.
12. The photobioreactor of claim 5, wherein said first interior angle, said second interior angle and said third interior angle are each independently between about 60 and about 140 degrees.
13. The photobioreactor of any one of claims 5 or 12, wherein at least two of said first interior angle, said second interior angle and said third interior angle are the same.
14. The photobioreactor of any one of claims 5 or 12, wherein at least two of said first interior angle, said second interior angle and said third interior angle are different.
15. The photobioreactor of any one of claims 5 or 12-14, wherein at least two of said first depth of said first substantially V-shaped feature, said second depth of said second substantially V-shaped feature and said third depth of said third substantially V-shaped feature are the same.
16. The photobioreactor of any one of claims 5 or 12-14, wherein at least two of said first depth of said first substantially V-shaped feature, said second depth of said second substantially V-shaped feature and said third depth of said third substantially V-shaped feature are different.
17. The photobioreactor of any one of claims 5-6 or 12-16, wherein the substantially V-shaped feature most proximate to said first substantially vertical portion and the substantially V-shaped feature most proximate to said second substantially vertical

portion define depths greater than at least one of the other substantially V-shaped features.

18. The photobioreactor of any one of claims 5-6 or 12-17, wherein the substantially V-shaped feature most proximate to said first substantially vertical portion and the substantially V-shaped feature most proximate to said second substantially vertical portion define interior angles smaller than at least one of the other substantially V-shaped features.
19. The photobioreactor of any one of claims 4-18, further comprising:
at least one gas delivery system disposed within said cavity and extending parallel to at least one of said first axis and said second axis.
20. The photobioreactor of claim 4-19, further comprising:
at least one carbon dioxide delivery system disposed within said cavity and extending parallel to at least one of said first axis and said second axis.
21. The photobioreactor of any preceding claim, further comprising a liner disposed within said cavity.
22. The photobioreactor of any preceding claim, further comprising a harvesting aperture through at least a portion of said proximal side wall.
23. The photobioreactor of any preceding claim, further comprising a nutrient injection system.
24. The photobioreactor of any one of claims 1-3 or 19-23, wherein said gas delivery system comprises a line comprising a plurality of disposed orifices along its length to provide congruent pressure for even gas dispersion.
25. The photobioreactor of any one of claims 1-3 or 19-24, wherein said gas delivery system comprises a line comprising a plurality of orifices disposed along its length, said orifices comprising a major dimension ranging between about 1 mm and about 5 mm.
26. The photobioreactor of any one of claims 1-3 or 20-23, wherein said carbon dioxide delivery system comprises a line comprising a plurality of orifices disposed along its length, said orifices comprising a major dimension ranging between about 0.001 microns and about 1 mm.

27. The photobioreactor of any one of claims 24-26, wherein said orifices comprise at least one of perforations, pores, injection points, or apertures.
28. The photobioreactor of any preceding claim, further comprising a slope from said proximal end to said distal end.
29. The photobioreactor of any preceding claim, further comprising a cover.
30. The photobioreactor of any preceding claim, further comprising a support structure, wherein at least a portion of said base is disposed on top of said support structure.
31. The photobioreactor of any preceding claim, further comprising a culture medium comprising biomaterials disposed within said cavity.
32. The photobioreactor of claim 29, said cover further comprising a glazing material fabricated from a material selected from the group consisting of polyethylene, lexan, polycarbonate, clear vinyl, clear polyvinyl chloride, glass, or a combination thereof.
33. The photobioreactor of claim 30, wherein said support structure comprises HDPE.
34. The photobioreactor of claim 30, wherein said support structure comprises foam.
35. The photobioreactor of claim 30, wherein said support structure is capable of disassembly and stacking.
36. The photobioreactor of claim 30, further comprising foam insulation disposed adjacent to at least a portion of said on a side opposite said cavity.
37. The photobioreactor of claim 30, wherein said support structure is installed in the ground.
38. The photobioreactor of claim 31, wherein said culture medium has a stable pH.
39. The photobioreactor of claim 31, wherein said biomaterials are harvested from said culture medium via a gravity line.
40. The photobioreactor of claim 31, wherein a flow of gas exiting said gas delivery system provides for a mixing rate of said culture medium.
41. The photobioreactor of claim 31, wherein said culture medium is driven from said proximal end to said distal end.
42. The photobioreactor of claim 31, wherein said gas and carbon dioxide delivery systems are used in conjunction with pH buffers for stabilizing the pH of said culture medium.

