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- (71) **Applicant (for all designated States except US):**
COASTAL WATERS BIOTECHNOLOGY GROUP, LLC [US/US]; 811 Loma Prieta Dr., Aptos, CA 95003 (US).
- (72) **Inventor; and**
- (75) **Inventor/Applicant (for US only):** **YANCEY Jr., Dennis, Dwayne** [US/US]; 811 Loma Prieta Dr., Aptos, CA 95003 (US).
- (74) **Agents:** **KIM, Elaine A.** et al.; Wilson Sonsini Goodrich & Rosati, 650 Page Mill Road, Palo Alto, CA 94304-1050 (US).

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(54) **Title:** SYSTEM AND METHODS FOR CULTIVATING BIOMASS AND CONCENTRATING NUTRIENTS

(57) **Abstract:** Vessels that include magnetic field sources for concentrating nutrients useful for growing microorganisms are provided. Systems for growing the microorganisms include modules with various functions, such as a bioharvester module and a magneto-concentrator module. Methods for growing biomass with the aid of magnetic fields sources used to concentrate nutrients are also provided.



SYSTEMS AND METHODS FOR CULTIVATING BIOMASS AND CONCENTRATING NUTRIENTS

CROSS-REFERENCE

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/495,896, filed June 10, 2011, which is hereby incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] Petroleum, or crude oil, is a naturally occurring liquid consisting of a complex mixture of hydrocarbons of various molecular weights and other liquid organic compounds, which are found in geologic formations beneath the Earth's surface. The hydrocarbons of crude oil may be used in current combustion engines.

[0003] The supply of crude oil is limited, and methods for extracting crude oil from various reserves are process intensive. Some scientists predict that crude oil production from current reserves will peak within this century. The decline in production will adversely affect various oil-based economies.

[0004] Renewable fuel research can provide an alternative to fuel separated from crude oil. Some renewable fuel research has focused on microalgae cultivated in freshwater ponds and bioreactors because of their high yield per hectare as well as their high lipid and protein composition relative to other photoautotrophs. See, e.g., B.S. Ingole, A.H. Parulekar, (1995), "Biochemical-Composition Of Antarctic Zooplankton From The Indian-Ocean Sector," Indian Journal Of Marine Sciences 24(2): 73-76, which is hereby incorporated by reference in its entirety.

[0005] There are problems with using microalgae from land based aquacultures, ponds, and bioreactors, such as the high capital cost associated with land-based agricultures, and that high fresh water consumption, generates waste streams, is not portable, and is not readily scalable.

[0006] Microorganisms, such as algae, require nutrients for growth. These nutrients include nitrates, phosphates, and other ionic and non-ionic species.

SUMMARY OF THE INVENTION

[0007] Recognized herein is a need for improved systems and methods for cultivating biomass. A further need exists for improved systems and methods for harvesting and processing biomass.

[0008] In an aspect of the invention, a vessel comprises a semi-permeable enclosure that retains a microorganism, and a magnetic field source outside of the semi-permeable enclosure. The magnetic field source adapted to induce a magnetic force that concentrates one or more water-soluble nutrients (e.g., ions) in a fluid current for introduction into the semi-permeable enclosure. In some situations, concentrated water-soluble nutrients are directed into the semi-permeable enclosure. In an embodiment, the vessel further comprises a sieved gate that is at least partially enclosed by the semi-permeable enclosure, where the sieved gate is movable between a blocking position and an open position. In another embodiment, the vessel further

comprises a self-orienting mechanism capable of orienting the direction of the vessel with respect to the direction of the fluid current flow when the vessel is positioned in the fluid current. In another embodiment, the vessel further comprises a pump for directing the nutrients into the semi-permeable enclosure. In another embodiment, the vessel further comprises a channel for increasing the velocity of the fluid current. In another embodiment, the one or more nutrients is an electrolyte. In another embodiment, the electrolyte comprises nitrate ions. In another embodiment, the electrolyte comprises phosphate ions. In another embodiment, the vessel further comprises one or more membranes that concentrate the nutrients. In another embodiment, the one or more membranes are an anion-selective membrane and a cation-selective membrane. In another embodiment, the magnetic field source is a permanent magnet. In another embodiment, the magnetic field source is an electromagnet. In another embodiment, the vessel further comprises a pipe for discharging water having a reduced concentration of the one or more nutrients, where the pipe is surrounded by the magnetic field source.

[0009] In another aspect of the invention, a system comprises a first module comprising a buoyant top, a buoyancy-controlled base, and a semi-permeable enclosure connecting the buoyant top to the buoyancy-controlled base, where the first module is adapted to retain one or more microorganisms upon the flow of a fluid stream through the first module. The system also comprises a second module adjacent to the first module, the second module having a magnetic field source that is configured to provide a magnetic field into the second module, where the second module is adapted to (i) concentrate ionic species upon the flow of the ionic species through the second module along a direction orthogonal to the magnetic field, and (ii) supply concentrated ionic species to the first module. The second module in some cases is in fluid communication with the first module, such as, for example, through a channel. In an embodiment, the magnetic field source is a permanent magnet or an electromagnet. In another embodiment, the magnetic field source is a permanent magnet in the form of a coil. In another embodiment, the first module is coupled to the second module via a pipe that is configured to direct fluid flow from the second module into the first module. In another embodiment, the system further comprises a third module adapted to transport the concentrated ionic species from the second module to the first module. In another embodiment, the third module comprises a pump. In another embodiment, the second module comprises an anion-selective membrane and a cation-selective membrane. In another embodiment, the semi-permeable enclosure is collapsible. In another embodiment, the buoyancy-controlled base is movable with respect to the buoyant top.

[0010] In another aspect of the invention, a method for collecting and/or generating biomass comprises providing a microorganism from an aquatic environment into a vessel configured to retain the microorganism, the vessel comprising at least one semi-permeable membrane that permits the unidirectional flow of the microorganism therethrough. The method also comprises concentrating one or more nutrients from the aquatic environment with the aid of a magnetic field applied to a fluid stream flowing from the aquatic environment into the vessel, and providing the one or more concentrated nutrients into the vessel. In an embodiment, the one or more nutrients comprise at least one electrolyte. In another embodiment, the at least one electrolyte comprises phosphate ions. In another embodiment, the at least one electrolyte comprises

nitrate ions. In another embodiment, the applied magnetic field is provided by a permanent magnet or an electromagnet. In another embodiment, the aquatic environment is seawater. In another embodiment, the method further comprises releasing water with a reduced concentration of the one or more nutrients into the aquatic environment. In another embodiment, the microorganism is selected from the group consisting of microalgae, plankton, diatoms, algae, phytoplankton and zooplankton. In another embodiment, the semi-permeable membrane allows fluid from the aquatic environment to pass freely while impeding diffusion of the microorganism out of the vessel. In another embodiment, the microorganism is provided in a fluid stream from the aquatic environment into the vessel. In another embodiment, the step concentrating one or more nutrients comprises retaining the one or more concentrated nutrients in the vessel.

[0011] In another aspect of the invention a method for recycling one or more agricultural fertilizers, comprises providing an agricultural runoff, filtering the agricultural runoff to form a first fluid, concentrating one or more fertilizers from the first fluid with the aid of a magnetic field applied to the first fluid to form a second fluid comprising one or more concentrated fertilizers, and collecting the second fluid comprising one or more concentrated fertilizers. In an embodiment, the one or more fertilizers comprises an electrolyte. In another embodiment, the electrolyte is a nitrate. In another embodiment, the electrolyte is a phosphate. In another embodiment, the filtering takes place on clarifier plates.

[0012] Other goals and advantages of the invention will be further appreciated and understood when considered in conjunction with the following description and accompanying drawings. While the following description may contain specific details describing particular embodiments of the invention, this should not be construed as limitations to the scope of the invention but rather as an exemplification of preferable embodiments. For each aspect of the invention, many variations are possible as suggested herein that are known to those of ordinary skill in the art. A variety of changes and modifications can be made within the scope of the invention without departing from the spirit thereof.

INCORPORATION BY REFERENCE

[0013] All publications and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually indicated to be incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] A better understanding of many of the features and advantages of the invention will be obtained by reference to the following detailed description that sets forth illustrative embodiments, in which many of the principles of the invention are utilized, and the accompanying drawings of which:

[0015] FIG. 1 shows a vessel design that incorporates a magnetic core to retain ferromagnetic iron sulfate and a porous material exterior to (a) retain the oxidized iron, other trace metals, and the induced microalgae and (b) allow hydrophilic micronutrients to enter the vessel, in accordance with an embodiment of the invention;

- [0016] FIG. 2A shows a vessel with a compression mechanism, which permits bioreactor volume reduction in an extended state, according to an embodiment of the invention; FIG. 2B shows the vessel shown in FIG. 2A in a compressed state, in accordance with an embodiment of the invention;
- [0017] FIG. 3A shows a vessel having a fiberglass composite top and based with a fiberglass mesh material that allows nutrients to be exchanged, while retaining marine microalgae within, in accordance with an embodiment of the invention;
- [0018] FIG. 3B shows an exposed electromagnetic solenoid and carbon dioxide bubbling from the fiberglass composite base, in accordance with an embodiment of the invention;
- [0019] FIG. 3C shows iron powder applied to a solenoid that can provide an induced magnetic field to orient and retain iron within the vessel, in accordance with an embodiment of the invention;
- [0020] FIG. 4A shows a top view of a two-liter vessel with a fiberglass fabric exterior and a centrally located electromagnet, in accordance with an embodiment of the invention;
- [0021] FIG. 4B shows a close-up top view of the two-liter vessel after three days, in accordance with an embodiment of the invention;
- [0022] FIG. 5 shows a vessel design incorporating baffles to circulate the microalgae through the vessel, in accordance with an embodiment of the invention;
- [0023] FIG. 6 shows an offshore aquaculture implementation to generate renewable hydrocarbon fuels and proteins, in accordance with an embodiment of the invention;
- [0024] FIG. 7 shows an implementation of vessels for nitrogen and phosphorus micronutrient bioremediation along rivers and tributaries prior to reaching coastal estuaries and deltas, in accordance with an embodiment of the invention;
- [0025] FIG. 8 is a diagram depicting microalgae processing into hydrocarbon fuels and purified proteins, in accordance with an embodiment of the invention;
- [0026] FIG. 9 shows a vessel base with an electromagnetic solenoid for producing a magnetic field and fluidic connections for providing a stream of carbon dioxide, in accordance with an embodiment of the invention;
- [0027] FIG. 10A shows a vessel for plankton cultivation having a collapsible magnetic coil, in accordance with an embodiment of the invention;
- [0028] FIG. 10B shows top view of a biomass processing system having a plurality of vessels connected to a processing platform that allows for farming of open water, e.g., the ocean, in accordance with an embodiment of the invention;
- [0029] FIG. 11 shows a table with calculations for determining the number of vessels required to produce 5 million gallons per year at various final concentrations of microalgae, in accordance with an embodiment of the invention;
- [0030] FIG. 12A shows an electromagnetic core design having a single electromagnet that can produce a constant and large enough electromagnetic field to ensure that trace metals remain in the vessel that can compress and extend with the vessel, in accordance with an embodiment of the invention;

- [0031] FIG. 12B shows an electromagnetic core having a first electromagnet positioned at the perimeter of the vessel and a second electromagnet positioned at the center of the vessel to promote mixing and/or movement of trace metals between the electromagnets, in accordance with an embodiment of the invention;
- [0032] FIG. 13 shows equations relating to the scaling of biomass production, in accordance with an embodiment of the invention;
- [0033] FIG. 14 shows a table showing system scaling based on final vessel plankton concentration and the US daily petroleum distillate consumption, in accordance with an embodiment of the invention;
- [0034] FIG. 15 schematically illustrates the effect of the Lorentz force in a magnetic field on charged particles, in accordance with an embodiment of the invention;
- [0035] FIG. 16 schematically illustrates a vessel that includes a bioharvester module and a magneto-concentrator module, in accordance with an embodiment of the invention;
- [0036] FIG. 17 schematically illustrates a magneto-concentrator module, in accordance with an embodiment of the invention;
- [0037] FIG. 18 provides another view of a magneto-concentrator module, in accordance with an embodiment of the invention;
- [0038] FIG. 19 provides another view of a magneto-concentrator module, in accordance with an embodiment of the invention;
- [0039] FIG. 20 schematically illustrates a fertilizer recycler, in accordance with an embodiment of the invention;
- [0040] FIG. 21 provides another view of a fertilizer recycler, in accordance with an embodiment of the invention;
- [0041] FIG. 22 provides a view of a magnetic concentrator, in accordance with an embodiment of the invention;
- [0042] FIG. 23 provides a view of a concentrator chamber of a magnetic concentrator, in accordance with an embodiment of the invention;
- [0043] FIG. 24 provides a view of a fluid intake screen of a magnetic concentrator, in accordance with an embodiment of the invention;
- [0044] FIG. 25 provides a view of the outer channels and the inner channel of a concentrator chamber of a magnetic concentrator, in accordance with an embodiment of the invention;
- [0045] FIG. 26 provides a view of an outer channel of a concentrator chamber of a magnetic concentrator, in accordance with an embodiment of the invention;
- [0046] FIG. 27 provides another view of an outer channel of a concentrator chamber of a magnetic concentrator, in accordance with an embodiment of the invention; and
- [0047] FIG. 28 provides a view of a fluid intake screen and a funnel of a magnetic concentrator.

DETAILED DESCRIPTION OF THE INVENTION

[0048] While preferable embodiments of the invention have been shown and described herein, it will be obvious to those skilled in the art that such embodiments are provided by way of example only. Numerous variations, changes, and substitutions will now occur to those skilled in the art without departing from the invention. It should be understood that various alternatives to the embodiments of the invention described herein may be employed in practicing the invention.

[0049] The invention provides systems and methods for cultivating, harvesting, and processing biomass. Various aspects of the invention described herein may be applied to any of the particular applications set forth below or for any other types of feedstock. The invention may be applied as a standalone system or method, or as part of a biofuel or biomass production system or method. It shall be understood that different aspects of the invention can be appreciated individually, collectively, or in combination with each other.

[0050] The invention provides for various designs, methods, and systems that allow for the growth of one or more microbial organisms and the various beneficial effects of the growth, including, without limitation, the production of a renewable fuel(s), remediation, and production of proteins. The growth of such microbial organism can be facilitated with the aid of nutrients concentrated from a source of nutrient, such as a body of water or fluid stream. The invention provides systems and methods for concentrating nutrients, and directing concentrated nutrients to the one or more microbial organisms during growth.

[0051] Some embodiments provide for design features that can improve the specific growth rates, product density/specificity, and prevent trace metals from being diluted by ocean or open-water currents. These features and combinations of these features have not been incorporated in prior ocean enclosure systems. See, e.g., U.H. Brockmann, E. Dahl, J. Kuiper, et al., "The Concept Of Poser (Plankton Observation With Simultaneous Enclosures In Rosfjorden)," Marine Ecology-Progress Series 14 (1): 1-8 (1983); S. Takeda, J. N., C.S. Wong, F. A. Whitney, W. K. Johnson, and T. J. Soutar, "Application of open-ocean enclosures to study the control of biological carbon dioxide pump in the subarctic North Pacific Ocean," Proceedings of the 2nd International Symposium Carbon Dioxide in the Oceans: 583-586 (1999); and J.K. Wang, "Conceptual Design of a Microalgae-based recirculating oyster and shrimp system," Aquacultural Engineering 28: 37-46 (2003), which references are entirely incorporated herein by reference.

[0052] FIG. 1 shows an example of an open water enclosure, in accordance with an embodiment of the invention. A collapsible porous material **100** is provided that can allow sea water to pass through but does not allow biomass to diffuse through. The collapsible porous material can be mesh netting. Open water enclosures can utilize mesh netting with small pore sizes. For example, mesh netting can utilize pore sizes less than about 50 micrometers (μm), 40 μm , 30 μm , 20 μm , or 10 μm . Such a mesh can allow continuous nutrient replenishment through the mixing by ocean currents, which captures the microalgae product. The mesh netting can be of any pore size and/or material that allows for selection against loss of trace metals and biomass while allowing transport of other nutrients. The selection can be charge, size, and/or hydrophobicity/hydrophilicity based.

[0053] The open water enclosure of FIG. 1 includes a magnetic core **102**. In some embodiments, the magnetic core can be a collapsible magnetic coil. The open water enclosure also includes a buoyant top **104** to support the structure. In some embodiment, the top structure can enclose the vessel. In some embodiments, the top structure can be an air filled hollow cap. In some embodiments, the structure can include a buoyancy controlled bottom **106**. Optionally, the vessel can include one or more reinforcement beams **108a**, **108b**, **108c**.

[0054] Open ocean/water cultivation can allow for the following advantages:

- Free nutrients,
- Free kinetic energy for mixing,
- Free organism cooling and hydration,
- The ocean's vast surface area eliminates natural scaling limitations, and/or
- Portability and ease of implementation in most ocean environments.

[0055] As a result of these advantages, the products generated, including renewable fuels, can be produced for significantly less cost. A hydrocarbon equivalent can also be produced at a significantly lower cost by various processes, including hydrotreating an oil extract.

[0056] Hydrotreating oil extracts allows for the production of a renewable diesel that can:

- Be a biofuel indistinguishable from petroleum diesel,
- Be a drop-in replacement for or can be blended to any proportion with traditional diesel,
- Be used in any proportion in today's infrastructure from pipelines and storage to gas pumps and automobiles,
- Be used in any proportion,
- Has excellent stability and is not oxygenated,
- Offer superior cold flow properties making it more suitable for very cold climate conditions,
- Have higher energy content per volume compared to Biodiesel, and/or
- Offer lower fossil energy requirements and reduction of Green House Gases and NOx emissions.

Iron Fertilization

[0057] In some embodiments of the invention, vessels can be used to capture all or substantially all biological growth induced by iron fertilization, which can be accomplished by the exposure of the organism to trace metals that are confined within the vessel. Metals within the vessel can include reduced iron. In order to prevent the reduced iron from diffusing outside the vessel, the vessels can include an electromagnetic or permanent magnetic core designed to minimize reduced iron dilution by ocean currents or other currents. Other nonmagnetic metals and oxidized iron can be captured by a charged fiberglass material that can allow hydrophilic nutrients through but retain the microalgae and trace element. The material need not be made of fiberglass and can be formed from other materials that provide similar selection characteristics.

[0058] Microalgae may require iron to assist in converting carbon dioxide into sugars using light energy from the sun. The oceans iron concentrations are generally well below the levels required to induce

exponential growth in marine algae. As a result, marine microalgae are by and large in a stationary phase until storms or other natural events transport iron from land sources to coastal waters. Trace metals, especially iron, are highly beneficial for inducing microalgae growth in ocean environments. See, e.g., Martin JH, Coale KH, et al (1994), "Testing The Iron Hypothesis In Ecosystems Of The Equatorial Pacific-Ocean" *Nature* 371 (6493): 123-129; Coale, KH, and et al. (1996). "A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean." *Nature* 383: 495-501; Zhou GJ, Bi YH, Zhao XM, et al. (2009) "Algal Growth Potential And Nutrient Limitation In Spring In Three-Gorges Reservoir, China" *Fresenius Environmental Bulletin* 18(9): 1642-1647; Marchetti A, Varela DE, Lance VP, et al. (2010) "Iron and silicic acid effects on phytoplankton productivity, diversity, and chemical composition in the central equatorial Pacific Ocean" *Limnology and Oceanography* 55(1) : 11-29; Coale, KH (1991). "Effects of iron, manganese, copper, and zinc enrichments on productivity and biomass in the subarctic Pacific" *Limnology and Oceanography* 36: 1851-1864; and Coale KH, Johnson KS, Chavez FP, et al. (2004). "Southern Ocean Iron Enrichment Experiment: Carbon Cycling in High- and Low-Si Waters." *Science* 304(5669): 408-414 (herein after the "2004 Coale paper"), which are hereby incorporated by reference in their entirety. Artificially elevating iron concentrations in the open ocean is one key to inducing marine microalgae growth as a feedstock for industrial scale renewable diesel and jet fuel production.

[0059] In the 2004 Coale paper, microalgae growth was induced by adding iron sulfate to 0.7 nM in a 225 km² area in the arctic polar front zone of the southern seas. The microalgae eventually covered approximate 2400 km² after 20 days of growth. Assuming the microalgae had at least a depth of 10 m and a density of at least 1 µg/L, this can yield a wet microalgae biomass of approximately 26.5 tons. In some embodiments, algae growth can be tailored toward biological sequestration of carbon dioxide. In other embodiments, algae growth can be tailored toward the production of a renewable fuel feedstock.

[0060] In order to control the cultivation and harvesting of the microalgae induced by iron fertilization, several vessels can be utilized with the following design goals:

- To contain microalgae and iron while allowing hydrophilic nutrients to pass between the vessel and the surrounding environment.
- To concentrate microalgae 15x prior to harvesting in order to reduce the volume of seawater to be processed and discarded and in turn to reduce the energy requirements to process the microalgae.

[0061] In some embodiments, the goal can be to capture all biological growth induced by iron fertilization, which can be accomplished by allowing the organism to be exposed to the trace metals only in the confines of the vessel.

Vessel Design

[0062] A semi-closed plankton cultivation and processing system, including a vessel, is shown in FIG. 1 and FIG. 10A. The system can include a control system (not shown) for analyzing and processing, among other things, environmental conditions, nutrient parameters and vessel status. This vessel has several innovations that improve the specific growth rates, product density/specificity, contain (or capture) organisms to be grown, and prevent trace metals from being diluted by ocean currents.

[0063] In some embodiments, the vessel can have a substantially cylindrical shape. For example, a cross-sectional area of the vessel can have a circular shape. In other embodiments, the vessel can have any other shape, which can include a prism with a square cross sectional shape, diamond cross-sectional shape, rectangular cross-sectional shape, triangular cross-sectional shape, pentagonal cross-sectional shape, hexagonal cross-sectional shape, octagonal cross-sectional shape, or elliptical cross-sectional shape. In some embodiments, the vessel cross-sectional shape can correspond to a shape of a top apparatus and/or bottom base.

[0064] In some embodiments, the vessel can include a collapsible porous material **100** that can allow sea or ocean water to pass through without allowing biomass to diffuse through. In some embodiments, the collapsible porous material can be a mesh netting. The collapsible porous material can be formed from a fabric or textile, such as a cotton canvas material. In some embodiments, the porous material can be formed of a synthetic, non-synthetic, or blended fiber. The porous material can be formed of one or more materials. The porous material can be a filtration membrane. The porous material can be flexible enough to allow stirring by ocean currents. In some embodiments, the porous material can be porous enough to allow sea/ocean/surrounding water to diffuse through. The material can also be dense enough to contain product within the vessel, by making its diffusion timescale sufficiently large. Various embodiments of the porous material are discussed further below.

[0065] The collapsible porous material may surround a magnetic core **102**. In some embodiments, the magnetic core may be one or more collapsible magnetic coil. The magnetic core may include any magnetic material. Preferably, the magnetic material may have a shape or configuration that may enable it to collapse in a vertical direction. For example, it may include a coil, telescoping features, sliding features, folding features, accordion-type features, small loose components, or other configurations that enable collapsing. Various embodiments of the magnetic core are discussed further below.

[0066] The collapsible porous material may be provided between a top apparatus **104** and a bottom base **106** of the vessel. One or more reinforcing beams **108a**, **108b**, **108c** may be provided between the top apparatus and the bottom base.

[0067] The exterior vessel design incorporates innovative ideas to reduce energy consumption and operating cost requirements. One feature is a buoyant top apparatus to support the structure. In some embodiments, the top apparatus may be filled with air. In other embodiments, the top can be filled with another gas or material that can have less density than water. In some embodiments, the top can be hollow or can include pores that can trap air or other gases. The top apparatus can be formed of any material or have any configuration that can allow the top apparatus to float on the ocean's surface.

[0068] The concept significantly improves the functionality of the vessel by adding a buoyancy controlled base as show in FIG. 1 and FIG. 10A. FIG. 2A shows that when the base **200** is filled with water, it expands the cultivation volume/depth of the vessel. In some embodiments, the vessel can be expanded so that the base reaches of a depth of 30m. In other embodiments, when the vessel is expanded, the base can be at any

depth, which can include but is not limited to about, up to about, or greater than about 100 m, 70 m, 50 m, 40 m, 35 m, 30 m, 25 m, 20 m, 15 m, 10 m, 7 m, or 5 m.

[0069] Once the biomass has reached a predetermined density, air is pumped into the base **200** causing the cultivation volume/depth to decrease as the base rises. The base can be brought closer to a top **202** of the vessel. As the vessel approaches the compressed state in FIG. 2B, the product concentration increases by as much as 15x. In some embodiments, the concentration can increase about, up to about, or greater than about 5, 10, 15, 20, 25, 30x. Concentration can be achieved by flow or efflux of water, such as seawater, through a semi-permeable meshing **204**. This critical processing step significantly reduces the volume of seawater and in turn reduces the energy requirements for the pumps and dewatering centrifuges during biomass processing.

Semi-permeable meshing

[0070] A variety of materials can be chosen for the flexible porous material that allows seawater to pass freely but impedes plankton (or other biomass or fuel) diffusion out of the vessel. In some embodiments, the vessel includes a porous material that can be constructed of Nitex netting with a pore size less than 20 μm , a fiberglass upper portion, and a lower buoyancy control base. The netting can be protected from rips by something similar to a high density cotton canvas exterior. Polyamine and polyethylene netting material with pores less than 20 μm can be used. Other materials can also be used. One, two, three, four, or more layers of flexible porous material can be provided. In some embodiments, the layers can be formed of the same material, while in other embodiments, the layers can be formed of different materials. In some instances, the layers can have the same pore size, while in other instances, the layers can have different pore sizes.

[0071] Functionally, the mesh can allow for transport of water and other small molecules through the mesh and retention of organisms to be grown, such as those described herein. The mesh can be a semi-permeable exterior wall that selectively retains the organisms over water-soluble nutrients. For example, the wall can retain more organisms than water-soluble nutrients. For example, the wall can retain 2x, 3x, 5x, 10x, 15x, 20x, 30x, 40x, 50x, 70x, 100x, 200x, 500x, 1000x or more organisms than water-soluble nutrients by mass, concentration or volume. The prototype can be tested in a 3 million gallon closed water environment at Moss Landing Commercial Park (MLCP) for construction and material quality. A plankton concentration time course can be conducted by inoculating the vessel interior with plankton so that a initial vessel concentration of 1 g/ L is achieved and measure for Chlorophyll a (Chl a) inside and outside the vessel.

[0072] Not only for efficiency concerns, but also for environmental concerns, the semi-permeable material can be selected to minimize the transport of biological mass to the surrounding environment. The correct combination of materials and construction can be achieved when the baseline Chl a levels in the seawater are maintained outside the vessel while maintaining close to the original 1 g/L plankton concentration inside the vessel.

Magnetic Core Design

[0073] Trace metals, such as iron, can induce plankton growth in ocean environments. Since the goal is to capture all biological growth induced by iron fertilization, it may be desirable for organism exposure to the trace metals to occur only in the confines of the vessel. In order to prevent the trace metals from diffusing outside the vessel, an electromagnetic core designed to minimize trace metal dilution by ocean currents is provided. Para- and ferromagnetic particles may be retained within the vessel.

[0074] Examples of potential electromagnetic cores are depicted FIG. 12A and FIG. 12B. The one electromagnetic field in FIG. 12A is constant and large enough to insure that the trace metals, especially iron, remain in the vessel. In some cases, a one-coil design can include a magnetic coil that can compress and extend with a vessel. It may be possible to tailor trace metal concentrations to the prevailing organism growth conditions by varying the electromagnetic field intensity as a form of controlled release. An alternative is the design in FIG. 12B that incorporates an electromagnetic field at the perimeter and in the center of the vessel. A two-coil design can be provided, which can compress and extend with the vessel. Alternating the electromagnetic field between the two electromagnets promotes trace metal mixing within the vessel while preventing them from being diluted.

[0075] One or more electromagnetic coils can be in electrical communication with a power source. The power source can be part of the vessel or can be external to the vessel.

[0076] As previously described, a magnetic core may include a magnet or electromagnet that may be compressible or collapsible. The magnetic core can preferably be compressible or collapsible in a vertical direction.

[0077] The magnetic core can be enclosed by the vessel. In an example, the magnetic core can be enclosed by a semi-permeable or porous material. The magnetic core can be entirely closed by the semi-permeable or porous material. In some embodiments, the magnetic core can be at least partially enclosed by the semi-permeable or porous material.

Exemplary Vessel Designs

[0078] One embodiment of a vessel is shown in FIG. 1 and FIGs. 2A and 2B. A vessel can have one or more of the following design features:

- Variable and/or collapsible electromagnetic core to retain the reduced iron sulfate as shown in FIG. 1.
- Constant replenishing of hydrophilic nutrients.
- Constant dilution of waste organic acids excreted by the microalgae.
- Culture never dehydrates or overheats.
- Concentrates organism by reducing vessel volume as shown in FIG. 2.

[0079] The vessel, as shown in FIG. 1, may have a maximal volume of 9.4 million liters, a diameter of 20 meters, and a height that can be adjusted from 2 meters to 30 meters. The vessel can contain a compressible or collapsible magnetic or electromagnetic core **102** that can facilitate retention of trace metals, e.g.,

magnetic trace metals, or iron. The vessel can be cylindrical in shape or any other suitable shape. Any discussion herein of a cylindrical shape can apply to any other shape and vice versa.

[0080] The circumferential walls **100** of the vessel can be made of a mesh material that allows selective transport of nutrients, e.g., nitrogen, phosphorus, water, waste products, trace metals, and biomass. The mesh material can be made of fiberglass with a particular pore size. In some embodiments, the porous material can be made of a plastic, a metal, a glass, an organic material, or any combination thereof that has the desired selectivity. In some embodiments of the meshes or nettings, or porous materials described herein can be fabricated using fiberglass fabric, carbon fiber fabric, polyethylene, polyvinylacetate, or hydrophilic polymer. These materials can be woven. In some embodiments of the invention, these materials can be charged, e.g., fiberglass fabric. Some other examples of materials include, e.g., a durable and inexpensive high density cotton canvas material, a filtration membrane, a metallic sheet, any woven hydrophilic fabric or polymer (e.g., woven polypropylene, woven polyethylene), or membrane with a selected pore size. Selected pore sizes include any pore size of about or up to about 1, 5, 10, 15, 20, 25, 30, 40, 50, 75, 100, 150, 200, 250, 300, 500, 1000, 2000, 3000, or 5000 microns. In some embodiments, the pore size can be variable or uniform across the surface of the mesh material or into the mesh material. Alternatively, pore size can vary within the mesh material. The pores can be evenly distributed over the mesh material, can be grouped into clusters, or can have any other distribution over the mesh material.

[0081] As stated previously, the selectivity can be achieved by pore size, charge, hydrophilicity/hydrophobicity, magnetism, or any combination thereof. In some embodiments, the selectivity is obtained by providing for a material that has a relatively greater diffusion time for the biomass and other materials to be retained as compared to materials that are to be exchanged with the surrounding environment.

[0082] The top **104** of the vessel and the base **106** of the vessel can be connected in a variety of manners. In some embodiments, the top and base are connected only by the cylindrical walls **100** of the vessel. An interior region of the vessel can be enclosed by the cylindrical walls and/or the top and base. IN some embodiments, the cylindrical walls can be flexible and/or collapsible. In some embodiments, the cylindrical walls are rigid. The top and base of the vessel can be movable with respect to one another. They can be movable in a vertical direction. They can be movable in a horizontal direction. In one example, when organisms are contained within the vessel, the top and base of the vessel can be brought into closer proximity with one another. The top and base can be brought into closer proximity while the walls are collapsed. The walls can optionally be collapsed without expanding horizontally. In some embodiments, the walls can be collapsed while maintaining a substantially same cross-sectional area enclosed therein. This can reduce the volume within the vessel. Reducing the volume of the vessel can result in increasing concentration of the organism therein.

[0083] In other embodiments, the top and base are connected by the cylindrical walls and one or more reinforcing beams **108a**, **108b**, **108c**. In some embodiments, one, two, three, four, five, six, seven, eight, or more reinforcing beams can be provided. The reinforcing beams can provide for a rigid connection between

top and base, while the cylindrical walls can remain flexible. The one or more reinforcing beams can limit them mobility of the base with respect to the top. For example, the reinforcing beam can limit the mobility of the base with respect to the top in a vertical direction. The base can move along the rigid reinforcing beams (as shown in FIG. 2) and/or the rigid cylindrical walls such that the base moves vertically and is prevented from translating horizontally away from the top of the vessel. In some embodiments, the reinforcing beams can remain fixed with respect to the top of the vessel, and the base can slide with respect to the reinforcing beams. Alternatively, the reinforcing beams can be fixed with respect to the base of vessel, and the reinforcing beams can slide with respect to the top of the vessel. In other embodiments the reinforcing beams can be movable with respect to both the top and bottom of the vessel. In some embodiments, the top and/or bottom can include one or more vertical channel or passage that can be capable of sliding with respect to the reinforcing beam. In other embodiments, the top and/or bottom of the vessel can be provided between the reinforcing beams. The top and/or bottom of the vessel can be configured to remain at a substantially fixed horizontal/lateral position with respect to the reinforcing beams.

[0084] The position of the vessel base relative to the top of the vessel can be controlled in a variety of manners, e.g., buoyancy and/or mechanically controlled. In some embodiments, the base and the top of the vessel can be buoyancy controlled. The top of the vessel can be an air filled hollow cap and the base of the vessel can be negatively buoyant. The base can also have one or more compartments that allow for buoyancy control. In some embodiments, the compartments can be or can contain bladders that can hold air or another gas. Once the bladders are filled with gas, the base can become positively buoyant and cause the base to rise toward the top of the vessel. The bladders can be filled in a manner such that the rate of vessel volume reduction or expansion is controlled. This may be important to increase the selectivity of porous cylindrical walls, e.g., to selectively allow transport of water and other undesired materials across the porous walls and retain iron and biomass. In some embodiments, the bladders can be in communication with one or more gas source. For example, one or more hose or channel can connect the bladders to a gas source. In some embodiments, a pump, or positive pressure source can be provided to force gas into the bladders to raise the base. The bladders can also be in communication with one or more gas vent, when it is desirable to lower the base. The bladders can vent directly to the surrounding water, or can be connected to a remote venting location via a hose or channel. In some embodiments, the remote venting location can be the same as, or different from, the gas source.

[0085] In some embodiments, a vessel base can be raised and/or lowered via one or more mechanical actuator. For example, the base and/or top can move relative to a reinforcing beam via an actuator. Examples of actuators can include but are not limited to, motors, solenoids, linear actuators, pneumatic actuators, hydraulic actuators, electric actuators, piezoelectric actuators, or magnets. Actuators can cause the base and/or reinforcing beam to move based on a signal received from a control system. In some embodiments, the actuators can be connected to a power source.

[0086] FIGs. 3A, 3B, 3C, 4A, and 4B show an example of a vessel described herein. The electromagnetic vessel can be referred to as the Iron Fertilization Vessel (IFV). A 2L IFV (FIG. 3A) has been built and has

successfully been shown to confine growth to IVF's interior (FIG. 4A and 4B), to limit iron exposure to the IVF's interior by inducing an electromagnetic field (FIG. 3C), to concentrate the culture 3X prior to harvesting by compressing IFV's volume, and to blow carbon dioxide gas from the base (FIG. 3B). FIG. 4A shows the 2L vessel prior to incubation in water ($t=0$). FIG. 4B shows the 2L vessel after three days of incubation in water. The grey matter is the reduced iron powder attached to the magnet. Red matter on the walls of the fiberglass fabric is mostly oxidized iron retained by the fiberglass fabric. The oily substance present throughout the interior of the vessel shown in FIG. 4B may indicate the presence and/or growth of microalgae.

[0087] An exemplary IFV is equipped with a two ply of an 8.5 oz 2x2 twill weave fiberglass mesh, a fiberglass composite top, and buoyancy controlled base, as shown in FIG. 3A. A fiberglass fabric may be selected as the mesh material because it is a strong, flexible, and hydrophilic material that allows nutrients to be replenished and simultaneously contain the microalgae inside the vessel. The fiberglass composite buoyancy control base can have two internal compartments. The upper compartment can be used to blow carbon dioxide from the base. The lower compartment can be filled with seawater during the growth phase to maximize surface area in which nutrients can diffuse across. The lower compartment can be filled with air during the harvesting phase to concentrate the algae by decreasing the IFV's volume prior to processing and/or harvesting the marine algae.

[0088] The vessel can include an electromagnetic core designed to retain the iron additions to the IFV, as shown in FIG. 3C. The electromagnetic coil in the 2L IFV includes two wires circumscribing an iron core with opposite polarities. A timing circuit can allow the current to alternate between the two wires, thus changing the direction of the magnetic field. The wave function in the magnetic field causes the iron to oscillate between the two ends of the solenoid allowing it to mix with the aqueous media and algae inside the vessel.

[0089] The electromagnetic field strength is approximated by Ampere's Law as $B = \mu_0 \eta I$, where μ_0 is the permeability of the core, η is the number of turns per unit length, and I is the current. The B field strength is directly proportional to the current. The current can be regulated by changing the resistance in the circuit. Once the magnetic field has been induced, its magnitude is determined by a calibrated Hall Effect sensor. The magnetic field exerting at least 6.4 mT can retain reduced iron inside the vessel 6.4 mT, as shown in FIG. 3C.

[0090] The invention also provides for designs that can be utilized to streamline the vessel's functionality and operation by increasing circulation and/or mixing within a vessel, as shown in FIG. 5. For example, the vessel can be designed to mimic fresh water raceway pond functionality but in a vertical fashion. Increased circulation can allow for better mixing of nutrients and allow for desired or selected exposure of the microalgae to sunlight. The mixing and flow dynamics can be controlled by the design of the vessel dimensions and shape. Baffles within the vessel can be used to control fluid velocity and volumetric flow rates for liquid flowing in a recirculating pattern within the vessel and for liquids flowing through the vessel. The current in the surrounding environment can also be utilized to prevent fouling of the mesh materials by

directed current flow across the mesh material or by powering a mechanical cleaning device. In some embodiments, the current can be used to generate power, which can be utilized by the vessel itself in any form, or by the processing platform.

[0091] To afford protection from the elements, the vessel, including the semi-permeable walls, can be rigid. In some embodiments of the invention, one wall can be rigid and the other can be flexible. The vessel can be designed to be resistant to damage by weather, current, or any large objects in the surrounding environment. The vessel can be designed to be rigid and protective, while not substantially restricting flow into and out of the vessel from the surrounding environment. In some embodiments, the vessel can be buoyancy controlled to allow the vessel to be submersed during inclement weather. Buoyancy control can be achieved by the top portion, the base, or any combination thereof.

[0092] Loss of microorganism and other nutrients through the upstream or current-facing side of the vessel is less of a concern than loss through the down-stream facing portion. In some embodiments, the upstream or current-facing side of the vessel can have a first pore size and the down-stream facing side portion can have pores of a second size that are smaller than the first size.

[0093] As shown in FIG. 5, a permanent magnet that spans the width of the vessel may be incorporated to increase the retentions time that the reduced iron sulfate (**C**) remains in the upper region of the vessel. The magnet can have a minimum field strength of 6.4mT. In addition to a component for retaining iron, the vessel may also include components for retaining other nutrients. In an example, the vessel can include mechanisms to concentrate nitrates and/or phosphates. The mechanism can include chromatography components, ion-exchange based materials, e.g., ion-exchange columns, and/or affinity based materials, e.g., affinity columns. Any of the vessels described herein may have components for concentration and/or retention of one or more nutrients, e.g., iron, nitrate, and/or phosphate compounds.

[0094] Stainless steel sieved gate (shown as dashed lines between **C** and **A** in FIG. 5) with a pore size less than the organism. In some embodiments, the gate is enclosed by the vessel. In an example, the gate can be entirely enclosed by the vessel, or at least partially enclosed by the vessel. In some embodiments, the gate can be movable between a blocking position and an open position. The gate can be lifted or moved out of a blocking position to an open position to allow the organism to circulate. The gate can be lowered or put in a blocking position to concentrate and harvest the organism (**A**). FIG. 5 shows the gate (dashed line) in a blocking position.

[0095] FIG. 5 indicates a deficient nutrient feed point (**B**). Feeds that are low in concentration in the surrounding environment can be added at point **B**. The deficient nutrients that can be fed to the vessel include any nutrient discussed herein. In some embodiments, the nutrients include iron, phosphate, and/or nitrate compounds. The iron can be fed as an iron compound, such as iron sulfate, or iron can be fed to the vessel as part of a biodegradable polymer or material that releases iron over time, as discussed herein. The biodegradable polymer or material can also include other nutrients, such as nitrate compounds and/or phosphate compounds. Nitrates can also be fed in the form of ammonium, ammonium ferrous(II) sulfate (magnetic), or ammonium bicarbonate. Nitrates and other nutrients can also be sourced from waste water,

secondary waste water, run off, chicken feed, agricultural waste, or any low-cost nutrient source and then fed to the vessel. The nutrient feed can be controlled automatically or manually. The nutrient feeding can be controlled based on the concentration of the nutrient in the vessel, the growth rate and/or the concentration of the organism. A nutrient feeding component for feeding one or more nutrients can be included in any of the vessels described herein.

[0096] Uses the current's kinetic energy to thoroughly mix the micronutrients and the microalgae. The mixing of nutrients and algae can be achieved by baffles within the vessel that direct the fluid in a recirculating pattern. The vessel can be positioned within a flowing current. In FIG. 5, current flows into the vessel at the right-hand side (**D** right) and exits the vessel at the left-hand side (**D** left). The movement from right to left forces circulation within the vessel in the direction indicated by the arrows, which forms a recirculating pattern. The circulation can be created by a Venturi effect caused by the flux of fluid through the reactor from the upstream portion of the vessel to the downstream portion of the vessel. The amount of current flow used for circulation can be selected in a variety of manners, e.g., by altering the exposed surface area on the right hand side of the vessel and/or the surface area on the left-hand side **D**. In this configuration, the vessel has an upstream, or current-facing side and a downstream or a side that is not facing the current. If the current of the surrounding environment is fixed, the vessel can be fixed in a proper orientation. If the current is not fixed, then the directionality of the vessel can be controlled based on the current's direction. The control of the vessel's orientation can be automatic or manual.

[0097] As described elsewhere herein, the orientation of the vessel relative to the current in the surrounding environment can play an important factor in determining the circulation rate within the vessel. To account for this, the vessel can be designed such that the orientation of the vessel with respect to the direction of current flow can be controlled. A self-orienting mechanism capable of orienting the direction of the vessel can be provided. Mechanical features, such as vane-like features, can be used to self-correct or self-orient the direction of the vessel such that a desired flow of water through the vessel is achieved. For example, one or more fin, protrusion, channel, flap, or shaped feature can be provided for the vessel. A self-orienting mechanism can be provided in a stationary position relative to the vessel, or can be movable relative to the vessel.

[0098] In some embodiments, the vessel orientation with respect to the current is such that maximal flow through the vessel is achieved. In other embodiments, the vessel orientation can be such that flow through the vessel is lower than the maximal flow through the vessel. For example, if maximal flow is achieved by placing the incoming mesh side the vessel perpendicular to the flow, a lesser amount of flow can be achieved by placing the incoming mesh side at an orientation that is not perpendicular to current flow in the surrounding environment.

[0099] Uses the current's kinetic energy to concentrate the microalgae. Once the sieve gate shown in FIG. 5 is placed in a blocking position, the circulation, as described above, can be utilized to concentrate the microalgae against the sieve gate.

[00100] All the microalgae spend the same cumulative time in the sun exposure zone (between **A** and **B** in FIG. 5). The amount of time spent exposed to the sun can be controlled based on the circulation rate through the vessel and the cross-sectional area of the channels that allow exposure to the sun relative to the cross-sectional area of the other channels in the vessel.

[00101] The recirculation caused by the flux of water through the vessel maintains a constant microalgae density throughout the circulating/recirculating portion of the vessel.

[00102] The vessel shown in FIG. 5 can be designed for high Reynolds and Péclet number to insure it is in the convection regime for consistent nutrient and organism density.

[00103] The pivot point (**G**) shown in FIG. 5 can control the incoming water velocity. As described above, circulation can be controlled by a variety of manners. Here, an incoming water gate can control or restrict the rate of water entering the vessel.

[00104] If necessary, the vessel percolates or sparges carbon dioxide from the base (**F**) shown in FIG. 5 in an effort to achieve higher microalgae densities.

[00105] A hydrophilic, charged, porous material (**D**) shown in FIG. 5 can allow environmental micronutrients and waste organic acids to cross freely but contain the microalgae. This can be achieved by selecting an appropriate pore size, e.g., less than about 5, 10, 15, 20, 30, 50, 100, or 150 μm pore size (or any other pore size described herein).