43. The photobioreactor of claim 36, wherein said foam insulation comprises said support structure.
44. The photobioreactor of claim 40, further comprising a slope from said proximal end to said distal end, wherein said slope and said mixing rate drive said culture medium in a direction from said proximal end to said distal end.
45. The photobioreactor of any one of claims 31, 38-42 or 44, further comprising at least one of a fluid pumping system and an agitation system for mixing and/or circulating said culture medium.
46. The photobioreactor of claim 45, wherein at least two of said gas delivery system, fluid pumping system and agitation systems operate to create a strategic mixing pattern.
47. The photobioreactor of any preceding claim, further comprising a return structure for recirculating harvested fluid back to the cavity.
48. The photobioreactor of claim 47, wherein the return structure comprises at least one of piping, tubing and channels.
49. The photobioreactor of any one of claims 47-48, wherein the return structure is disposed outside the cavity.
50. The photobioreactor of any one of claims 47-48, wherein the return structure is disposed within the cavity.
51. The photobioreactor of any one of claims 48-50, wherein at least one of the piping, tubing and channels are transparent.
52. The photobioreactor of claim 51, wherein light is applied to at least one of piping, tubing and channels.
53. The photobioreactor of claim 52, wherein the light is applied to at least one side of the at least one of piping, tubing and channels.
54. The photobioreactor of claim 52, wherein the light is applied to more than one side of the at least one of piping, tubing and channels.
55. The photobioreactor of claim 52, wherein the light is provided by a light source selected from at least one of LEDs and micro-LEDs.
56. The photobioreactor of claim 55, wherein the light source comprises light bars.

57. The photobioreactor of any one of claims 52-56, wherein the light is applied continuously.
58. The photobioreactor of any one of claims 52-56, wherein the light is applied non-continuously.
59. The photobioreactor of any preceding claim, further comprising a light source directed into said cavity.
60. The photobioreactor of claim 59, wherein the light source comprises LEDs or micro-LEDs
61. The photobioreactor of any one of claims 51-60, wherein the light comprises light having wavelengths in the range of at least one of: about 600 nm to about 700 nm, about 650 nm to about 700 nm, about 620 nm to about 650 nm and about 680 nm to about 700 nm.
62. The photobioreactor of any one of claims 51-61, wherein the light comprises light having wavelengths in the range of at least one of: about 400 nm to about 550 nm, about 450 nm to about 550 nm and about 400 nm to about 500 nm.
63. The photobioreactor of any one of claims 51-62, wherein the light comprises light having wavelengths of at least one of about 430 nm, about 453 nm, about 643 nm, about 662 nm, 680 nm and about 700 nm.
64. The photobioreactor of any one of claims 48-52, wherein at least one of carbon dioxide, air and ozone are introduced into at least one of the piping, tubing and channels.
65. The photobioreactor of any preceding claim, further comprising at least one of a coating, covering or film which separates light into selected wavelengths.
66. The photobioreactor of claim 65, wherein at least one of the coating, covering or film is incorporated into at least one of a cover, tubing and piping.
67. A kit for assembling a photobioreactor, comprising:
 - a) two base walls;
 - b) a proximal side wall;
 - c) a distal side wall; and
 - d) a first liner capable of being folded, collapsed, or rolled up;which, when assembled into a photobioreactor, comprises a cavity defined by:

- i) a substantially V-shaped base comprising said base walls, said base walls meeting proximate to an axis defining an interior angle, each base wall comprising:
 - 1) a sloped portion and a substantially vertical portion;
 - 2) a proximal end and a distal end; and
 - 3) a length extending along said axis and a width extending perpendicular to said axis;
 - ii) said proximal side wall, disposed adjacent to said proximal end; and
 - iii) said distal side wall, disposed adjacent to said distal end.
68. The kit of claim 67, wherein said base walls and said side walls comprise foam blocks.
69. The kit of any one of claims 67-68, further comprising a second liner which, when assembled, at least partially contains said base walls and said side walls.
70. A kit for assembling a photobioreactor, comprising:
- a) a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel;
 - b) a proximal side wall;
 - c) a distal side wall; and
 - d) a first liner capable of being folded, collapsed, or rolled up;
- which, when assembled into a photobioreactor, comprises a cavity defined by:
- i) said contoured base, said contoured base comprising:
 - 1) a first substantially vertical portion;
 - 2) a first sloped portion;
 - 3) a second sloped portion;
 - 4) a third sloped portion;
 - 5) a fourth sloped portion;
 - 6) a second substantially vertical portion;
- wherein said first sloped portion and said second sloped portion meet proximate to a first axis defining a first interior angle;

wherein said first sloped portion and said second sloped portion define a first substantially V-shaped feature defining a first depth;

wherein said third sloped portion and said fourth sloped portion meet proximate to a second axis defining a second interior angle; and

wherein said third sloped portion and said fourth sloped portion define a second substantially V-shaped feature defining a second depth;

- 7) a length extending along said axes and a width extending perpendicular to said axes;
- ii) said proximal side wall, disposed adjacent to said proximal end; and
- iii) said distal side wall, disposed adjacent to said distal end.