Organisms and Metabolic Engineering

[00106] While microalgae and plankton have been referred to as organisms to be grown within the vessels, a variety of organisms can be grown in the vessels described herein. These organisms can include plankton, diatoms, algae, phytoplankton, and zoo plankton. The organisms to be grown can be selected based on geographic considerations. The organism can be any autotrophic or photoautotrophic organism. In some embodiments, the organisms grown within the vessels are more than one type of organism. For example, symbiotic organisms can be grown in conjunction with each other, or one organism can be grown during a first phase and a second organism can be grown during a second phase. In some embodiments, the organisms grown in the vessel can include an organism that performs nitrogen fixation. Nitrogen-fixing organisms can be grown with algae or any other organism in a symbiotic relationship. Examples of organisms that perform nitrogen fixation include *Richella intracellularis*, nitrogen-fixing blue-green algae, nitrogen-fixing cyanobacteria, and *Trichodesmium*.

[00107] The organisms, e.g., microalgae, utilized herein can be metabolically engineered for the efficient conversion of the nutrients to further increase the microalgae growth rate, improve product yields, decrease vessel requirements, and maximize the overall system productivity. The microalgae can be engineered to: increase fatty acid content and renewable fuels, e.g., biodiesel, productivity, manufacture industrial enzymes, synthesize personal care/medicinal proteins, and/or manufacture specialized fuels, e.g., jet fuel.

Isolate Local Wild Type Strains and Seed Culture Growth

[00108] In some embodiments, a large microalgae seed culture can be inoculated at the time the iron is added to the vessel to accelerate microalgae growth relative to diatoms. Microalgae can be the dominant

species grown and harvested due to its higher initial concentration. Local wild type strains, which may be preferred, can be used such that new species are not introduced into the local environment. Local microalgae and diatom strains can be characterized for specific growth and nutrient requirements. As well, environmental parameters can be determined such that microalgae or diatom growth can be selectively induced.

Processing Platform

[00109] The vessel products (e.g., biomass produced by growth of or production by organisms grown within the vessels) can be harvested using a processing platform **1010** (see FIG. 10B). The processing platform can be a mobile unit that can be connected to the vessels **1012** described herein. The processing platform can be in fluid communication with an interior region of one or more vessel. In some embodiments, the processing platform can be connected to the vessels via a connector **104**. In some embodiments, a connector can be a hose, pipe, or channel. In some embodiments, the processing platform and/or vessels can include a pump, a positive pressure source, or a negative pressure source, to transfer organisms within the vessel to and/or from the processing platform. The processing platform can optionally connect to each vessel directly. Alternatively, the processing platform can connect to one or more hubs, which can connect to one or more vessel. A processing platform can be connected to any number of vessels, including but not limited to one or more, two or more, three or more, four or more, five or more, six or more, seven or more, eight or more, nine or more, ten or more, twelve or more, fifteen or more, twenty or more, thirty or more, forty or more, or fifty or more vessels.

[00110] The processing platform can be located on a rig or an oil tanker. The processing platform can be located on a buoyant or floating support. The processing platform can also be located on land, which can be in close proximity to a body of water. For example, the processing platform can be located on a shoreline.

[00111] The processing platform can process organisms in real-time, after a certain period of time, or periodically. Lipids contained within organisms can be recovered and processed into biodiesel. Carbohydrates and proteins contained within the organisms can be collected and used in products for human or animal consumption. Seawater can be rejected and returned to the ocean. The processing platform can produce substantially no toxic or hazardous waste streams.

Methods

Microalgae Physiology:

[00112] The target culture density can be controlled. In some embodiments, the target control density is in the range of about 1 µg/L to 100 g/L, 100 µg/L to 50 g/L, or 1 to 10 g/L.

[00113] Nutrient uptake rates can be measured and accounted for to sustain selected growth rates or biomass production rates.

[00114] The waste organic acid accumulation rate can be measured and accounted for. The rate of waste organic acids transport out of the vessel through the permeable mesh membrane can also be controlled by adjusting the circulation rate, or by selecting preferred mesh materials.

[00115] The iron concentration can be measured and controlled. Iron concentration can be a limiting factor for growth or can provide a means to control growth rate.

[00116] The concentration of silica, nitrogen, phosphorus, and carbon nutrients can also be measured and controlled. In some embodiments, these nutrients can pass through the membrane at a higher rate than iron and biomass. The concentration of silica, nitrogen, phosphorus, and carbon nutrients can affect growth and productivity of the microalgae and a lower non-inhibitory concentration for these compounds can be determined.

[00117] The iron feed profile can be selected for a number of parameters. The iron feed profile can be adjusted based on the growth of the organism within the vessel, or the iron feed profile can be adjusted to maintain constant or varying iron concentration.

[00118] In some embodiments, various strains can have different specificity for different iron compounds. The iron compound used can be selected for efficient growth of the organism of choice or vice-versa, the organism can be selected for efficient growth using a predetermined iron compound.

[00119] The production of renewable fuel and protein yield per gram iron can be measured and optimized based on other parameters described herein.

[00120] Various environmental parameters that naturally select for and maximize specific growth rate can be monitored and accounted for.

Iron Fertilization Vessel

[00121] Iron containment and the concentration of iron within the vessel can be measured using optical density or chelating/pH measurements on samples taken inside and outside the vessel.

[00122] Microalgae containment can be measured using optical density measurements from samples taken inside and outside the vessel during growth experiments.

[00123] Membrane material investigation can be selected such that it is durable and hydrophilic.

Vessel Automation, Sampling and Processing

[00125] In some embodiments, LCMS can be used to measure water samples upstream and downstream of the vessels. Other parameters that can be measured include optical density (to determine the concentration of the culture), iron concentration in the culture, and culture pH. These procedures, including sampling and processing of the biomass using the methods described herein, can be automated.

Organism selection and preparation

[00127] The following provides one example of organism selection and preparation. First, local sea water can be retrieved, which can include seawater from the Sea Cliff Beach Pier in the Monterey Bay, to be used as a first source of seawater. Low silicate sea water can be used as a second source of seawater. Iron can be added to each sea water type to bring its iron concentration to 5 nM. 1 mM sodium bicarbonate can be added to each sea water type as a substitute for CO₂ gas. Both sea water stocks can be filtered with a 0.2 µm hydrophilic membrane. 15g agar can be added to 500 mL of each sea water stock. The agar can be dissolved by microwaving until everything is melted. The sea water stocks can be removed from the

microwave and shaken. The petri dishes can be filled to about half full. The petri dishes can be allowed to solidify and stored upside down in a cold room.

[00128] Next, unfiltered local marine water can be streaked on both plate types. They can be incubated on the bench in the presence of a constant full spectrum light source. From the filtered local marine water plates, an isolated diatom colony can be picked and streaked on new local marine water plates. From the low silicate plates, an isolated microalgae colony can be picked and streaked new low silicate plates. These plates can be incubated until single colonies grow. A single diatom or microalgae colony can be picked from a plate and a sterile test tube filled with 5 ml of filtered local marine water stock and with 5 nM Fe and 1 mM NaHCO₃ (Solution C) can be inoculated. This can be incubated in a shaker with a full spectrum light source present until the culture reach 1 OD at 600nm. Next, a sterile 500 mL flask filled with 50 mL of Solution C and all 5mL of the first generation seed culture can be inoculated. This can be incubated in a shaker in the presence of a full spectrum light source present until it reaches 1 OD at 600nm. The secondary seed culture should either be (i) used to inoculate a closed water time-course experiment and/or (ii) split into a master stock for each specimen.

Electromagnetic Intensity

[00129] The minimum electromagnetic field required to bind the bulk of the trace metals can be determined. In a clear fresh water tank with constant agitation, the electromagnetic potential can be maximized to bind all the trace metals to the sealed coil. Starting from the maximum potential, the electromagnetic potential may be incrementally decreased until trace metals start to release from the coil allows for the determination of the minimum electromagnetic field required to bind the trace metals. After each field adjustment, a spectrophotometer measurement at 595 nm can be taken. This can continue until the spectrophotometer readings increase 10% over or under the baseline.

Iron compound selection

[00130] Introducing iron into an ocean environment typically induces the largest biological response of all the trace metals. Iron sulfate has been the substrate used in most open water fertilization experiments. However, it may not be the best choice because it induces the growth of both plankton and diatoms. Based on the multiple composition profiles in the literature, plankton is preferred over diatoms because it has a significantly larger lipid and protein composition. The diatom composition is skewed towards ash/fertilizer products. Therefore, an iron compound that is preferentially selected by plankton may be preferred.

[00131] A selected iron compound can be chosen by performing laboratory growth time course experiments using different iron compounds and 0.2 μ m filtered seawater. The idea is to maximize plankton specific growth while minimizing the diatoms' at the same time. Also fed-batch introduction of the iron compound may promote plankton growth over diatoms.

[00132] Iron compounds can be selected for specificity for diatoms and microalgae. As well, the amount of iron can be selected such that a minimal amount of iron is used to maintain a desired growth rate. Iron concentrations can be about or up to about, or at least about 5.00, 2.50, 1.25, 0.63, 0.31, 0.16, 0.08, 0.04, 0.02, 0.01, or 0.005 nM iron.

[00133] In some embodiments of the invention, the iron compound is formed within a biodegradable material. The biodegradable material can be any suitable polymer that allows for desired release of iron compound at the proper concentration. The biodegradable material can allow for time-release of the iron compound and can also allow for the iron compound to be encapsulated within a large particle that will not pass through the semi-permeable walls of the vessel. Furthermore, encapsulation of the iron compound can reduce or prevent oxidation of the iron compound. Oxidation of the iron compound can change the magnetic properties of the iron.

[00134] The following is an exemplary procedure to test for desired iron concentration:

[00135] First, make a stock local sea water solution with 1 mM sodium bicarbonate (Solution A), a carbon source substitute for the CO₂ gas. Add iron sulfate to 250 mL of the Solution A to achieve a concentration of 5 nM (Solution B). Achieve the above growth media iron concentrations by serially diluting Solution A with Solution B. Add iron contain solutions to test tubes and inoculate with the appropriate strains. Incubate the test tubes in the presence of a continuous full spectrum light source. From the above experiment, the highest iron concentration level that will induce microalgae and impede diatom exponential growth (lowest concentration level diatoms) can be determined.

Maximize Microalgae/Plankton Specific Growth Rate

[00136] Iron is one of the first limiting compounds in ocean environments (See, e.g., Scharek R, Van Leeuwe MA, De Baar HJW (1997). "Responses of Southern Ocean Phytoplankton To The Addition Of Trace Metals" Deep-Sea Research II Vol. 44 (1-2): 209-227). Once iron is supplemented, the next limiting trace metal or nutrient can be identified. Utilizing microbial physiology, plankton specific growth rate can be maximized by supplementing quickly depleted nutrients and/or trace metals to the vessel. In essence, the vessel can be used as an open-water fermenter to achieve high growth rates and plankton density. After maximizing growth by regulating extracellular factors, the plankton can be metabolically engineered for the efficient conversion of the nutrients to further increase the plankton growth rate, improve product yields, decrease vessel requirements, and maximize the overall system productivity.

[00137] Time-courses can be conducted to track the depletion rates of important nutrients and trace metals by microalgae, diatoms and other organisms. Depleted nutrients can be fed at a rate that sufficiently alleviates the observed rate-limiting factor that occurs during the exponential growth phase. At that point, a new rate limiting compound can be identified and fed accordingly. This process of identifying and feeding deficient nutrient can repeat itself until the predetermined growth rate is achieved or all the environmental parameter modification options have been exhausted.

[00138] In a 20-55 L closed water environment, add filter sterilized local sea water with 1 mM sodium bicarbonate or blow carbon dioxide from the base of the 2L prototype as shown in FIG. 9. At time zero, inoculate the vessel interior with the 50 mL seed culture and start feeding iron and other depleted nutrients. The feed rate of the iron and depleted nutrients will be ramped up according to their utilization profile from previous experiments and the current instantaneous growth rate. Take samples at 2 hr intervals until the culture reaches the stationary phase. At each sampling point measure the pH, the optical density at 600 nm,

and the mass density inside and outside the vessel. Analyze the samples for micronutrient concentrations and their depletion rates, especially phosphates, nitrates and bicarbonates. Analyzing for nitrates can give some insight in to whether this concept can effectively be used to remove excess nitrates that have a hand in inducing Harmful Algae Blooms (HABs). Analyzing Bicarbonate concentrations may give some insight as to how large a role this concept may play in recycling greenhouse gases and global warming. With total microalgae amounts, how much carbon dioxide and nitrates are being removed from the environment and converted to microalgae that will be processed into renewable fuels, protein extract, and glycerol can be determined.

Additional technologies

[00139] In conjunction with the systems, methods, and devices described herein, techniques and scientific knowledge from the following areas can also be harnessed:

1. Fatty acid extraction and transesterification
2. Glycerol purification and recovery to sell to pharmaceutical and personal care product manufacturers.
3. Bulk protein, amino acids, and carbohydrate recovery and packaging.

Microalgae Bioprocessing

[00140] One example of a conversion process from microalgae growth to the renewable fuel and protein products, described herein, is shown in FIG. 8. The biomass grown in the vessels described herein are initially screen filtered prior to dewatering with a screw press. The microalgae oils are dried prior to being fed to the delayed coking unit and then hydrotreated. During the early implementation of this process, the extracted microalgae oil can be sold to fossil fuel refiners to be coprocessed with their incoming crude oil.

[00141] During an implementation, the biomass from the vessels may be screen filtered and then dewatered with a screw press. The dried biomass may undergo protein separation. Then solar drying may occur to for purified proteins.

Delayed Coking

[00142] Delayed coking is a thermal process which has two major reactions - thermal cracking and polymerization. Thermal cracking is the mechanism through which molecules of high molecular weight in the feed stock are decomposed into smaller, lighter molecules that are fractionated into their end products. Polymerization is a reaction through which many small hydrocarbon molecules are combined to form a single large “coke” molecule of high molecular weight. A typical coke has 100 to 200 carbon molecules.

[00143] The main objective of the delayed coking unit is to convert microalgae oil to lighter products of higher value and to produce a coke product. In some embodiments, fresh microalgae feed is preheated through a heat exchange system prior to entering the bottom of the coker fractionating tower. The fresh microalgae feed is mixed with recycle from the unit before being pumped through two fired heaters. The effluent from the heaters then enters the bottom of the coking drums where the gaseous products pass out the top and the liquid soaks in the drum until it cracks into lighter products that will exit the top of the drum or forms coke. The liquid and gaseous products resulting from the thermal cracking are separated into the

desired products by fractionation in a distillation tower before being deoxygenated via hydrotreating. The coke product in the coke drum is removed batchwise from the drums after cooling.

[00144] *Hydrotreating*

[00145] Conventional hydrotreating technology of microalgae oil extract produces a high quality product that is compatible with existing fuel infrastructure. Hydrotreating deoxygenates microalgae feedstock by adding hydrogen to produce a highly-stable renewable diesel fuel with a higher cetane value, lower cloud point and lower emissions than biodiesel and traditional petrodiesel.

Facilities / Location

[00146] The vessels can be implemented at sites that are near seawater, rivers, estuaries, oceans, lakes, or any body of water. In some embodiments, the site is near rail service to facilitate transportation of goods.

[00147] The growth parameters can be optimized and the microalgae's metabolic pathways can be engineered to achieve a significantly higher specific growth rate. Increases in the microalgae's specific growth rate, the initial culture density (P_i) and final culture density (P_f) can increase the overall system productivity and lower the total vessel requirement.

[00148] As shown in FIG. 11, a final microalgae concentration can be at least about, up to about, or about 25g/L, thus requiring only 16 vessels to produce 5M gallons of fuel per year. Sixteen vessels can utilize or require only 1.25 acres of ocean surface area.

Advantages

[00149] The invention provides for a systems, devices, and methods that allow for the growth, concentration, and harvesting of mass marine biomass induced by iron fertilization for commercial biofuel, e.g., biodiesel, production. The benefits of ocean and open-water farming are numerous and far outweigh any benefits of any land based algae efforts.

[00150] The devices and methods describe herein have comparatively low feedstock production costs. The reduced production and distribution costs are largely due to the following advantages: (i) very little overhead is required to run and maintain farms in the open ocean, (ii) production vessels can be quickly fabricated and deployed off any coast, close to end users particularly in major urban areas and near transit arteries with very little initial capital, (iii) the ocean has a free and abundant supply of all the required nutrients to produce renewable fuels, except the very inexpensive iron compounds, (iv) feedstock production is highly scalable, and (v) virtually no waste streams are generated, which would require additional disposal costs and fees.

Capital and Operational Costs

[00151] The systems described herein have a number of advantages. The vessel construction is extremely low compared to bioreactors. The vessels are modular and portable. The vessels do not require highly skilled labor to operate and optimize it like bioreactors. As a result, they can be established in most coastal regions of the world; moreover, they do not require laborers with specialized skills.

[00152] The vessels do not utilize limited resources like land and fresh water. It reduces rents/mortgages requirements due to the minimum land use. The cultivation, harvesting, and microalgae fuel processing stages can be done at sea thus eliminating the cost of leasing land. Most land requirements can be for storage

and management office space. The invention does not compete with other developed land uses such as farming for food or residential/commercial developments. In fact, the only resource that is required is the widely abundant iron. This minimizes or reduces chemical purchasing requirements to iron and downstream processing chemicals such as ethanol/methanol and base catalyst. The majority of the cultivation nutrients are provided and continuously replenished by the ocean for free, thus lowering the raw material expenses.

[00153] The magnetic iron retention and/or mixing mechanism increase the overall yield and productivity of the system thus minimizing the vessel requirements and capital investment. The ocean provides the kinetic energy required to keep the system well mixed for free thus further reducing energy costs and requirements.

[00154] Additionally, no waste streams are produced. There are no waste streams because (1) the supernatant is returned to the ocean (during growth and during dewatering/harvesting), (2) the biomass lipids are converted to biodiesel, (3) and the carbohydrate/protein extract are packaged for human/animal consumption.

[00155] The use of buoyancy as the concentrating mechanism to reduce vessel volume prior to processing in order to minimize the volume that needs to be pumped and centrifuged provides a significant advantage. Using buoyancy is a less energy intensive method other mechanical methods.

[00156] In comparison to open-ocean iron fertilization where biomass grown is not harvested, the invention provides for product revenue streams that are generated from (1) converting the microalgae lipids to renewable fuels, and (2) extracting the algal carbohydrate/protein for human/animal consumption.

[00157] Also, tax credits from both carbon sequestration and biodiesel/renewable fuel production can be obtained.

Manufacturing Benefit

[00158] In addition to the cost benefits, there are several manufacturing benefits to take into account. The system that we described above is constructed of modular components that can be easily fabricated out of composite materials, e.g., fiberglass or carbon fiber composite materials, once the molds for the parts have been made. Because of the modular composite components, these vessels can easily be repaired, replaced, and relocated. When the vessel is displaced by a storm, they can easily be located if the system components are both filled with air making them buoyant and a locating beacon is installed. Finally, the system is scalable to sizes that are impractical on land due to a variety of reasons, including volume and surface area limitations.

Economic

[00159] The invention provides for system, devices, and methods that can create a domestic and worldwide renewable hydrocarbon fuel source, create worldwide distribution, bioprocessing, manufacturing, and engineering jobs, and can potentially replace the need for all imported diesel fuel products. Also, it ensures the US maintains a technological advantage in developing and deploying energy technologies.

Engineering

[00160] The invention provides for a platform technology that can be used for generating medicinal, industrial, and nutritional proteins worldwide.

Military

[00161] The invention allows for local fuel production and depots around the world. This can be useful to military installations that are dispersed throughout the world, but have access to aqueous environments.

Environmental and Safety Issues

[00162] The environmental benefits are straight forward but just as important as the other benefits. The biomass produced fixes dissolved CO₂, causing surrounding atmospheric CO₂ pressure to decrease. The ocean waters are also simultaneously deacidified. The oceans can be deacidified by fixation of dissolved carbonate and bicarbonate

[00163] The invention can be used to restore coastal ecosystems through bioremediation. The invention can be used to remediate coastal estuaries and river deltas by reducing nitrogen and phosphorus concentrations and eliminating unwanted hazardous algae blooms.

[00164] Another benefit worth discussing is the ramification and cleanup of an accidental spill of biodiesel or unprocessed marine biomass. Since the biomass/biodiesel is biodegradable, it can be either consumed or degraded by other organisms in an ocean environment over the course of no more than 17 days.

[00165] In some instances, the organisms to be grown can be contained within the vessels. This can reduce the environmental impact of organisms on the surrounding environment. For example, genetically modified organisms can be substantially contained within the vessel.

[00166] The devices and methods herein can be designed such that compliance with EPA, NEPA, and London Protocol regulations is met. In the open ocean, time courses experiments can be conducted to determine if there is any perturbation to the surrounding marine ecology and how fast the surrounding marine environment recovers after cultivating and harvesting large quantities of plankton. The invention provides for systems, devices, and methods that allow for farming of the oceans without disrupting ecological systems and continue to comply with NEPA and the London Protocol.

[00167] Another potential environmental and safety concern is what effect does creating an artificial magnetic field has on the surrounding ecological system. Electromagnetic field intensity can be controlled such that the ocean habitat's health and the safety of the employees is protected.

[00168] Because the plants can be located throughout the world, this can minimize the fuel consumed while distributing fuels to end users.

[00169] With all these benefits, the cost and energy balance equations are very much in favor of our system.

Quantitative Impact: Scaling Calculation

[00170] The following calculations were made to determine the number of vessels and ocean surface area required to replace the US daily consumption of petroleum distillate. First, the time needed for a culture to start at an initial concentration, P_i , and grow to a final extended vessel concentration, P_f , needs to be

calculated from Equation 1, shown in FIG. 13. Once the time is calculated the biomass and lipid production rates per vessel can be determined from equations 2 and 3 shown in FIG. 13, respectively.

[00171] Since glycerol is replaced by methanol or ethanol during the triglyceride transesterification, we assumed that the lipid content weight is approximately equal to the biodiesel product weight. As a result, the biodiesel production rate per vessel is approximated by equation 4 shown in FIG. 13.

[00172] Now that the biodiesel production rate per vessel has been approximated, we can determine the ocean farm size required to displace the petroleum distillates used by the United States each day by equations 5 and 6 shown in FIG. 13.

[00173] The results of the above calculations based on literature values for the growth rate are listed in the table shown in FIG. 14. In order to greatly reduce the vessel requirement numbers in FIG. 14, we can engineer the vessel and the strains to achieve a significantly higher specific growth rate, initial culture density (P_i) and final culture density (P_f). Improving the above three factors can increase the overall system productivity and lower the total vessel requirement. At the very least, we believe that this system can replace 25% of the petroleum fuel consumption in the United States.

Application: Renewable Fuel and Protein Synthesis

[00174] In some embodiments of the invention, the vessels are located around oil drilling platforms off the US Pacific and Gulf of Mexico coastlines. Offshore drilling platforms have been in the service of the oil industry for decades. Once the oil reserves are depleted, these platforms are capped and left to decay into man-made reefs. These inactive offshore platforms dot the Gulf of Mexico coastline without a useful purpose until now. Offshore platforms are ideal for mooring aquacultures. FIG. 6 displays a possible layout around an out of service drilling platform **600**. The platform offers a place to harvest and process the microalgae on site into renewable hydrocarbon fuels, protein supplements, and glycerol which is preferred because it is more efficient to transport liquid fuels. As shown in FIG. 6, a tanker or river barge retrofitted with the tools necessary for doing the microalgae to renewable fuels conversion at sea is also a viable option.

[00175] In some embodiments, one or more vessel **602** may be provided upstream of the platform **600**.

Application: Bioremediation of Coastal Estuaries and River Deltas

[00176] The devices and methods described herein can be used for remediating coastal estuaries and river delta regions, as shown in FIG. 7. The right-hand side of FIG. 7 shows two potential implementation points on tributaries that release into the Chesapeake Bay estuary. As an example, the vessels **700** can be implemented for nitrogen and phosphorus micronutrient bioremediation along rivers and tributaries prior to reaching coastal estuaries and river deltas. Microalgae grown in vessels described herein can be processed into purified proteins and hydrocarbon fuels that may be packaged and sold in the local markets. There may be fewer policy hurdles to cross to clean up coastal dead zones and an opportunity to build a positive reputation with the United States government and the American people.

[00177] Along the coast and tributaries, iron is usually not the limiting nutrient. Once the deficient nutrients for microalgae growth are identified, they can be fed into the vessel in quantities that correlate to the biomass density. The rate at which nutrients are fed into the vessel may be proportional to the uptake

rate determined in a laboratory closed water time course experiment. Controlling the harvest rate may directly affect the microalgae concentration and indirectly affect the nitrogen and phosphorus uptake rate. As described before, the harvested microalgae can be processed on site into renewable hydrocarbon fuels, concentrated proteins, and glycerol to be sold on the local markets. These alternative profit streams ensure that this remediation endeavor is economically viable. As shown in FIG. 7, the processing plant **702** can be located on land rather than on water because land is nearby.

[00178] Any components, configurations, characteristics, features, or steps as known in the art may be used in any of the embodiments discussed herein. See, e.g., Kalra, A. and W. S. LLP. (2006). "BiodieselTax Credits"; Walford, L. A. (1958). *Living Resources of the Sea: Opportunities for Research and Expansion*. New York, Ronald Press; and Löscher, B. M. (1999). "Relationships among Ni, Cu, Zn, and major nutrients in the Southern Ocean." *Marine Chemistry* 67: 67-102, which are hereby incorporated by reference in their entirety.

Nutrient Concentration

Vessel with a bioharvester and a magnetic field source

[00179] Nutrients that can promote the growth of microorganisms, herein also "fertilizers," may be concentrated and/or recycled. Nutrients may be concentrated and/or recycled using a Magneto Hydro Fertilizer Concentrator (MHFC), operating on the principle of magnetohydrodynamics. In some cases, the size of the concentrator can be the size of a railroad car or truck trailer (e.g., having a characteristic dimension, such as a length, of about 50-100 feet) in order to facilitate its transport from the manufacturer to the end user, or it can be smaller, such as the size of a room (e.g., having a characteristic dimension of about 10-20 feet), or even smaller, such as the size of a cabinet (e.g., having a characteristic dimension of about 1-2 feet) that can fit on top of a regular-sized desk. Ion separation using magnetohydrodynamics is described in, for example, U.S. Patent No. 6,768,109 to Brokaw et al. and U.S. Patent No. 7,033,478 to Harde, which are entirely incorporated herein by reference. Nutrients may be concentrated directly in vessels described herein. In some cases, the vessels may be adapted with one or more devices that allow for concentration of nutrients from the ambient environment, such as an aquatic environment, and direct the nutrients into a region of the vessel, such as an enclosure, where microorganisms, such as algae, may grow.

[00180] A vessel can include a semi-permeable enclosure and a magnetic field source outside (or external to) the semi-permeable enclosure. The enclosure can retain a microorganism. The magnetic field source is capable of inducing a magnetic force that directs one or more water-soluble nutrients in a fluid current into the semi-permeable enclosure. The vessel can be located in an aquatic environment, such as an ocean. In such cases, the fluid in the fluid current may be, without limitation, seawater, river water, or lake water. The vessel can further include a sieved gate, which can be partially enclosed by the semi-permeable enclosure. The gate can be movable between a blocking position and an open position. The gate can be formed of stainless steel or other materials. An example of sieved gate is shown in FIG. 5 (shown as dashed lines between **C** and **A**).

[00181] The vessel can also include a self-orienting mechanism capable of orienting the direction of the vessel with respect to the direction of the fluid current flow when the vessel is positioned in the fluid current. Mechanical features, such as vane-like features, can be used to self-correct or self-orient the direction of the vessel such that a desired flow of water through the vessel is achieved. For example, one or more fin, protrusion, channel, flap, or shaped feature can be provided for the vessel. A self-orienting mechanism can be provided in a stationary position relative to the vessel, or can be movable relative to the vessel.

[00182] The vessel can include a mechanism for directing water-soluble nutrients into the semi-permeable enclosure. In some embodiments, the mechanism can be a pipe, a pump, a channel, or a passageway for conveying the nutrients, whose concentration in the fluid may be increased with the aid of a magnetic field source, into the semi-permeable enclosure. The nutrients being directed or conveyed into the enclosure can be fully dissolved in the fluid, or they can be partially precipitated, forming a slurry or suspension with the fluid. In some cases, the fluid can be seawater, such as ocean water. In other cases, the fluid can be fresh water, such as river water.

[00183] The magnetic field source can increase the concentration of the nutrients in the fluid relative to the fluid untreated with a magnetic field source by a factor of at least 1.1, or at least 1.2, or at least 1.3, or at least 1.4, or at least 1.5, or at least 2, or at least 2.5 or at least 3, or at least 3.5, or at least 4, or at least 4.5, or at least 5, or at least 6, or at least 7, or at least 8, or at least 9, or at least 10, or at least 15, or at least 20, or at least 25, or at least 30, or at least 40, or at least 50, or at least 100. In some cases, the concentration of one or more nutrients can exceed the solubility limit of the nutrient in the fluid, such that precipitation can occur. In those cases, the one or more nutrients can form a slurry or a suspension with the fluid. In those cases, the pipe, pump, channel, or passageway for conveying the nutrients can be large enough (e.g., can have a large enough diameter) such that the nutrients can be conveyed into the semi-permeable enclosure without clogging or otherwise blocking the pipe, pump, channel, or passageway. In other cases, the pipe, pump, channel, or passageway can include a filter or a membrane such that precipitated or undissolved materials in the fluid can be removed. In those cases, the fluid can be saturated with water-soluble nutrients by the time it reaches the semi-permeable enclosure.

[00184] The concentration of a nutrient in a fluid, after the fluid including the nutrient passes through an area under the influence of a magnetic field source, can increase relative to the concentration of the nutrient in the fluid that did not pass through an area under the influence of a magnetic field source. In some embodiments, the concentration of a nutrient in the fluid can increase to 0.0001 mol/L (M), or 0.0005 M, or 0.001 M, or 0.005 M, or 0.01 M, or 0.05 M, or 0.1 M, or 0.5 M, or 1 M, or 1.5 M, or 2 M, or 3 M, or 4 M, or 5 M, or 6 M, or 7 M, or 8 M, or 9 M, or 10 M after the fluid including the nutrient passes through the area under the influence of a magnetic field source. After the fluid including the nutrient enters the area under the influence of a magnetic field source, the fluid can be separated into two or more streams. One of the streams can include the fluid with a higher concentration of the nutrient than the fluid before it reached the area under the influence of a magnetic field source, while another stream can include the fluid with a lower concentration of the nutrient than the fluid before it reached the area under the influence of a magnetic field

source. In some cases, the two or more streams can be separated. The stream including the nutrient with an increased concentration can be conveyed into the semi-permeable enclosure, while the stream including the nutrient with a reduced concentration can be conveyed back into an area outside the vessel, such as an aquatic environment.

[00185] The vessel can include a mechanism for increasing the velocity of the fluid current. The fluid current, such as a current of the flow of seawater or river water, can have its own natural velocity. The mechanism can increase the velocity by, for example, reducing the flow cross-sectional area, such as by a narrowing passageway, or channel, that focuses the flow of current from the ambient environment into the vessel, including the part of the vessel that can be under the influence of a magnetic field source. The channel can increase the velocity of the natural current by a factor of at least 1.1, or at least 1.2, or at least 1.3, or at least 1.4, or at least 1.5, or at least 2, or at least 2.5 or at least 3, or at least 3.5, or at least 4, or at least 4.5, or at least 5, or at least 6, or at least 7, or at least 8, or at least 9, or at least 10, or at least 15, or at least 20, or at least 25, or at least 30, or at least 40, or at least 50, or at least 100. The velocity of the current, after the current undergoes an increase in the velocity in the passageway or channel, can be at least 0.5 m/s, or at least 1 m/s, or at least 1.5 m/s, or at least 2 m/s, or at least 2.5 m/s, or at least 3 m/s, or at least 3.5 m/s, or at least 4 m/s, or at least 4.5 m/s, or at least 5 m/s, or at least 5.5 m/s, or at least 6.5 m/s, or at least 7 m/s, or at least 8 m/s, or at least 8.5 m/s, or at least 9 m/s, or at least 9.5 m/s, or at least 10 m/s, or at least 12 m/s, or at least 15 m/s, or at least 20 m/s, or at least 25 m/s, or at least 30 m/s, or at least 40 m/s, or at least 50 m/s.

[00186] The water-soluble nutrients can include electrolytes. Electrolytes in some cases can include free, or dissociated, ions in a solution. The ions can be dissolved in water or other fluid. In some cases, the electrolytes can be in the form dissolved salts, but they can also be solutions of acids and bases. Electrolytes can make the substance in which they are dissolved electrically conductive.

[00187] Electrolytes described herein can include various ionic, acidic, or basic substances. Among ionic substances, some can include cations such as lithium, sodium, potassium, rubidium, cesium, magnesium, calcium, strontium, barium, scandium, yttrium, titanium, zirconium, vanadium, niobium, tantalum, chromium, manganese, tungsten, manganese, rhenium, iron, ruthenium, cobalt, rhodium, iridium nickel, palladium, platinum, copper, silver, gold, zinc, aluminum, gallium ammonium, phosphonium, and other cations. These cations can have the charge of +1, +2, +3, +4, +5, +6, or +7. Among ionic substances, some can include anions such as fluoride, chloride, bromide, iodide, oxide, sulfide, nitride, carbonate, nitrate, nitrate, phosphate, phosphite, tungstate, molybdate, chlorite, chlorate, bromite, bromate, acetate, sulfite, sulfate, hydrogen carbonate, hydrogen phosphate, silicate, borate, aluminate, cyanide, thiocyanate, hydroxide, permanganate, oxalate, vanadate, chromate, and dichromate. These anions can have the charge of -1, -2, -3, -4, -5, -6, or -7. In a fluid solution, the cations and anions are separated from one another and are typically surrounded by molecules of the fluid, such as water. In an undissolved form, these cations and anions can be combined to form salts, such magnesium chloride, potassium nitrate, calcium carbonate, sodium phosphate, calcium bromide, silver oxalate, copper chloride, nickel phosphate, zinc iodide,

ammonium chloride, tetrabutylammonium bromide, and barium silicate, where the cations and anions are bound to each other via ionic bonds, sometimes in an ionic lattice.

[00188] Electrolytes described herein can also include acids, such as acetic acid, phosphoric acid, phosphorous acid, carbonic acid, hydrochloric acid, hydrobromic acid, sulfuric acid, sulfurous acid, or hydrogen sulfide; or bases, such as potassium hydroxide, sodium hydroxide, magnesium hydroxide, calcium hydroxide, nickel hydroxide, or silver hydroxide. As with the other electrolytes described herein, these materials can be bound together via ionic bonds in their respective undissolved forms, and can be surrounded by molecules of a fluid, such as water, once dissolved. Acids and bases can also form suspensions or slurries with the fluid.

[00189] The magnetic field source, which can be located outside of the semi-permeable enclosure, can include a permanent magnet. A permanent magnet can be formed of iron alloy, cobalt alloy, nickel alloy, or another suitable material. The magnetic field source can also include an electromagnet that can induce a magnetic field. An electromagnet can be formed of coils and include a core. An example of an electromagnet is shown in FIG. 3C. Other examples of electromagnets are shown in FIGs. 12A and 12B. The field strength of the electromagnet is approximated by Ampere's Law as $\mathbf{B} = \mu_0 \eta \mathbf{I}$, where μ_0 is the permeability of the core, η is the number of turns per unit length, $\mathbf{I}$ is the current, and $\mathbf{B}$ is the magnetic field strength. The magnetic field strength, or $\mathbf{B}$, is directly proportional to the current. The current can be regulated by changing the resistance in the circuit. In some cases, the electric current can flow through an electrode, which may be a graphite electrode. The electrode can further be connected to a wire that may be used to complete the circuit.

[00190] Either the permanent magnet or the electromagnet can have the field strength of at least about 1 millitesla (mT), or at least about 2 mT, or at least about 3 mT, or at least about 4 mT, or at least about 5 mT, or at least about 6 mT, or at least about 7 mT, or at least about 8 mT, or at least about 9 mT, or at least about 10 mT, or at least about 15 mT, or at least about 15 mT, or at least about 20 mT, or at least about 25 mT, or at least about 50 mT. In some cases, the magnetic field source can fully or partially surround the fluid current. In some cases, the strength of the magnetic field provided by a magnet can be amplified by plates positioned near the magnet, such as plates formed of steel or iron.

[00191] When the magnetic field source fully or partially surrounds the fluid current, a force can be imparted on charged particles within the fluid current. The force $\mathbf{F}$ is determined by the formula $\mathbf{F} = (q\mathbf{v})(\mathbf{B})$, where q is the charge of the particle (e.g., +1, +2, +3, -1, -2, -3, and so on), $\mathbf{v}$ is the velocity of the fluid current flow (e.g., the velocity of the charged particle), and $\mathbf{B}$ is the magnitude of the magnetic field. The force can be orthogonal both to the direction of the magnetic field and to the direction of the fluid current flow, and the direction of the force can vary depending on whether the charge is positive or negative. This force is sometimes called electromotive force (EMF) or a Lorentz force. FIG. 15 schematically illustrates the effect of the Lorentz force on charged particles (where the direction of the magnetic field $\mathbf{B}$ is up out of the plane of the page).

[00192] The vessel can further include one or more membranes that aid in the concentration the nutrients. The membranes selectively allow passage of charged particles through the membranes. In some cases, a membrane can selectively allow anions to pass through, and block out most or all other species (e.g., cations or uncharged species). Such a membrane may be called an anion-selective membrane. In other cases, a membrane can selectively allow cations to pass through, and block out most or all other species (e.g., anions or uncharged species). Such a membrane can be called a cation-selective membrane. In some cases, anion-selective membranes can be positively charged, and cation-selective membranes can be negatively charged. Anions and cations can be driven toward the anion-selective membrane and the cation-selective membrane, respectively, by the Lorenz force acting on the anions and the cations. In some cases, anions that have passed through an anion-selective membrane and cations that have passed through the cation-selective membrane flow through two separate channels that are then joined in a single channel where the cations and anions are combined. In such cases, the concentration of anions and cations in the single channel can be higher than in the fluid current flow before it experienced the influence of a magnetic field. The anions and cations can be further directed into the semi-permeable enclosure, for example via a passageway or a pipe. In some cases, each of the channels can have one or more electrodes, which can be used to provide a current for a magnetic field. In some embodiments, each channel can have two oppositely charged electrodes. In some cases, the electrodes can be parallel to one another.

[00193] In contrast to the charged particles, uncharged particles (e.g., molecules of the fluid solvent, such as water, or oil molecules, such as hydrocarbon molecules), may not experience a Lorentz force and may not deviate from the direction of the current flow as may charged particles schematically depicted in FIG. 15. Such particles may not pass through the cation or anion-selective membranes, and can become directed to a different channel or channels than the charged particles. Such particles can further be directed away from the semi-permeable enclosure, for example via pump or a pipe. In some cases, such particles can be directed back into the aquatic environment as part of a discharged fluid. The discharged fluid can have a lower anion and cation concentration than in a fluid current flow before it experienced the influence of a magnetic field. In some embodiments, a sensor or a probe can be located downstream of a location where a fluid current passes the influence of a magnetic field, so that changes in electrolyte, including ion, concentrations can be measured. The sensor or probe can also measure the rate of increase or decrease of electrolyte concentration over time. For example, a probe can be inserted into the channel or channels expected to have an increased concentration of electrolytes, or into the channel or channels expected to have a depleted concentration of electrolytes. Some probes can be equipped to measure concentrations of a specific ion, such as nitrate or phosphate.

[00194] FIG. 16 schematically illustrates a vessel that includes a bioharvester and a magnetic field source, in accordance with an embodiment of the invention. The vessel **100** includes a bioharvester module **110**, such as a module depicted in FIGs. 2a and 2b, and magneto-concentrator module **120**. The bioharvester module **110** includes a semi-permeable membrane **130**, a gate **140**, which may be a sliding gate, and an enclosure **150**, where microorganisms such as algae may grow. Magneto-concentrator module **120** may

include a magnetic field source **160**, which may be a permanent magnet or an electromagnet, and which may partially or fully surround other components of the magneto-concentrator module **120**. Magnetic field source **120** may generate a magnetic field **170**, depicted herein by an “X” which indicates that the direction of magnetic field **170** is into the plane of the page. Magnetic field **170** generates a Lorentz force **180** on charged particles that enter the magneto-concentrator module **120** via a fluid current **190**, which may have velocity “**v**.” A channel **200** may increase the velocity **v** of the fluid current. The channel **200** can be a narrowing channel, having a width (as measured along an axis orthogonal to the direction of flow) that decreases along the direction of flow. Once inside the magneto-concentrator module **120**, charged particles in the fluid current (positively charged particles are indicated by “+” and negatively charged particles are indicated by “-”) experience Lorentz force **180**, which drives negatively charged and positively charged particles in opposite directions. Positively charged particles may pass through a cation-permeable membrane **210** and negatively charged particles may pass through an anion-permeable membrane **220**, as indicated by the arrows. A fluid with reduced anion and cation (e.g., electrolyte) concentration (relative to electrolyte concentration in the fluid current **190**) continues to flow in the diluent channel **230** and is removed from vessel **100** via a discharge pipe **240** (circle indicates flow direction of the discharged fluid is out of the plane of the page). Cations and anions that have passed the cation- and anion-permeable membranes, respectively, enter electrolyte channel **250**, which carries the fluid with an increased electrolyte concentration relative to electrolyte concentration in the fluid current **190**. As electrolytes are being collected from electrolyte channel **250** into bioharvester module **110**, gate **140** may be open. After collection is complete, gate **140** may be closed so that bioharvester module **110** and magneto-concentrator module **120** may be isolated from one another. Some electrolytes thus collected may include nutrients, and they may aid in the growth of microorganisms, such as algae, within enclosure **150**.

A system including a module that retains microorganisms and a module that includes a magnetic field source

[00195] An aspect of the invention includes a system having a first module comprising a buoyant top, a buoyancy-controlled base, and a semi-permeable enclosure connecting the buoyant top to the buoyancy-controlled base. The first module can be adapted to retain one or more microorganisms upon the flow of a fluid stream through the first module. The system further comprises a second comprising a magnetic field source that is configured to provide a magnetic field into the second module, such that the second module is adapted to concentrate ionic species upon the flow of the ionic species or a fluid having the ionic species through the second module along a direction generally orthogonal to the magnetic field. The magnetic field source can be as described elsewhere herein. The second module can be adjacent to the first module. In some cases, the second module is not adjacent the first module. For example, the second module can be disposed remotely with respect to the first module, such as at a different depth and/or lateral location than the first module. Ionic species concentrated in the second module can be directed to the first module with the aid of a pumping system and one or more channels bringing the first module in fluid communication with the second module.

[00196] In some embodiments, the first module and the second module can be separated by a distance. The distance can be about 1 cm, or about 10 cm, or about 1 m, or about 10 m, or about 100 m, or 500 m about 1 km, or about 2 km, or about 3 km, or about 4 km, or about 5 km, or longer. In some cases, the first module can be positioned at the same depth, e.g., the same depth in the aquatic environment, as the second module. In other cases, the first module can be positioned at a different depth than the second module. In an example, the second module can be positioned deeper than the first module. In some cases, the first module can be positioned closer the fluid surface, while the second module can be positioned closer to the floor of the fluid, such as, for example, ocean floor. In some cases, the second module can be configured in such a way as to withstand fluid pressure. In some embodiments, the second module can be positioned in an area of the aquatic environment where fluid current velocity is high relative to other areas of the aquatic environment. Fluid current velocity can be measured by techniques known in the art, such as described in, for example, U.S. Patent No. 6,820,008 to van Smirren et al., which is entirely incorporated herein by reference. In some embodiments, the second module can be positioned in an area of the aquatic environment where electrolyte concentration is high relative to other areas of the aquatic environment. Electrolyte concentration can be measured by sensors known in the art, such as described in, for example, U.S. Patent Publication. No. 2008/0302660 to Kahn et al., which is entirely incorporated herein by reference. Such sensors can be electrically coupled to a control system that is adapted to regulate the buoyancy of one or both of the modules.

[00197] The buoyancy of the first and second modules can be regulated with the aid of a device that regulates depth, such as, for example, a gas tank that operates under Archimedes' principle. The control system can be coupled to sensors that measure ionic concentration to regulate the depth of the second module to aid in optimizing ion capture. For example, the depth of the second module can be selected such that the concentration of ions is increased or maximized in relation to another depth.

[00198] Concentrated ions from the second module may be directed to the first module either manually (e.g., manually removing the ions from the second module), or with the aid of a fluid flow system that directs the concentrated ions to the first module. The fluid flow system can comprise a pipe or channel that brings the first module in fluid communication with the second module. The fluid flow system can include a pump for facilitating fluid flow.

[00199] The first module may be a vessel-type object such as that depicted in Figs. 2A and 2B, and further described herein. The first module can be a bioharvester module, such as that depicted in FIG. 16 (e.g., bioharvester **110**). Microorganisms such as algae may be grown in the first module, a semi-permeable membrane may enable the first module to selectively retain microorganisms from a fluid stream, such as a seawater or river current.