71. The kit of claim 70, wherein said contoured base further comprises:

- 1) a fifth sloped portion; and
- 2) a sixth sloped portion;

wherein said first fifth portion and said sixth sloped portion meet proximate to a third axis defining a third interior angle; and

wherein said fifth sloped portion and said sixth sloped portion define a third substantially V-shaped feature defining a third depth.

72. The kit of claim 71, wherein said contoured base further comprises at least one additional substantially V-shaped feature.

73. The kit of any one of claims 70-72, wherein said contoured base and said side walls comprise foam blocks.

74. The kit of any one of claims 70-73, further comprising a second liner which, when assembled, at least partially contains said contoured base and said side walls.

75. The kit of any one of claims 69 or 74, wherein said first and said second liners are folded, collapsed, or rolled up, and said support structure is disassembled.

76. The kit of any one of claims 69 or 74-75, wherein said first and said second liners are secured to one another.

77. A method of producing a biomass comprising:
- a) dispensing a biomass culture medium in a photobioreactor, the photobioreactor comprising:
 - i) a cavity defined by:
 - 1) a substantially V-shaped base comprising two base walls, said base walls meeting proximate to an axis defining an interior angle, each base wall comprising:
 - A) a sloped portion and a substantially vertical portion;
 - B) a proximal end and a distal end; and
 - C) a length extending along said axis and a width extending perpendicular to said axis;
 - 2) a proximal side wall adjacent to said proximal end;
 - 3) a distal side wall adjacent to said distal end;
 - ii) at least one gas delivery system disposed within said cavity and extending parallel to said axis; and
 - iii) at least one carbon dioxide delivery system disposed within said cavity and extending parallel to said axis;
 - b) supplying a gas through said gas delivery system, producing bubbles having diameters between about 1 and about 3 mm; and
 - c) supplying carbon dioxide through said carbon dioxide delivery system, producing bubbles having diameters between about 0.001 and about 500 microns.
78. A method of producing a biomass comprising:
- a) dispensing a biomass culture medium in a photobioreactor, the photobioreactor comprising:
 - i) a cavity defined by:
 - 1) a contoured base defining multiple tapering inner dimensions which form at least two substantially V-shaped features in parallel, the contoured base comprising:

- A) a first substantially vertical portion;
- B) a first sloped portion;
- C) a second sloped portion;
- D) a third sloped portion;
- E) a fourth sloped portion;
- F) a second substantially vertical portion;

wherein said first sloped portion and said second sloped portion meet proximate to a first axis defining a first interior angle;

wherein said first sloped portion and said second sloped portion define a first substantially V-shaped feature defining a first depth;

wherein said third sloped portion and said fourth sloped portion meet proximate to a second axis defining a second interior angle; and

wherein said third sloped portion and said fourth sloped portion define a second substantially V-shaped feature defining a second depth;

- G) a proximal end and a distal end; and
- H) a length extending along said axes and a width extending perpendicular to said axes;

2) a proximal side wall adjacent to said proximal end; and

3) a distal side wall adjacent to said distal end;

ii) at least one gas delivery system disposed within said cavity and extending parallel to at least one of said first axis and said second axis; and

iii) at least one carbon dioxide delivery system disposed within said cavity and extending parallel to at least one of said first axis and said second axis;

b) supplying a gas through said gas delivery system, producing bubbles having diameters between about 1 and about 3 mm; and

- c) supplying carbon dioxide through said carbon dioxide delivery system, producing bubbles having diameters between about 0.001 and about 500 microns.
79. The method of claim 78, wherein said contoured base further comprises:
- 1) a fifth sloped portion; and
 - 2) a sixth sloped portion;
- wherein said first fifth portion and said sixth sloped portion meet proximate to a third axis defining a third interior angle;
- wherein said fifth sloped portion and said sixth sloped portion define a third substantially V-shaped feature defining a third depth;
- wherein said at least one gas delivery system is disposed within said cavity and extending parallel to at least one of said first axis, said second axis and said third axis; and
- wherein said at least one carbon dioxide delivery system is disposed within said cavity and extending parallel to at least one of said first axis, said second axis and said third axis.
80. The method of claim 79, wherein said contoured base further comprises at least one additional substantially V-shaped feature.
81. The method any one of claims 77-80, wherein solids are substantially prevented from settling by flow of gas exiting said gas delivery system.
82. The method of any one of claims 77-81, further comprising operating an ozone sensor and control system such that ozone levels in said culture medium are maintained between about 0.5 and about 1 mg/mL.