[00200] The second module may include a magneto-concentrator, such as that depicted in FIG. 16 (e.g., magneto-concentrator **120**). As depicted in FIG. 16, the direction of the fluid current, including that of ionic species (e.g., electrolytes), is orthogonal to the direction of the magnetic field generated by a magnetic field source. Ionic species may be concentrated with the aid of cation- and/or anion-selective membranes, in the

manner shown in FIG. 16 (e.g., membranes **210** and **220**) and described herein. The magnet may be a permanent magnet or an electromagnet, and have a field strength of at least about 1 millitesla (mT), or at least about 2 mT, or at least about 3 mT, or at least about 4 mT, or at least about 5 mT, or at least about 6 mT, or at least about 7 mT, or at least about 8 mT, or at least about 9 mT, or at least about 10 mT, or at least about 15 mT, or at least about 15 mT, or at least about 20 mT, or at least about 25 mT, or at least about 50 mT. The magnet may partially or fully surround the second module. The magnet may be in the form of a coil, as depicted, for example, in FIGs. 12A and 12B.

[00201] In some cases, the second module may be attached to the first module. In other cases, the second module may be coupled to the first module via a pipe or a channel. The pipe or channel may be configured to direct fluid flow from the second module to the first module. In some cases, the pipe or channel may direct a fluid including concentrated ionic species from the second module to the first module, as in the manner depicted in FIG. 16 (e.g., from magneto-concentrator **120** to bioharvester **110**). Concentrated ionic species may also be actively transported from the second module to the first module via a third module, which may be a device such as a pump. The second module may also include a pipe, channel, or pump for discharging a fluid with reduced concentration of ionic species into the aquatic environment.

[00202] In some cases, the semi-permeable membrane of the first module is collapsible or compressible, as depicted in FIGs. 2A and 2B. In some cases, the buoyancy-controlled base of the first module is movable with respect to the buoyant top, as described herein.

[00203] FIG. 17 schematically depicts an example of a second module. A current of fluid, including electrolytes, flows into the second module through a channel (**A**), which may increase the velocity of the current and the electrolytes within the current. After the magnetic field source operates on the electrolyte current to concentrate electrolytes in the manner described herein, the fluid with a reduced concentration of electrolytes flows out of the second module via a discharge pipe (**B**). The concentrated ionic species are collected into a pipe (**C**) and driven with the aid of a pump into the first module.

[00204] FIG. 18 provides another schematic view of a second module. A current of fluid, including electrolytes, flows into the second module through a channel (**A**), which may increase the velocity of the current and the electrolytes within the current. A magnetic field source (**E**) may surround the channel. The magnetic field creates a Lorentz force such that a dipole is effectively formed across the second module, with a “cathode” region (**D**) to which cations are attracted, and an “anode” region (**F**) to which anions are attracted. The concentrated ionic species are collected with into a pipe (**C**) and driven with the aid of a pump into the first module. The fluid with a reduced concentration of electrolytes flows out of the second module via a discharge pipe (**B**).

[00205] FIG. 19 provides still another schematic view of a second module. A current of fluid, including electrolytes, flows into the second module through a channel (**A**), which may increase the velocity of the current and the electrolytes within it. A magnetic field source (**E**) may surround the channel. The concentrated ionic species are collected with into a pipe (**C**) and driven with the aid of a pump into the first

module. The fluid with a reduced concentration of electrolytes flows out of the second module via a discharge pipe (B).

Methods for generating biomass

[00206] An aspect of the invention includes a method for collecting and/or generating biomass. The method includes providing a microorganism from an aquatic environment into a vessel configured to retain the microorganism, with the vessel comprising at least one semi-permeable membrane that permits the unidirectional flow of the microorganism through the membrane, concentrating one or more nutrients from the aquatic environment with the aid of a magnetic field applied to a fluid stream flowing from the aquatic environment into the vessel, and providing the one or more concentrated nutrients into the vessel. The semi-permeable membrane can allow fluid from the aquatic environment to pass freely while impeding diffusion of the microorganism out of the vessel.

[00207] The nutrients can be water-soluble. The nutrients can include electrolytes, such as salts, acids, and basis, as described herein. In water or another fluid, such as a fluid providing a fluid current, electrolytes can be dissociated into cations and anions. In some cases, the electrolytes can function as nutrients, aiding, for example, in the growth of microorganisms such as algae. Nutrient cations in fluid streams that can be concentrated with the aid of a magnetic field source include sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), aluminum (Al^{3+}), ammonium (NH_4^+) and other cations as described herein. Nutrient anions in fluid streams that can be concentrated with the aid of a magnetic field include nitrate (NO_3^-), phosphate (PO_4^{3-}), chloride (Cl^-), acetate ($\text{H}_3\text{C}(\text{O})\text{O}^-$), carbonate (CO_3^{2-}) and other anions as described herein.

[00208] In some cases, the magnetic field applied to a fluid stream is provided by a permanent magnet. In other cases, the magnetic field applied to a fluid stream is provided by an electromagnet. The permanent magnet or electromagnet can be in the form of a coil.

[00209] An aquatic environment can include a natural aquatic environment such as river water, seawater, ocean water, or lake water, or a man-made aquatic environment such as a pool, algae farm, or tank. In some cases, the aquatic environment can provide its own (e.g., natural) electrolytes and/or nutrients. In other cases, the electrolytes and/or nutrients can be provided from an external source, which can include recycled nutrients. The nutrients from the aquatic environment can be concentrated in the vessel with the aid of a magnetic field and with the further aid of one or more ion-selective membranes, which can include a cation-selective membrane and an anion-selective membrane. The nutrients can be driven into the vessel with the aid of a pipe and/or a pump, and retained in the vessel with the aid of the vessel's semi-permeable membrane. After the concentration of one or more nutrients in the vessel, a fluid, such as water, with a reduced concentration of nutrients can be released back in to the aquatic environment.

[00210] Ion-selective membranes can include polymeric species, such as materials used in electrodialysis applications. For example, an anion-selective membrane can include metalloporphyrins or metallo-crown ethers bound in a polymeric array, while a cation-selective membrane can include carbonate, phosphate, or acetate groups bound in a polymeric array. The polymer backbone of anion- or cation-selective membranes can include a polyethylene, polypropylene, polystyrene, or polystyrene-pyridine co-polymer.

[00211] In some cases, the one or more ion-selective membrane(s) can operate chemoselectively. The membranes can permit nutrients such as nitrates and phosphates to pass through into the vessel, but may not permit electrolytes that may be less nutritively valuable, such as chlorides, to pass through into the vessel. In some embodiments, the membranes can include one or more zeolites or other functionalities or surface-active agents that are configured to trap, for example, chloride ions preferentially over other ions such as phosphates or nitrates. Such agents may include sodalite, zeolite A, zeolite XY, and zeolite Y. In some cases, chloride ions can be trapped preferentially over nitrates or phosphates in part because of the size difference between the smaller chloride ion relative to the larger phosphate or nitrate ions, such that the latter (e.g., phosphate, nitrate) might not fit into the zeolite structure. In such cases, the membrane, such as an anion-selective membrane, can still function to separate anions from cations because anions will be attracted to the positive charge on the zeolite, but the larger anions (e.g., phosphate, nitrate), will not be trapped and pass through to the vessel, while the smaller anions (e.g., chloride) may be trapped in the zeolites. In some cases, zeolitic structures can be incorporated into polymeric backbone of the anion- or cation-selective membranes.

[00212] In some embodiments, ions pass through the ion-selective membranes on the basis of their charge. In an example, magnetic field strength can be adjusted (e.g., reduced or increased) in such a way that the Lorentz force is sufficient to enable only trivalent ions (e.g., phosphate) to pass through an ion-selective membrane, while the Lorentz force on monovalent ions (e.g., chloride) may not be sufficiently strong to enable a chloride ion to pass through an ion-selective membrane. In other cases, the magnetic field strength can be adjusted such that certain ions are selectively separated in relation to other ions. For example, trivalent ions can be selectively separated in relation to monovalent and/or divalent ions by appropriately selecting the magnetic field strength. In some cases, magnetic field can be adjusted throughout the period that ions are collected to permit selective concentration of monovalent, divalent, trivalent, or tetravalent cations at desired times. In some cases, higher-valent ions, such as phosphates, can have higher nutritive value than lower-valent ions, such as chlorides. Selective ion separation in some cases can be facilitated with the aid of ion permeable membranes that are selected to permit only certain ions to pass through.

[00213] A microorganism can include algae, microalgae, plankton, diatoms, phytoplankton, zooplankton, or other species as described herein. The microorganisms naturally occur in the aquatic environment, or can be provided from an external source into the aquatic environment. The microorganisms can flow into the vessel from the aquatic environment in a fluid stream, or can be placed into the vessel by a human operator.

Methods of fertilizer concentration and electrolyte removal

[00214] An aspect of the invention provides a method for recycling one or more agricultural fertilizers. The method includes providing an agricultural runoff, filtering the agricultural runoff to form a first fluid, concentrating one or more fertilizers from the first fluid with the aid of a magnetic field applied to the first fluid, thereby forming a second fluid comprising one or more concentrated fertilizers. The second fluid comprising one or more concentrated fertilizers can then be collected.

[00215] Electrolytes such as fertilizers can also be removed from fluids using methods and modules (e.g., magnetic concentrator modules) described herein. Electrolytes can be concentrated and/or removed from

fluids using methods and modules (e.g., magnetic concentrator modules) described herein. In some cases, electrolyte concentration in a fluid containing one or more electrolytes, such as water containing fertilizers from agricultural run-off, can be reduced with the aid of a magnetic concentrator. Fertilizers can include nitrates and phosphates. In some cases, the fluid can be filtered before coming under the influence of a magnetic field source. The fluid can be filtered through, for example, clarifier plates.,

[00216] A magnetic concentrator utilizing an applied magnetic field can be used to separate a fluid into a first stream comprising a high electrolyte concentration and a second stream comprising a low electrolyte concentration. In an example, a unit such as magnetic concentrator **120** depicted in FIG. 16 may be used, with except that the concentrated electrolyte stream **250** may be recovered not in a bioharvester, but in a different kind of unit, such as for example, a tank for collecting fluid, and that the depleted electrolyte stream **230** may be recovered in a different tank rather than discharged into the aquatic environment. In some cases, the fluid can be filtered to remove some solids before reaching the magnetic concentrator.

[00217] FIG. 20 schematically illustrates a fertilizer recycler, in accordance with an embodiment of the invention. Agricultural runoff (**A**) enters a chamber comprising clarifier plates (**C**) and solids drainage point (**B**). Clarifier plates filter away some of the solids in the agricultural runoff, which enters the drainage point. The resulting solids sludge (**E**) is removed from the chamber via a pump. The filtered fluid enters fertilizer concentrator chamber (**D**), which can then come under an influence of a magnetic field. Upon operation of a magnetic field, concentrated electrolyte stream (**H**) is recovered via a pump to make concentrated fertilizer (**J**), which may be reused. The concentrated electrolyte may be partially recycled in the system via loop (**I**).

[00218] FIG. 21 provides another view of a fertilizer recycler. A clarified fluid enters a fertilizer concentrator chamber (**D**), and then comes under an influence of a magnetic field source (**F**), creating a diluted stream (**G**) and a concentrated stream, such as that shown as (**H**) in FIG. 20. Diluted stream (**G**) may be discharged into the aquatic environment or reused (as, for example, potable water).

Example 1

[00219] FIG. 22 illustrates an exemplary magnetic fertilizer concentrator (or recycler) **300**. The fertilizer concentrator (or recycler) **300** has a fluid intake screen **310** which has one or more holes **320** that can help, for example, control fluid flow. The concentrator can also have a funnel or narrowing channel **330** that can help, for example, increase the velocity of fluid flow. Fluid flows into concentrator chamber **340** which can be equipped with a magnet **350**, which can be a permanent magnet, and an electrode **360**, which can be a graphite electrode. The concentrator chamber **340** can also be equipped with membrane **360**, which can be an electrodialysis membrane, and plate **380**, which can be formed of steel or iron and can aid in increasing the strength of the magnetic field. The concentration chamber **340** can be further equipped with probe **390**, which can be configured to measure, for example, ion (e.g., nitrate, sodium, chlorine, etc.) concentration in the fluid in the chamber, and wire **395**, which can be connected to electrode **360** and used to complete an electric circuit.

[00220] During use, fluid flows into the concentrator **300** from the intake screen **310** and into the narrowing channel **330**. Fluid then flows into the concentration chamber **340**. Upon the flow of charged

species through a magnetic field provided by the magnet **350**, the force generated by the charged species affects the concentrations of the ions in various chambers of the concentrator **300**.

[00221] FIG. 23 illustrates a close-up of the concentrator chamber **340**, which can have a magnet **350**, an electrode **360**, a membrane **370**, a plate **380**, a probe **390**, and a wire **395**.

[00222] FIG. 24 illustrates a view of the fluid intake screen **310** having one or more holes **320** and optionally equipped with an attachment point **325**, which can be configured to attach, for example, a pump. A fluid, such as water (for example, seawater in a current, which can include electrolytes such as salts), can pass through the holes **320** in the screen **310** and enter the fertilizer concentrator or recycler.

[00223] FIG. 25 illustrates a view of a concentrator chamber **340** which can have an inner channel **410** and outer channels **420a** and **420b**. The outer channels **420a** and **420b** can have magnets **350a** and **350b**, outer channel electrodes **360a** and **360b** (which have opposite charge – for example, **360a** can be positively charged and **360b** can be negatively charged), membranes **370a** and **370b**, and plates **380a** and **380b**. The inner channel **410** can have a probe **390**, which can be a nitrate probe and can measure changes in electrolyte concentrations, and inner channel electrodes **430a** and **430b**, which can have a charge opposite to that of the nearest outer channel electrode. For example, when outer channel electrode **360a** is positive and outer channel electrode **360b** is negative, inner channel electrode **430a** is negative and inner channel electrode **430b** is positive. When electrolytes, such as salts having positively and negatively charged ions, flow into concentrator chamber **340**, the magnetic field generated by magnets **350a** and **350b** can direct ions of opposite charge through membranes **370a** and **370b**. For example, when electrode **360a** is positively charged and electrode **360b** is negatively charged, negatively and positively charged ions can flow into inner channel **410** through membranes **370a** and **370b**, respectively. This can result in increased ion concentration in inner channel **410** and decreased ion concentration in outer channels **420a** and **420b**. The outer channels **420a** and **420b** can further be equipped with a probe adapter **440** such that a probe, such as probe **390**, can be inserted in order to measure the rate of electrolyte depletion.

[00224] FIG. 26 illustrates a view of an outer channel **420** of a concentrator chamber having magnet **350**, electrode **360**, and plate **380**.

[00225] FIG. 27 illustrates another view of an outer channel having magnet **350**, electrode **360** (which can be a graphite electrode), membrane **370**, and plate **380**. The magnet is parallel to the electrode **360**. The magnet **350** and electrode **360** are oriented parallel to the general direction of fluid flow through the concentrator chamber **340**.

[00226] FIG. 28 illustrates another view of a fluid intake screen **310** having one or more holes **320** and funnel **330**. A width (or other characteristic dimension orthogonal to the general direction of fluid flow, such as diameter) of the funnel **330** gradually decreases along the direction of fluid flow (from left to right). In some cases, the width experiences a sudden decrease, as may be the case in a flow restricting Venturi, such as in a converging-diverging nozzle.

Example 2

[00227] A magnetic concentrator, such as magnetic concentrator **300**, is placed in ocean water at a depth of about 150 meters (m). The size of the concentrator can be the size of a railroad car or truck trailer in order to facilitate its transport from the manufacturer to the end user. The magnetic concentrator is connected to a bioharvester at ocean surface level and a longitudinal distance of 200 m away from the magnetic concentrator. At time (t) = 0 (e.g., immediately upon placement of a concentrator in ocean water), a nitrate probe, such as probe **390**, measures a concentration of 40 μM of nitrate ions in the inner channel of the magnetic concentrator's concentration chamber, such as inner channel **410**. At t = 1 hour (e.g., 1 hour upon placement of a concentrator in ocean water), the concentration of nitrate ions is 840 μM in the inner channel of the concentration chamber. In other locations, such as rivers with filled with agricultural runoff, the concentrator can be locate at the water surface rather than at some depth within the water, since in such aquatic environments the electrolyte concentration can be highest at the water surface rather than deeper in the aquatic environment, as in ocean water.

[00228] It should be understood from the foregoing that, while particular implementations have been illustrated and described, various modifications can be made thereto and are contemplated herein. It is also not intended that the invention be limited by the specific examples provided within the specification. While the invention has been described with reference to the aforementioned specification, the descriptions and illustrations of the preferable embodiments herein are not meant to be construed in a limiting sense. Furthermore, it shall be understood that all aspects of the invention are not limited to the specific depictions, configurations or relative proportions set forth herein which depend upon a variety of conditions and variables. Various modifications in form and detail of the embodiments of the invention will be apparent to a person skilled in the art. It is therefore contemplated that the invention shall also cover any such modifications, variations and equivalents.

CLAIMS

WHAT IS CLAIMED IS:

1. A vessel, comprising:
a semi-permeable enclosure that retains a microorganism; and
a magnetic field source outside of the semi-permeable enclosure, said magnetic field source adapted to induce a magnetic force that concentrates one or more water-soluble nutrients in a fluid current for introduction into the semi-permeable enclosure.
2. The vessel of Claim 1, further comprising a sieved gate that is at least partially enclosed by the semi-permeable enclosure, wherein the sieved gate is movable between a blocking position and an open position.
3. The vessel of Claim 1, further comprising a self-orienting mechanism capable of orienting the direction of the vessel with respect to the direction of the fluid current flow when the vessel is positioned in the fluid current.
4. The vessel of Claim 1, further comprising a pump for directing the nutrients into the semi-permeable enclosure.
5. The vessel of Claim 1, further comprising a channel for increasing the velocity of the fluid current.
6. The vessel of Claim 1, wherein the one or more nutrients is an electrolyte.
7. The vessel of Claim 6, wherein the electrolyte comprises nitrate ions.
8. The vessel of Claim 6, wherein the electrolyte comprises phosphate ions.
9. The vessel of Claim 1, further comprising one or more membranes that concentrate the nutrients.
10. The vessel of Claim 9, wherein the one or more membranes are an anion-selective membrane and a cation-selective membrane.
11. The vessel of Claim 1, wherein the magnetic field source is a permanent magnet.
12. The vessel of Claim 1, wherein the magnetic field source is an electromagnet.
13. The vessel of Claim 1, further comprising a pipe for discharging water having a reduced concentration of the one or more nutrients, wherein the pipe is surrounded by the magnetic field source.
14. A system, comprising:
(a) a first module comprising a buoyant top, a buoyancy-controlled base, and a semi-permeable enclosure connecting the buoyant top to the buoyancy-controlled base, wherein the first module is adapted to retain one or more microorganisms upon the flow of a fluid stream through said first module; and
(b) a second module adjacent to said first module, said second module having a magnetic field source that is configured to provide a magnetic field into said second module, wherein said second module is adapted to (i) concentrate ionic species upon the flow of said ionic species through said second module along a direction orthogonal to said magnetic field, and (ii) supply concentrated ionic species to said first module.
15. The system of Claim 14, wherein the magnetic field source is a permanent magnet or an electromagnet.
16. The system of Claim 15, wherein the magnetic field source is a permanent magnet in the form of a coil.

17. The system of Claim 14, wherein the first module is coupled to the second module via a pipe that is configured to direct fluid flow from said second module into said first module.
18. The system of Claim 14, further comprising a third module adapted to transport said concentrated ionic species from the second module to the first module.
19. The system of Claim 18, wherein the third module comprises a pump.
20. The system of Claim 14, wherein the second module comprises an anion-selective membrane and a cation-selective membrane.
21. The system of Claim 14, wherein the semi-permeable enclosure is collapsible.
22. The system of Claim 14, wherein the buoyancy-controlled base is movable with respect to the buoyant top.
23. A method for collecting and/or generating biomass, comprising:
 - (a) providing a microorganism from an aquatic environment into a vessel configured to retain said microorganism, said vessel comprising at least one semi-permeable membrane that permits the unidirectional flow of said microorganism therethrough;
 - (b) concentrating one or more nutrients from said aquatic environment with the aid of a magnetic field applied to a fluid stream flowing from said aquatic environment into said vessel; and
 - (c) providing said one or more concentrated nutrients into said vessel.
24. The method of Claim 23, wherein said one or more nutrients comprise at least one electrolyte.
25. The method of Claim 24, wherein said at least one electrolyte comprises phosphate ions.
26. The method of Claim 24, wherein said at least one electrolyte comprises nitrate ions.
27. The method of Claim 23, wherein said applied magnetic field is provided by a permanent magnet or an electromagnet.
28. The method of Claim 23, wherein said aquatic environment is seawater.
29. The method of Claim 23, further comprising (d) releasing water with a reduced concentration of said one or more nutrients into said aquatic environment.
30. The method of Claim 23, wherein said microorganism is selected from the group consisting of microalgae, plankton, diatoms, algae, phytoplankton and zooplankton.
31. The method of Claim 23, wherein the semi-permeable membrane allows fluid from the aquatic environment to pass freely while impeding diffusion of the microorganism out of the vessel.
32. The method of Claim 23, wherein, in (a), said microorganism is provided in a fluid stream from said aquatic environment into said vessel.
33. The method of Claim 23, wherein (c) comprises retaining said one or more concentrated nutrients in said vessel.
34. A method for recycling one or more agricultural fertilizers, comprising:
 - providing an agricultural runoff;
 - filtering said agricultural runoff to form a first fluid;

concentrating one or more fertilizers from said first fluid with the aid of a magnetic field applied to said first fluid to form a second fluid comprising one or more concentrated fertilizers; and collecting said second fluid comprising one or more concentrated fertilizers.

35. The method of Claim 34, wherein said one or more fertilizers comprises an electrolyte.
36. The method of Claim 35, wherein said electrolyte is a nitrate.
37. The method of Claim 35, wherein said electrolyte is a phosphate.
38. The method of Claim 34, wherein said filtering takes place on clarifier plates.

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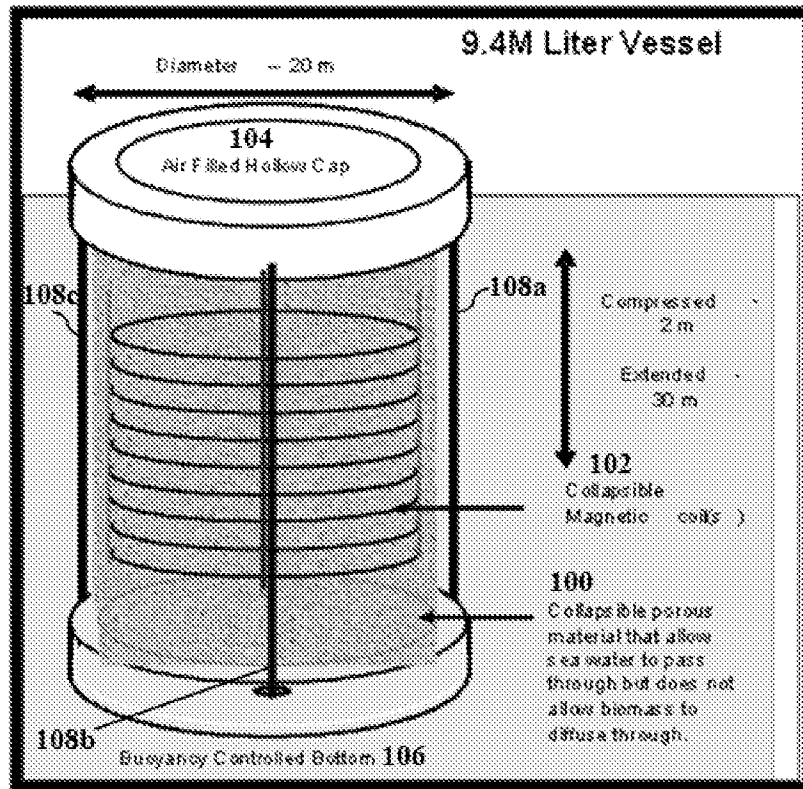


FIG. 1

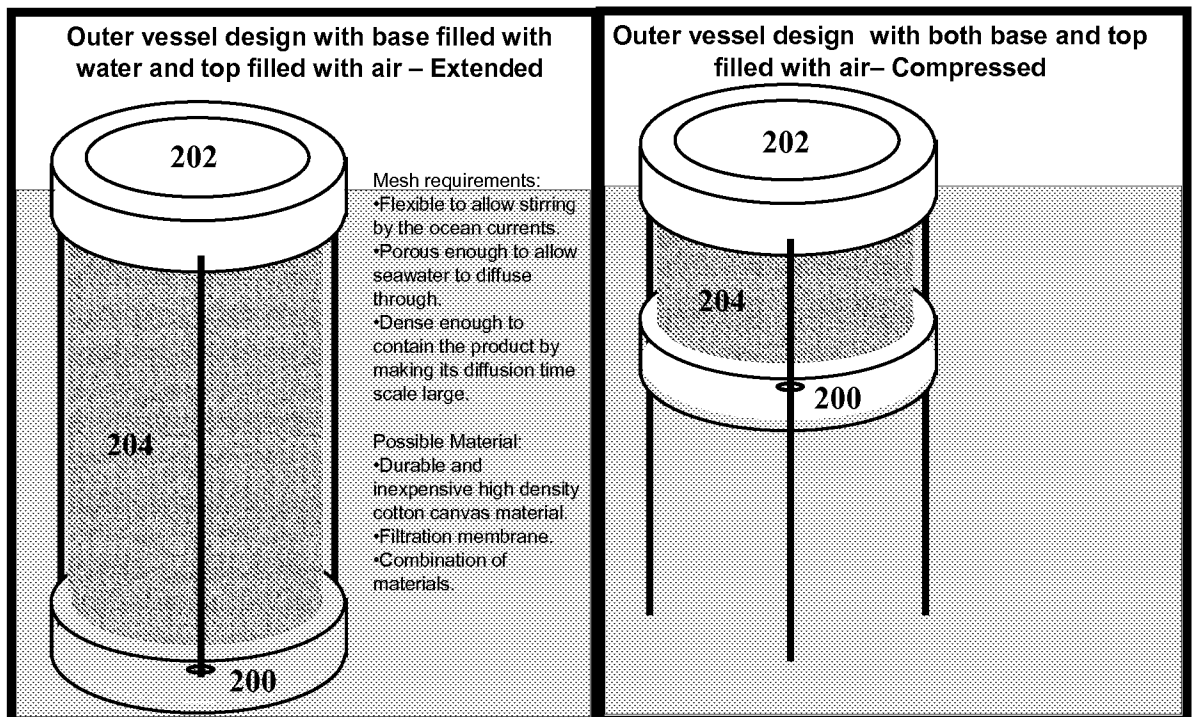


FIG. 2A

FIG. 2B

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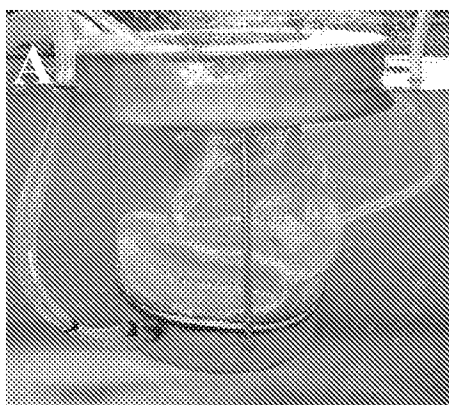


FIG. 3A

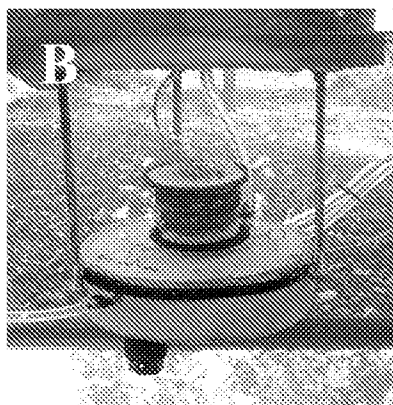


FIG. 3B

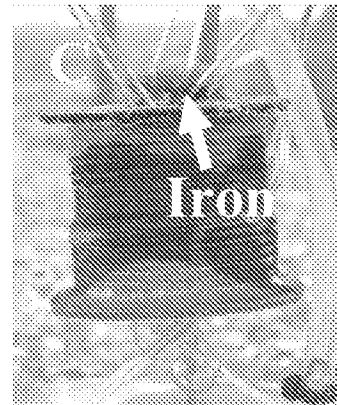


FIG. 3C

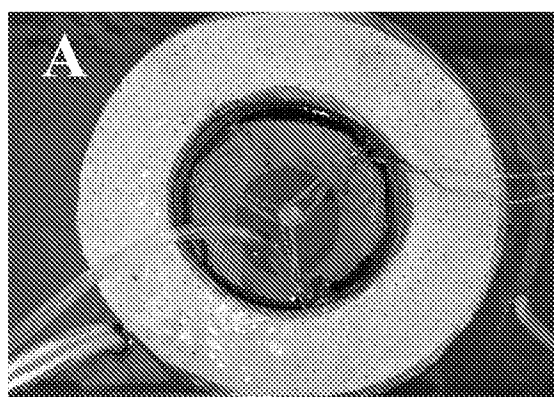


FIG. 4A

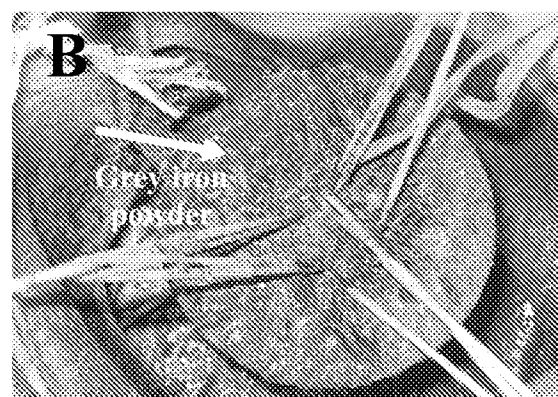


FIG. 4B

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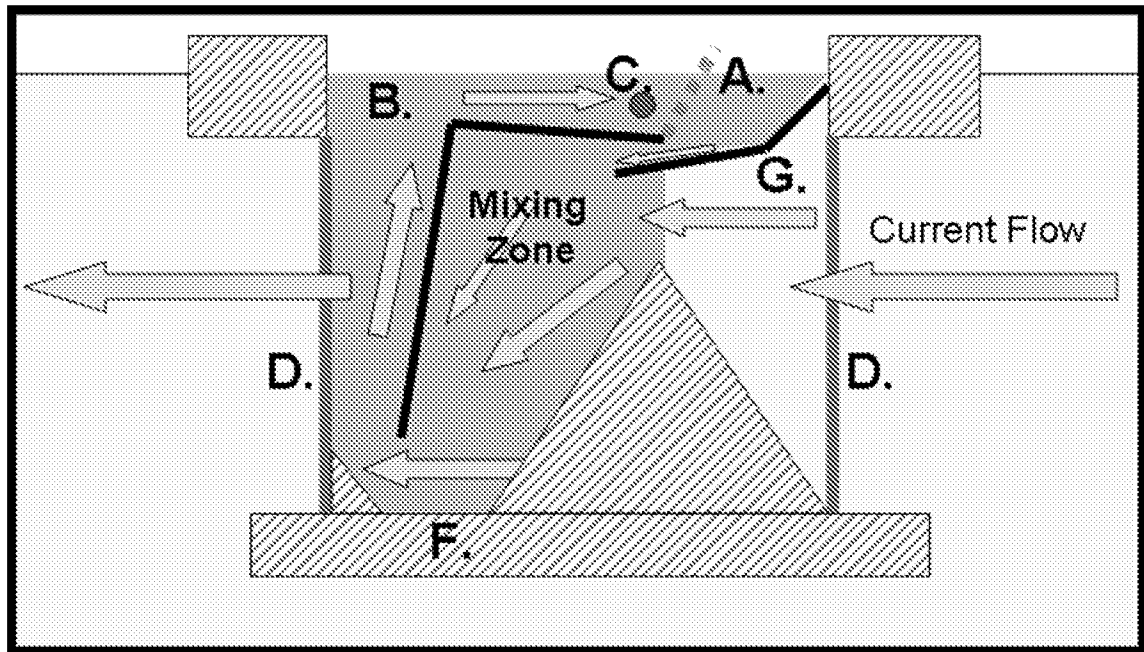


FIG. 5

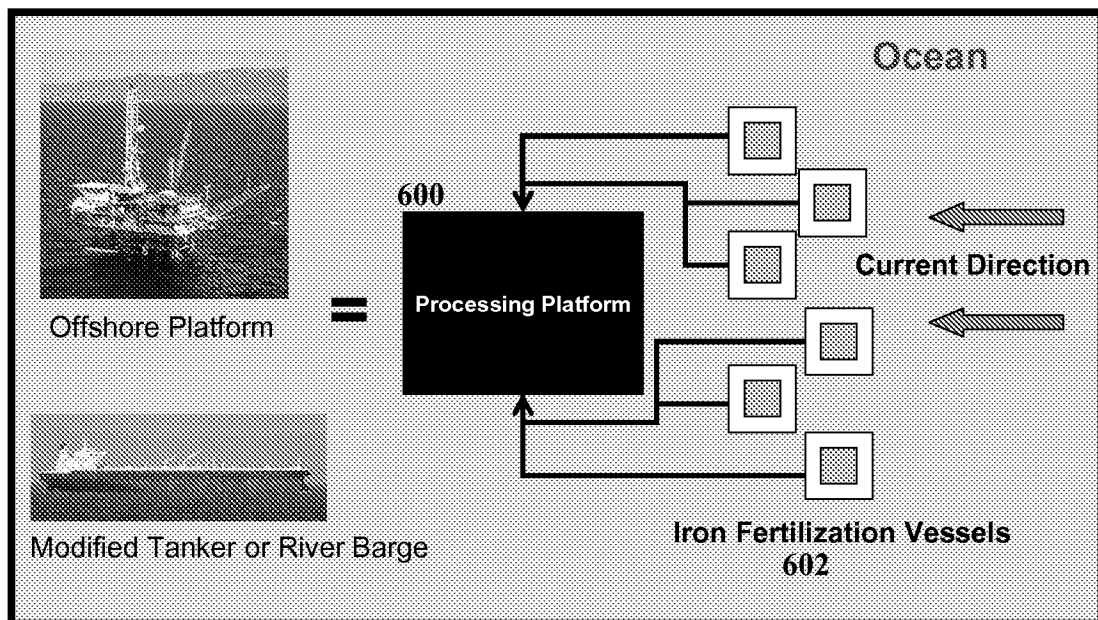


FIG. 6

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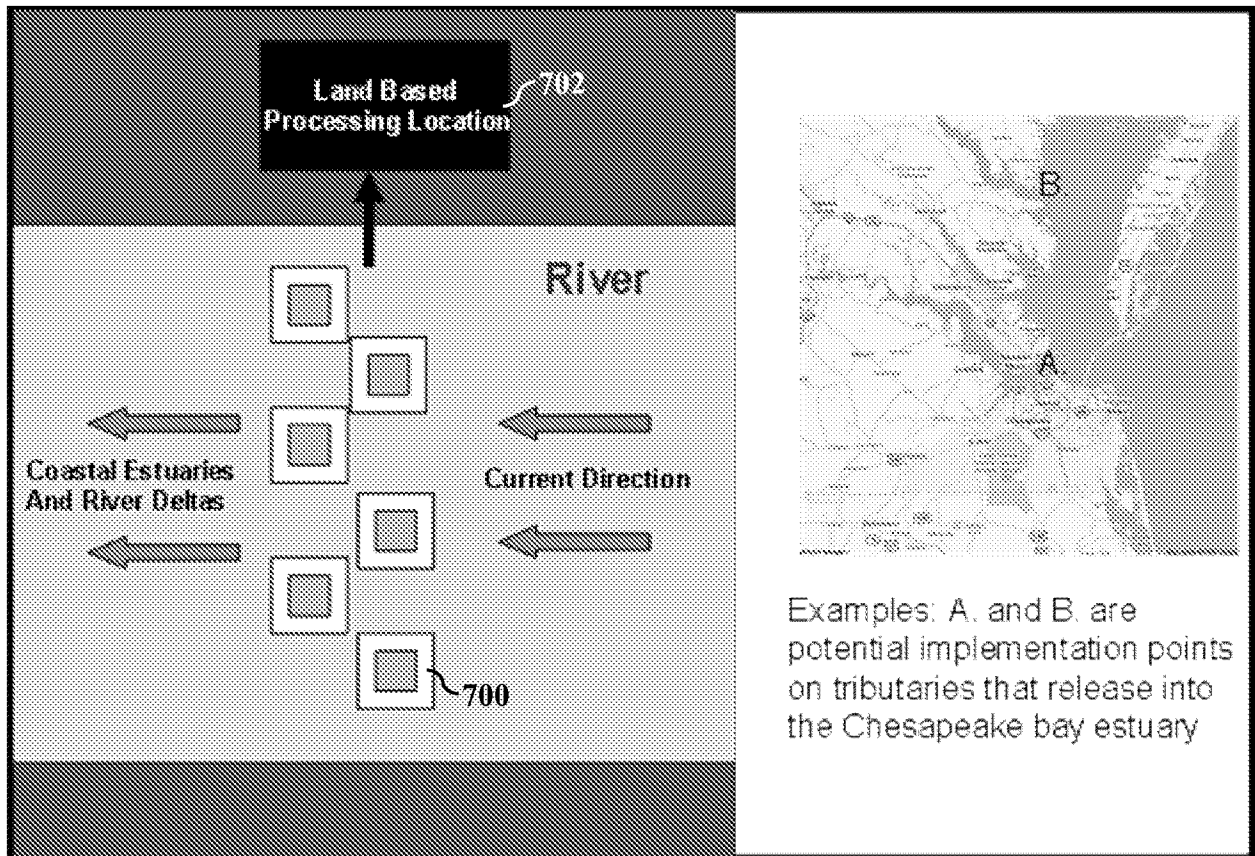


FIG. 7

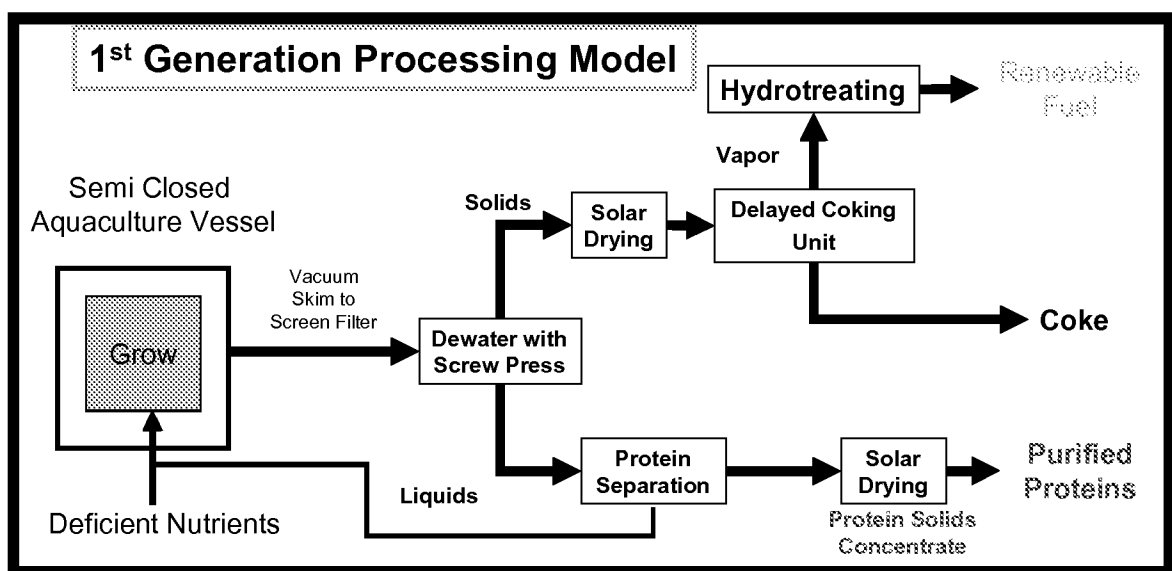


FIG. 8

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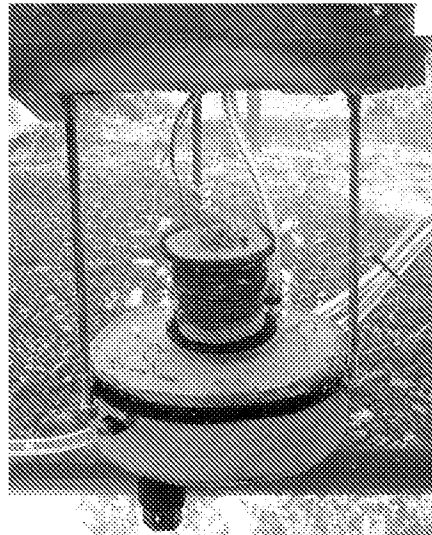


FIG. 9

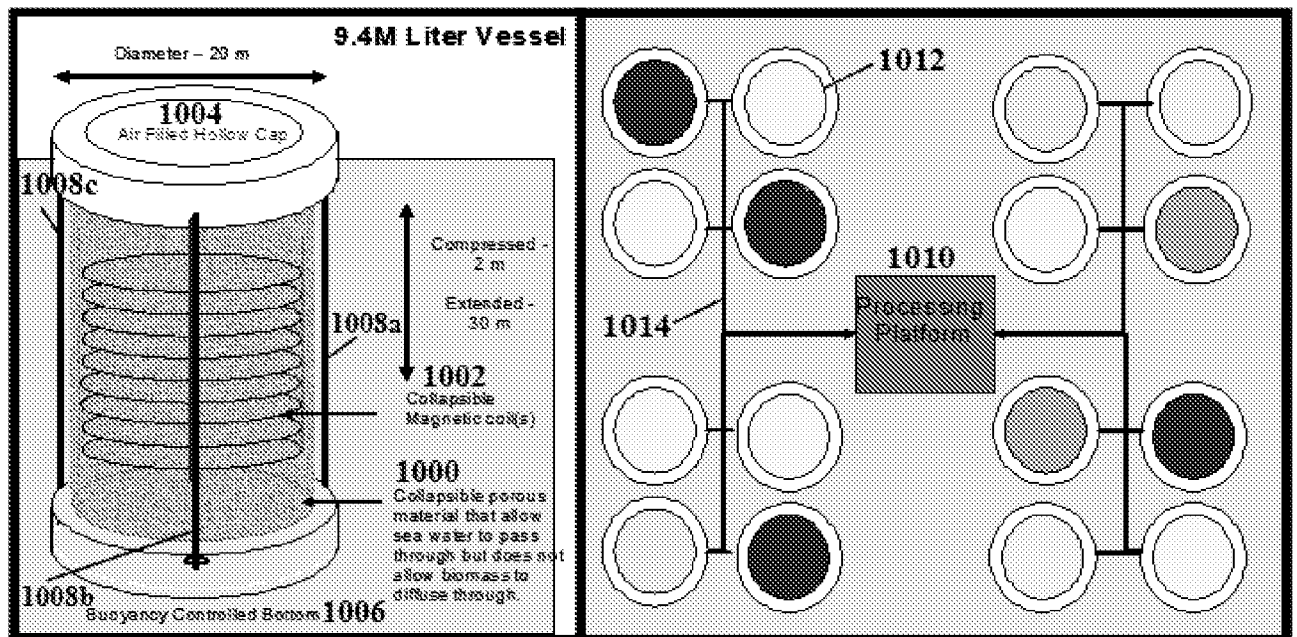


FIG. 10A

FIG. 10B

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Assumptions				
Initial Plankton Concentration (Pi) =	0.0001 g/L	Biodiesel Density=	0.88 g/mL	
Specific Growth Rate (mu) =	0.5 per Day	Lipid Content=	30%	
Vessel Expanded Volume =	9,400,000 L			
5 million gallons per year biodiesel				
Daily	326 Barrels	51,889 Liters	13,699	gallons
yearly	119,139 Barrels	18,939,394 Liters	5,000,000	gallons
Plankton (PF) (g/L)	Time (Days)	L Biodiesel/Vessel/Day	Vessels Required	Ocean Surface Area (Acres)
100	27.6	11597.6	4	0.35
50	26.2	6105.1	8	0.66
25	24.9	3222.8	16	1.25
10	23.0	1391.7	37	2.89
1	18.4	174.0	298	23.13
0.1	13.8	23.2	2,237	173.50

FIG. 11

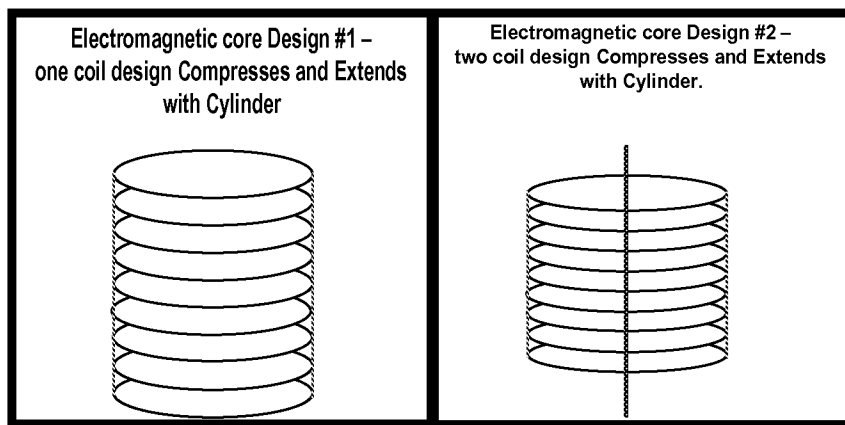


FIG. 12A

FIG. 12B

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$$\Delta T \text{ (Day}^{-1}\text{)} = \frac{\ln[P_f/P_i]}{\mu} \quad \text{Eq. 1}$$

$$\frac{\text{Biomass(g)}}{\text{Day} * \text{Vessel}} = \frac{P_f * \text{Volume per vessel}}{\Delta T} \quad \text{Eq. 2}$$

$$\frac{\text{Lipids (g)}}{\text{Day} * \text{Vessel}} = \frac{\text{Biomass(g)}}{\text{Day} * \text{Vessel}} \times 20\% \text{ (max. lipid content)} \quad \text{Eq. 3}$$

$$\frac{\text{Biodiesel (L)}}{\text{Day} * \text{Vessel}} = \frac{\text{Lipid (g)}}{\text{Day} * \text{Vessel}} \times \frac{\text{Biodiesel(g)}}{\text{Lipid (g)}} \times \frac{1}{880 \text{ g L}^{-1}} \quad \text{Eq. 4}$$

$$\# \text{ of Vessels} = \frac{\text{US Daily Distillate Consumption}}{\text{Biodiesel (L) / (Day * Vessel)}} \quad \text{Eq. 5}$$

$$\text{Vessel Area (m}^2\text{)} = \mu * r^2 \quad \text{Eq. 6}$$

FIG. 13

Assumptions				
Initial Plankton Concentration (Pi) =	0.0001 g/L	Biodiesel Density=	0.88 g/mL	
Specific Growth Rate (mu) =	1.2 per Day	Maximum Lipid Content=	20%	
Vessel Expanded Volume =	9,400,000 L			
US Petroleum Distillate Consumption				
Daily	4,300,000 Barrels	688,000,000 Liters		
yearly	1,569,500,000 Barrels	251,120,000,000 Liters		
Plankton (Pf) (g/L)	Time (Days)	L Biodiesel/Vessel/Day	Vessels Required	Ocean Surface Area (Acres)
100	11.5	18556.2	37,077	2,876
50	10.9	9768.2	70,433	5,463
25	10.4	5156.5	133,425	10,348
10	9.6	2226.7	308,971	23,963
1	7.7	278.3	2,471,768	191,705
0.1	5.8	37.1	18,538,260	1,437,790

FIG. 14

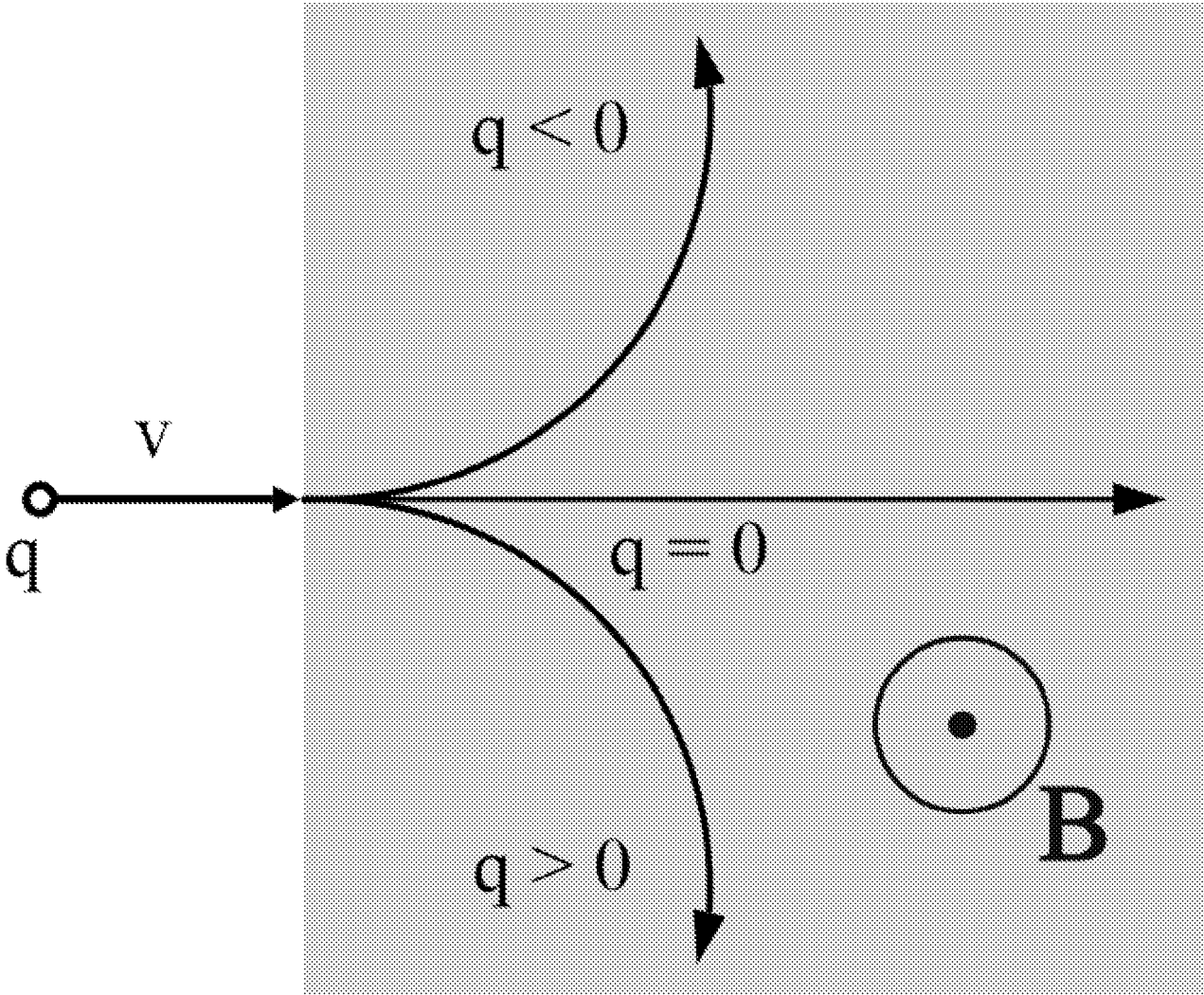


FIG. 15

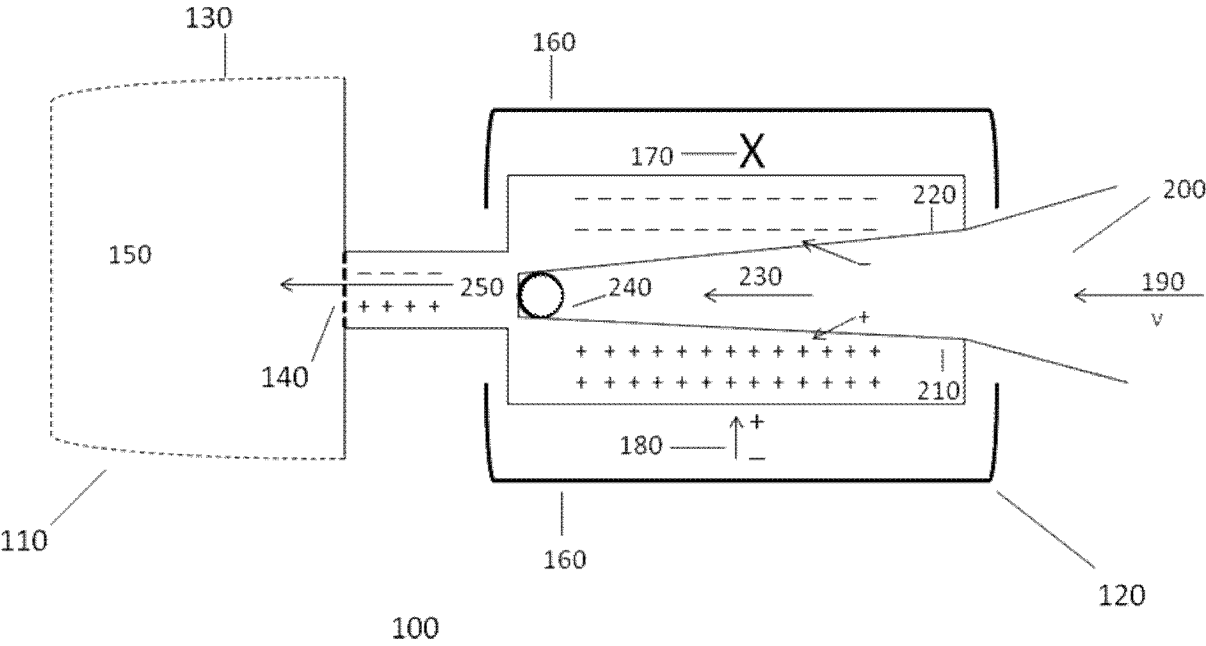


FIG. 16

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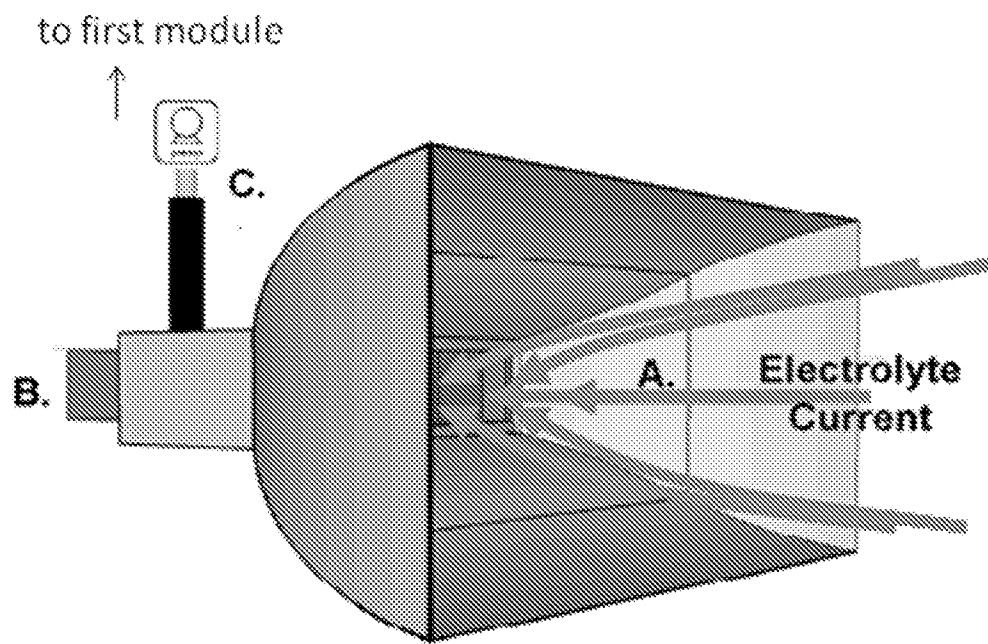


FIG. 17

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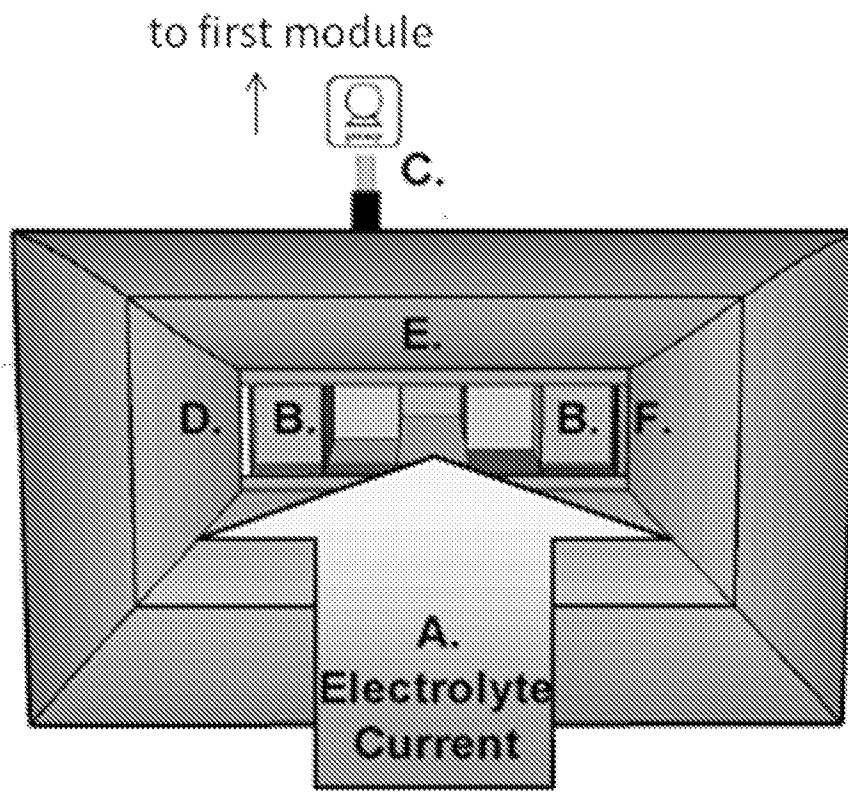


FIG. 18

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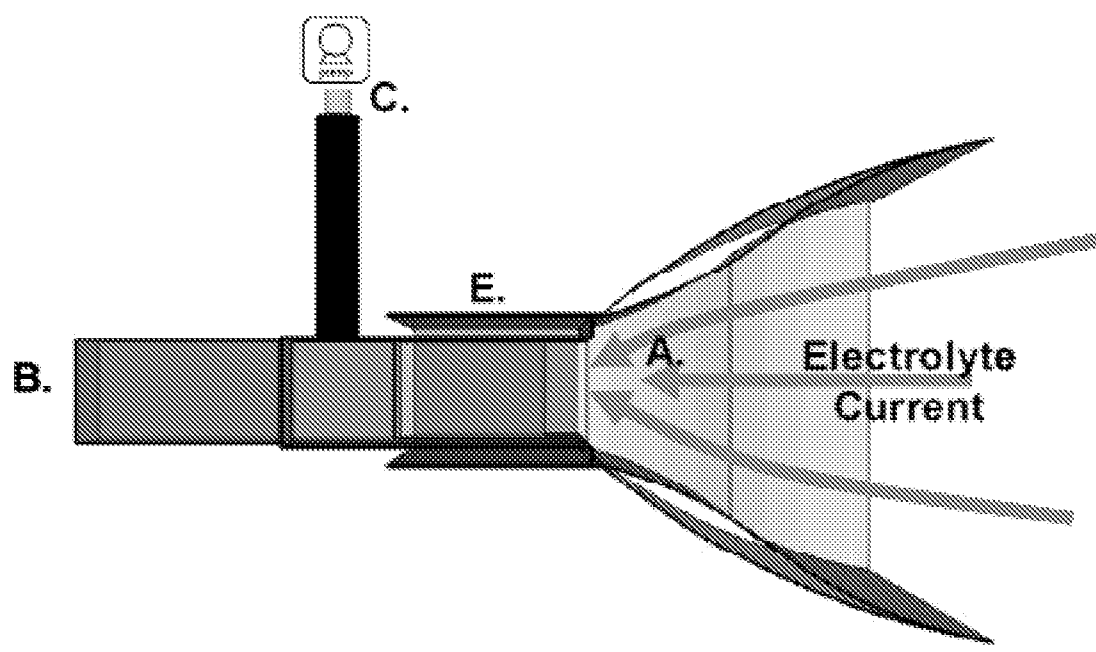


FIG. 19

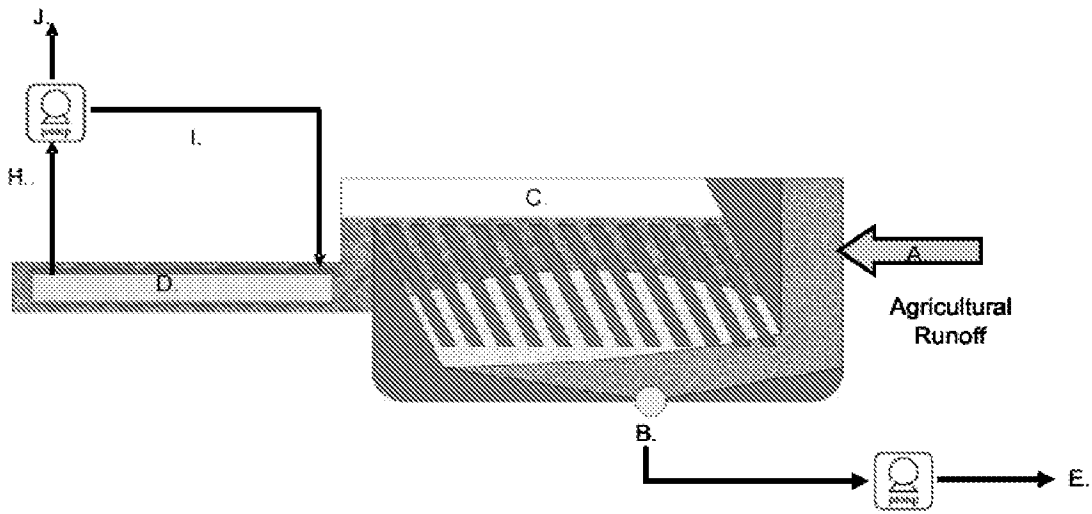


FIG. 20

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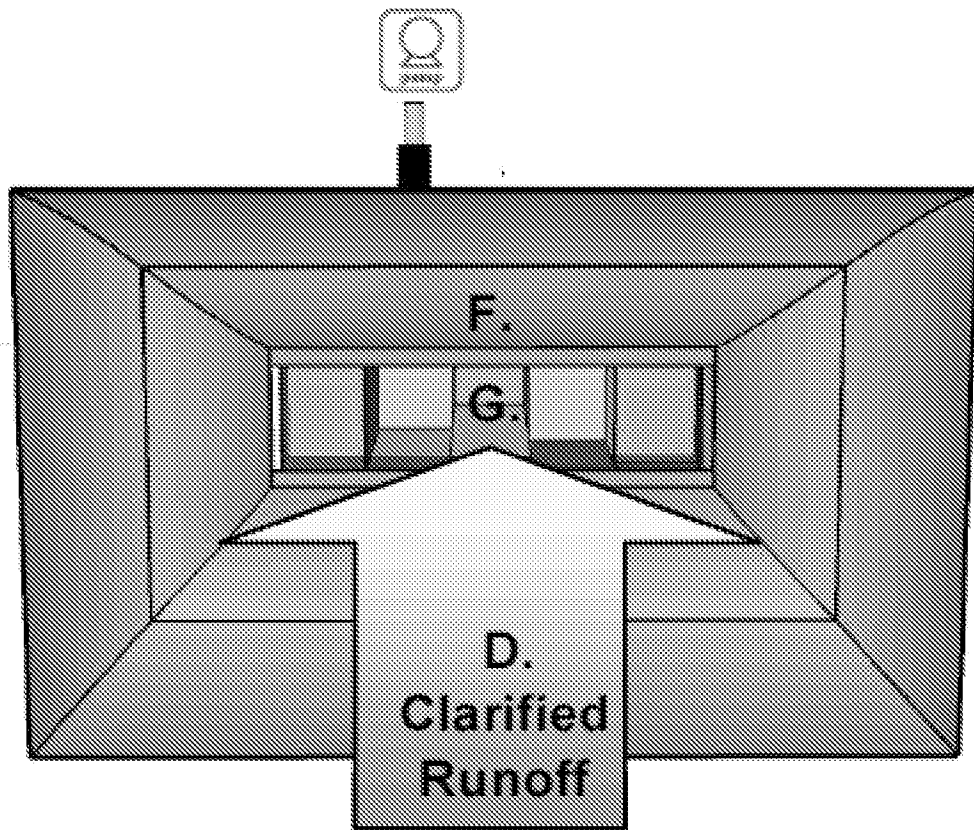
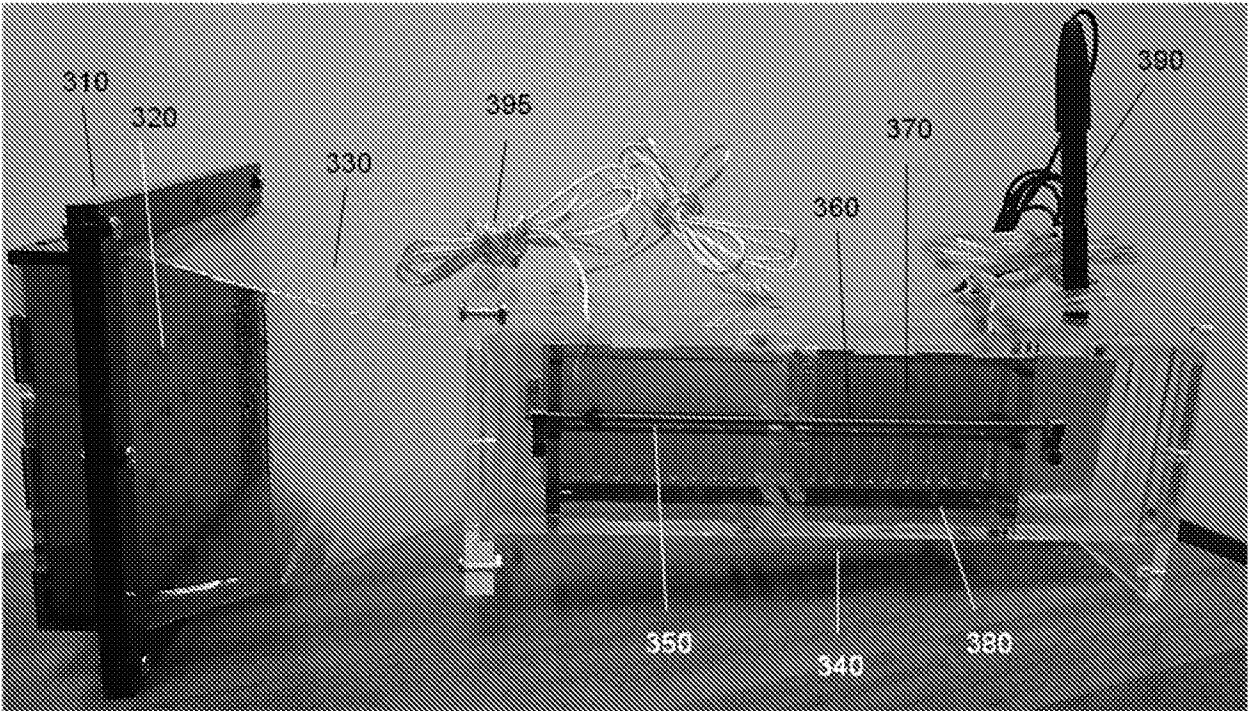


FIG. 21



300

FIG. 22

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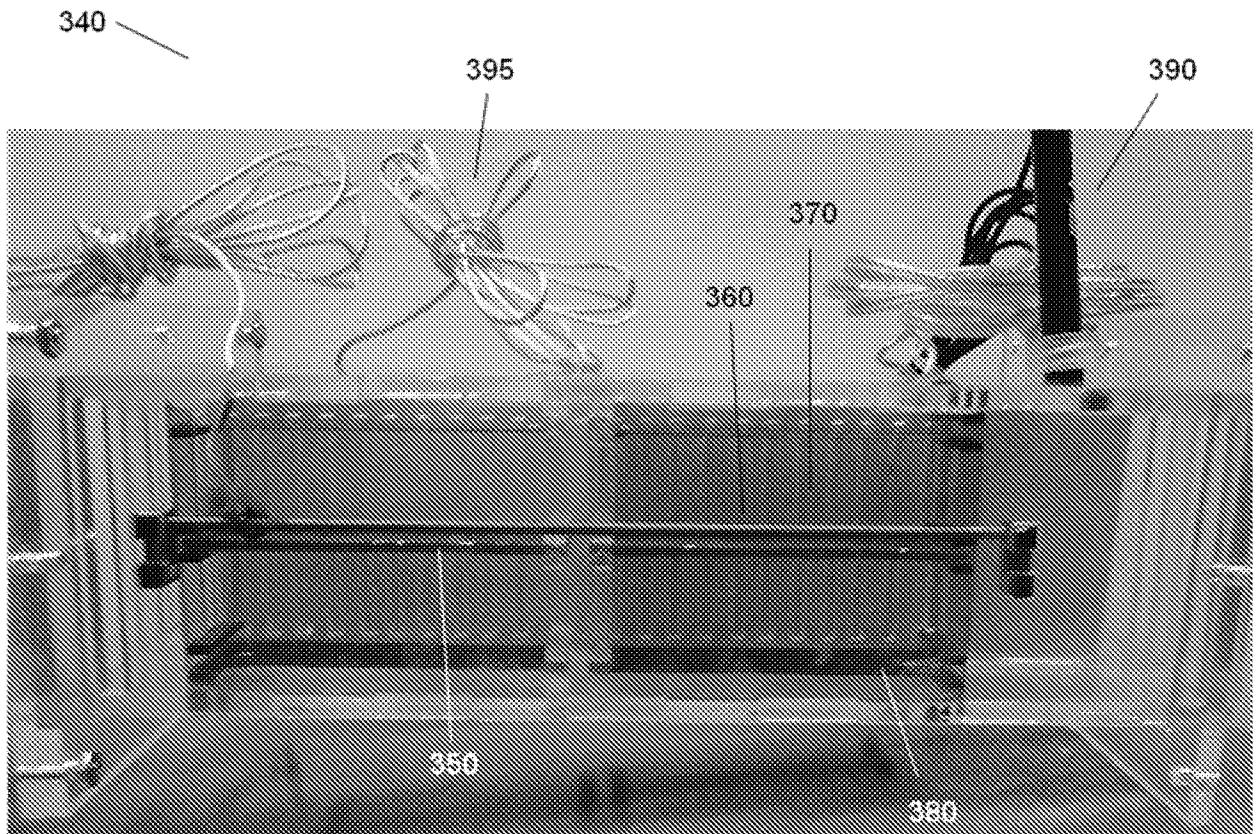


FIG. 23

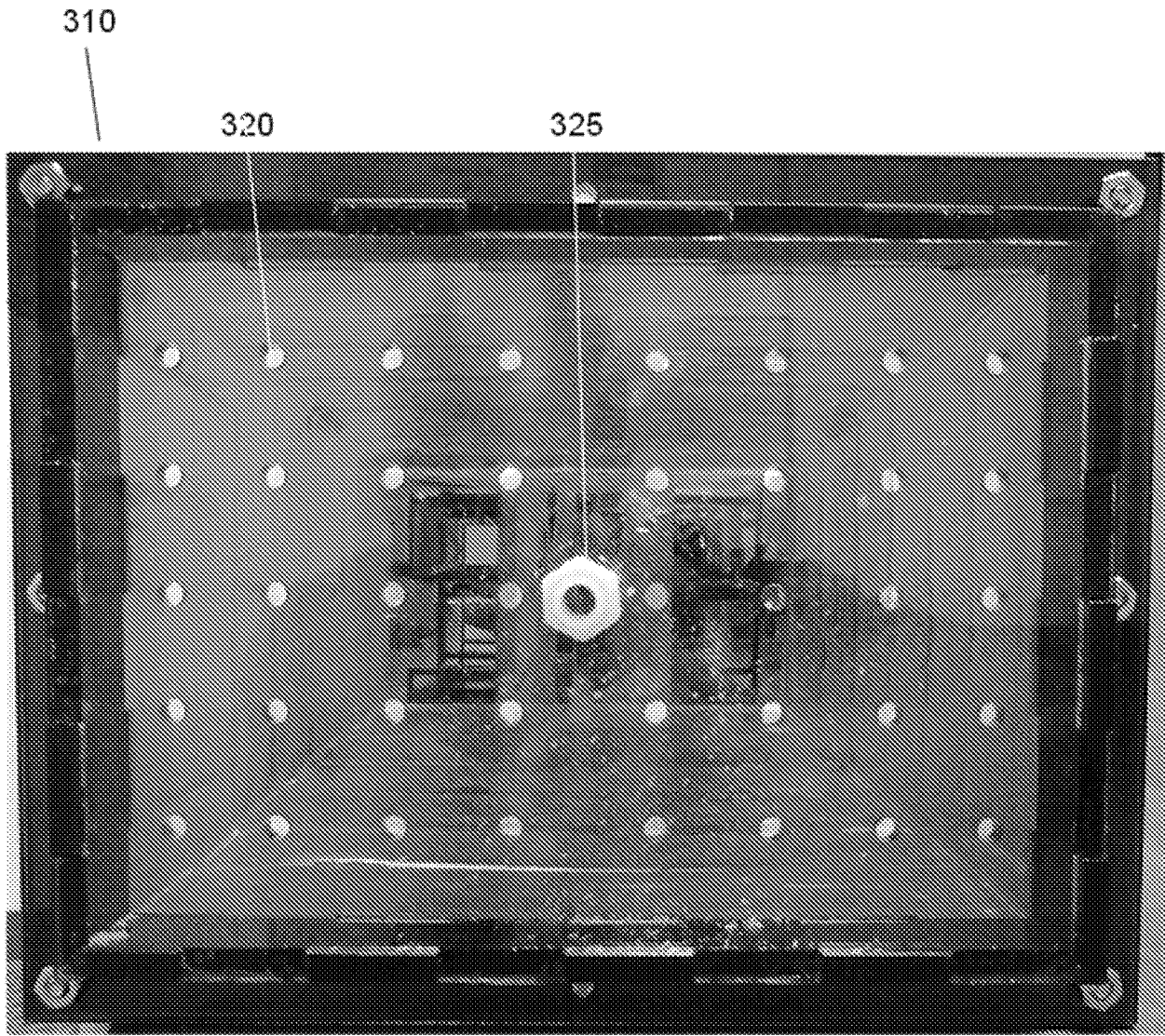


FIG. 24

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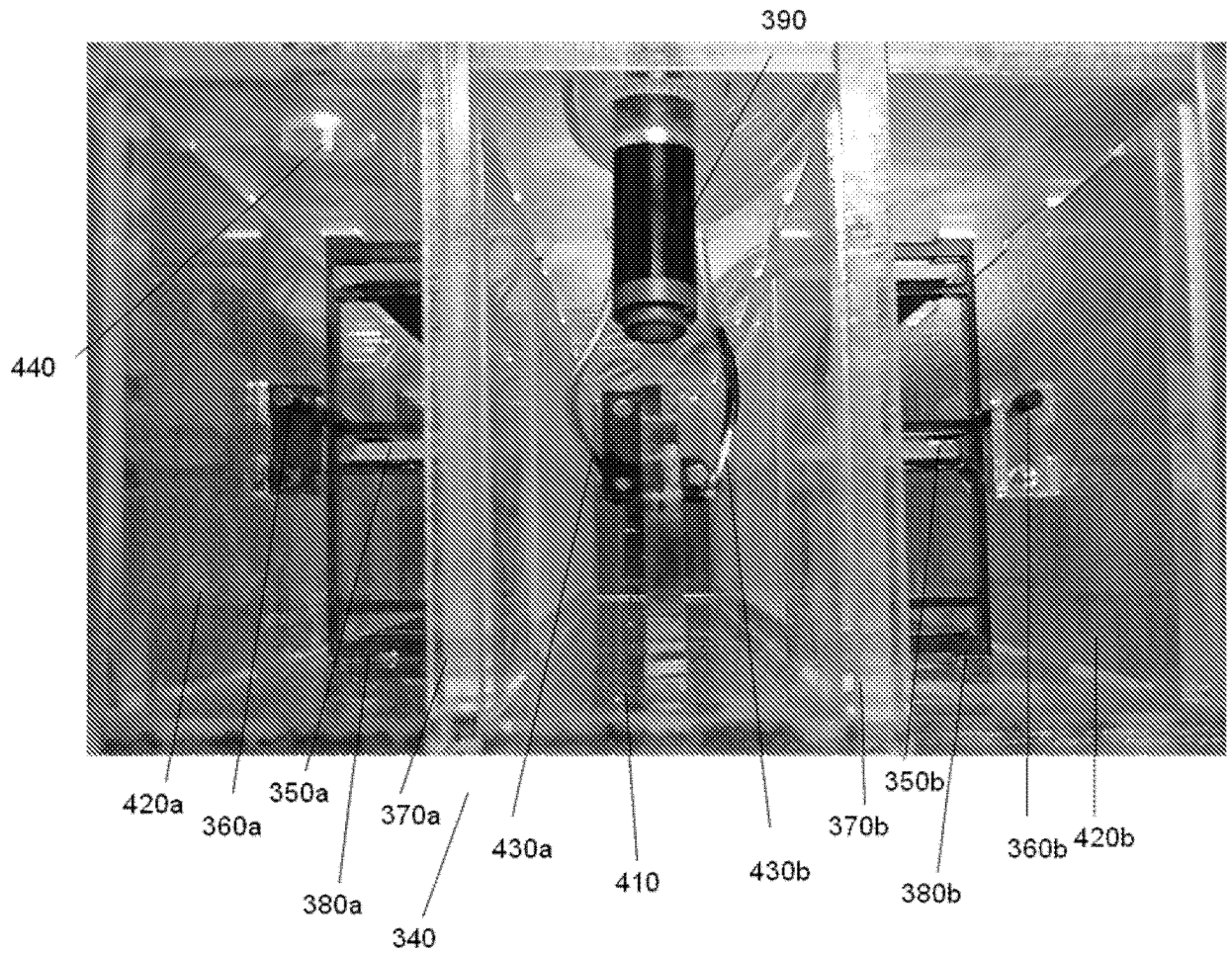


FIG. 25

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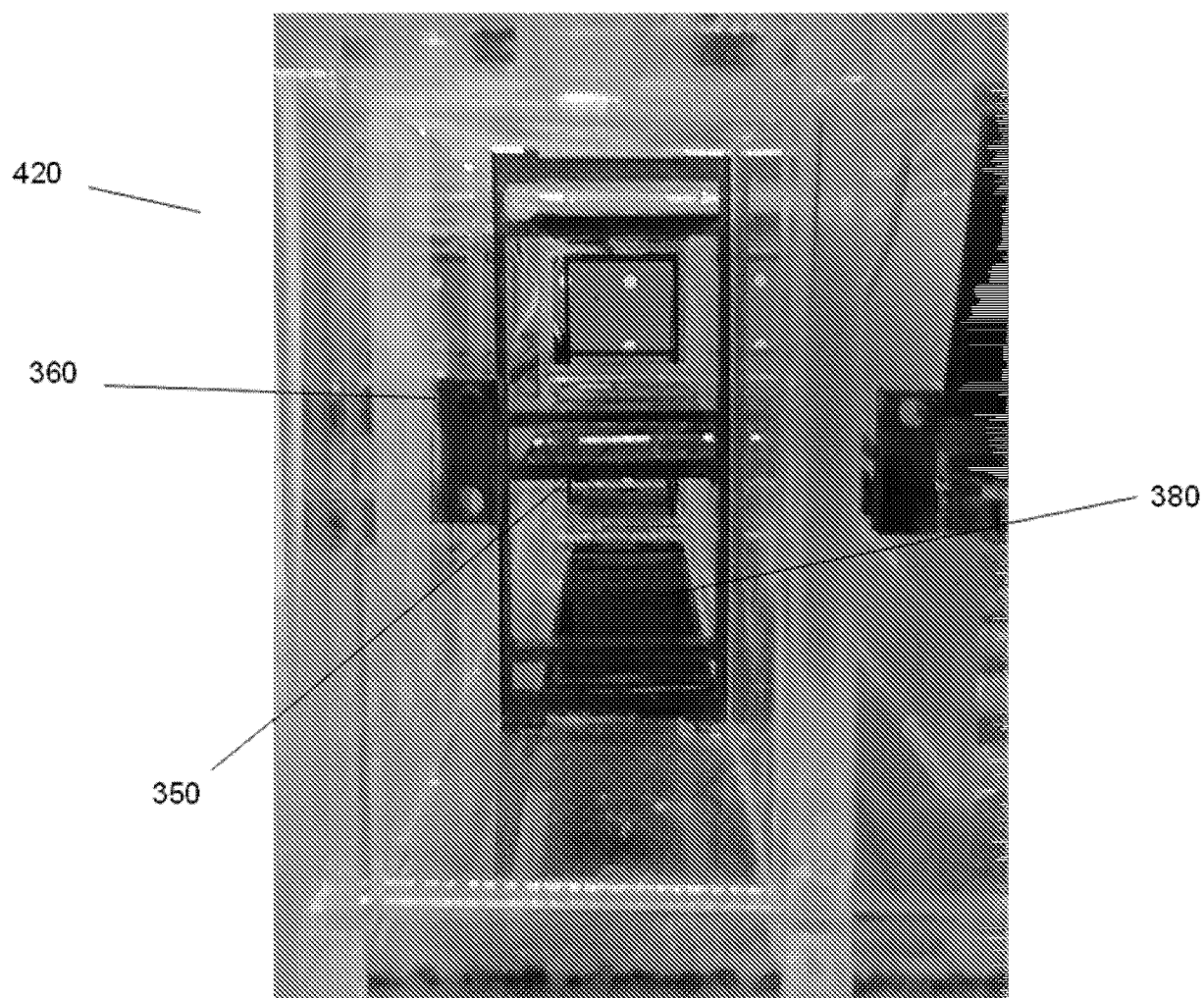


FIG. 26

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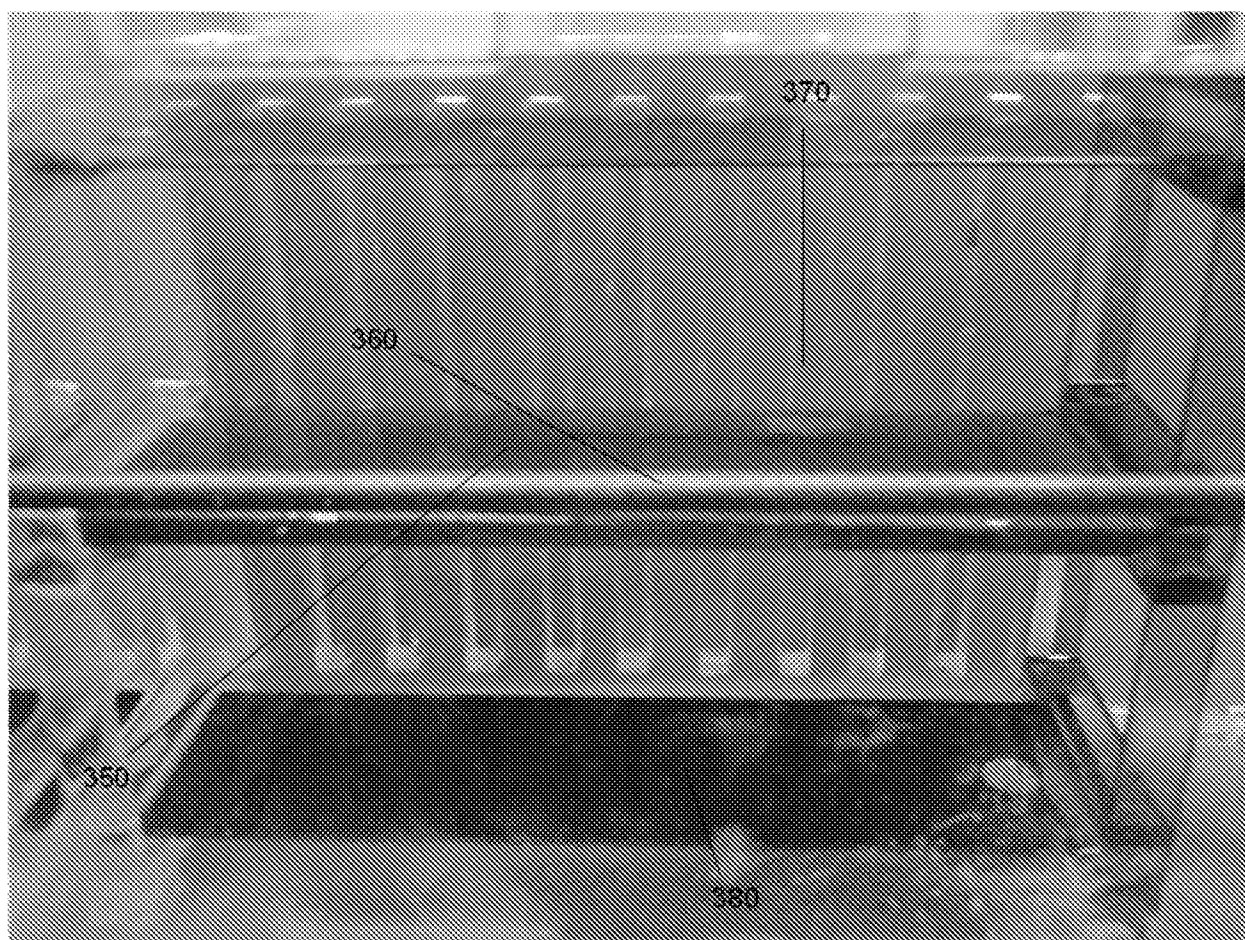


FIG. 27

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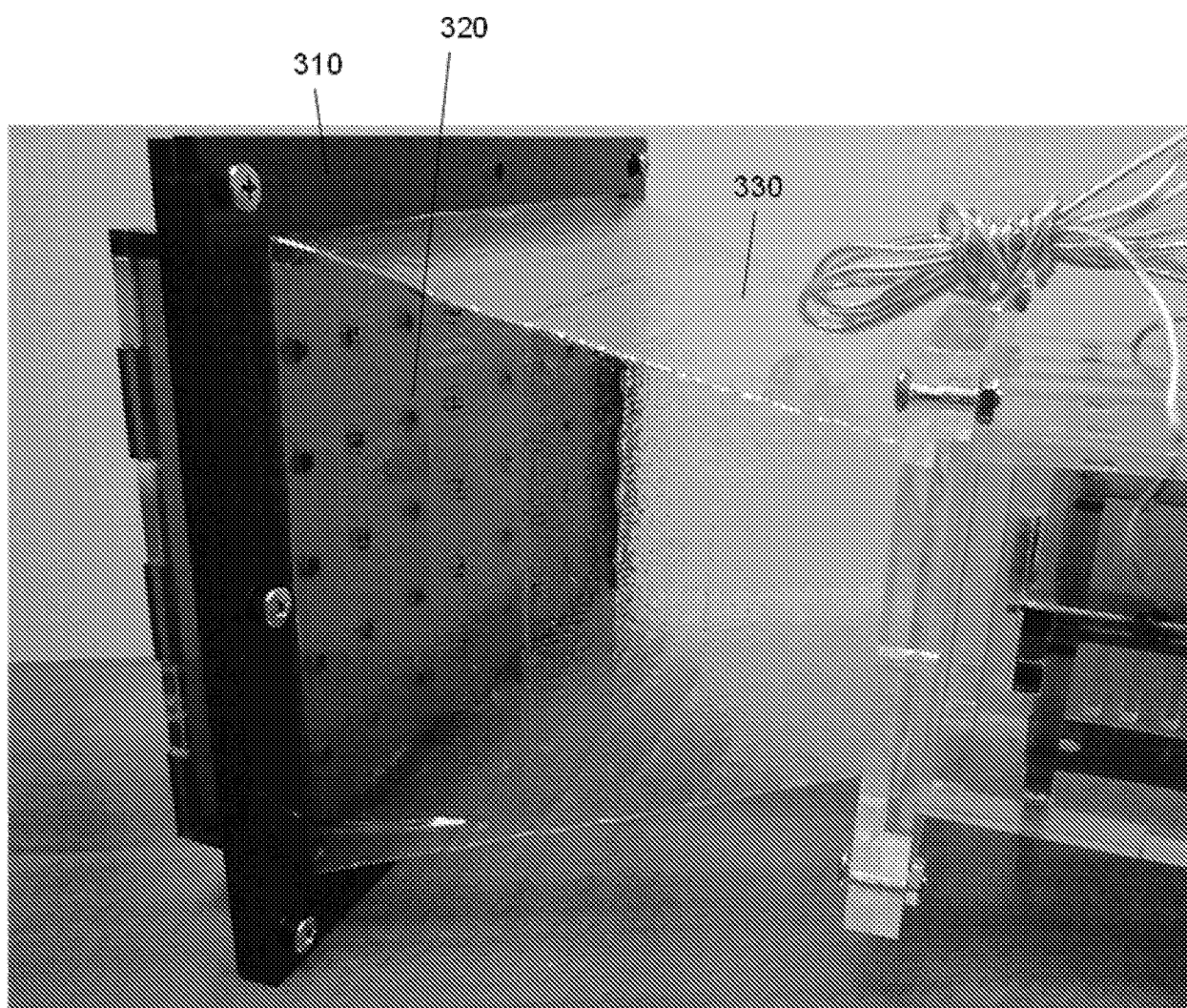


FIG. 28