

BIOREACTOR SYSTEM AND METHODS

FIELD

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The invention is in the field of biomass production, particularly via the use of microbial or cellular bioreactors, more particularly in the field of photobioreactor systems.

BACKGROUND

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The increasing global demand for bioproducts, such as speciality molecules, chemicals or food ingredients, has resulted in growing interest in microbial sources for such materials. The escalating growth of human populations, coupled with evolving consumption patterns and the perils of climate change, are jointly imposing unparalleled pressure on the global food, drug, and chemical production systems. By the year 2100 the human population is expected to exceed 11 billion and contemporary agriculture already exerts a significant environmental footprint in terms of greenhouse gas emissions, freshwater use, eutrophication, topsoil degradation and loss of biodiversity. The necessary expansion of the global food production system during the next few decades will simply increase environmental pressures if conventional agricultural and food production methods are relied upon.

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Photobioreactors (PBRs) are typically used to cultivate microalgae, cyanobacteria, and macroalgae. Many conventional photobioreactors suffer from several limitations, particularly poor light distribution, inefficient gas-transfer, inefficient mixing, inefficient biomass extraction, and the consumption of large amounts of water and energy. For example, microalgae have traditionally been cultivated in open photobioreactors such as "open raceways" due to the simplicity and apparently low operating cost of this type of design. Unfortunately, these open photobioreactors allow only limited control of the operating conditions. Moreover, the cultures can easily be contaminated. Hence, there is a need to move to improved photobioreactors that are closed systems and that can provide optimal growth conditions and thus enable the production of biomass from microalgae and other photosynthetic organisms.

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The transfer of gas into biomass production systems such as photobioreactors (closed or open systems) is usually achieved by using sparging technologies, such as by compressing CO₂, O₂, or air, and delivering the compressed gas into the liquid media through nozzles, or by bubbling or sparging the gas into the liquid media (see for example US2015/0230420, WO2015/116963). These techniques can be used to add a desired gas or can also work to remove excess gas which is not wanted (see for example US2015/0093924).

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Techniques of this kind can be disadvantageously inefficient in both energy requirements and infrastructure cost. When a soluble gas is bubbled through a liquid, only a small proportion of the gas

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will be successfully dissolved; consequently, the remaining gas is wasted, leading to a waste of energy and inefficient gas uptake. Furthermore, the soluble gas needs to be delivered in a pressurised state, therefore, the soluble gas needs to be pressurised, thus increasing energy consumption for its pressurisation or increasing costs for the supply of pressurised gas. Gas removal by this technique is limited by the gas which can be trapped in the bubbles produced, which provide only a limited surface area for effective gas exchange.

Further, for operation in countries with warmer climates, problems can arise with build-up of humidity and condensation within parts of photobioreactor assemblies that are predominantly filled with gas or that are exposed to liquid. This can lead to reduced operational performance as well as accumulation of heat within the system as a whole, placing stress upon organisms that are being grown for biomass. It would be desirable to improve systems to allow better handling of humidity and heat resulting in higher operating efficiencies.

While photosynthetic microorganism based photobioreactors have several advantages such as high biomass productivity, the ability to grow in non-arable regions, and potential for carbon capture; they also have several current-day challenges limiting scalability. Some of these obstacles include:

1. High capital and operating costs: where the cost of constructing a dedicated system can be several times that of a conventional open pond system. In addition, the energy required for pumping and mixing the culture media, as well as for illumination, if necessary, can also be expensive.
2. Risk of contamination: microorganism cultures are susceptible to contamination by rotifers, amoebas, bacteria, fungi, and/or other microorganisms that reduce the yield or quality of the biomass. Further, contamination can occur during the cultivation process or during the handling and processing of the harvested microorganism.
3. Difficulty in scale-up: photobioreactor systems are currently limited in size, which can hinder their scalability. Scaling up the production is strenuous due to economical and technical complexities of the systems.
4. Light attenuation: sufficient light is required for photosynthetic microorganisms, however, light penetration into the culture medium can be limited, resulting in reduced growth rates or biomass productivity. Moreover, the use of high-density cultures can exacerbate this problem.
5. Energy consumption: prior art photobioreactor systems require energy for mixing and circulation of the culture media, as well as for providing illumination to the cultures. The energy required for these processes can be significant, leading to increased greenhouse gas emissions and overall energy costs.

Some of the most widely used photobioreactor systems in prior art currently face several technical and economical challenges that need to be addressed to make them viable alternatives to traditional sources of energy and other products. Specifically, in prior art photobioreactor systems such as flat-

panel photobioreactors, or glass-panel photobioreactors, or tubular photobioreactors, or open-cascade raceways, or conventional open pond systems, some of the significant disadvantages may be limited control over environmental conditions or operational parameters respectively, which include but are not limited to pH, and dissolved gases. Moreover, the existing prior art solutions demand for a comparatively larger land area or footprint.

Sparging is an important aspect of prior art photobioreactor systems, as it provides the necessary gases for algae growth, mass transfer and circulation of nutrients. There can be several challenges associated with sparging such as; when gas bubbles are introduced into the culture medium, they can coalesce and form large bubbles that can disrupt the flow within the system and may eventually lead to foam formation. Foam can accumulate on the surface of the culture and reduce the amount of light that penetrates into the culture, which can decrease photosynthesis and hinder growth rates. Several transfer limitations might arise where the efficiency of gas transfer from air bubbles to the culture medium is constrained by bubble size, bubble density, viscosity of culture medium, dispersion and distribution of bubbles within the culture medium. Further, there can be added risk of contamination from airborne bacteria, fungi or other microorganisms. In addition, sparging requires air pumps, compressors and other equipment which are high energy consuming that can further reduce the overall economic viability of the system. Other disadvantages may include complexity in cleaning and sterilisation, and photobioreactors being limited cultivating few species, respectively.

Some photobioreactor systems in the prior art attempt to make use of porous membranes. However, these too have associated disadvantages even if they are hydrophobic. At industrial scale, the hydraulic pressure of the system can exceed the liquid entry pressure of a porous membrane, resulting in liquid media leaking through the material. In some cases, the presence of biofilms can further lower the liquid entry pressure of a porous membrane. Biofilms can alter the surface properties of the membrane. If the biofilm is hydrophilic, it can reduce the hydrophobicity of a hydrophobic membrane, thereby decreasing the liquid entry pressure. Moreover, in some cases, the presence of cells and biofilms on the surface and/or on the pores of a hydrophobic porous membrane can enable liquids to travel through the biofilm into the pores by capillarity, allowing liquid media to pass through the membrane. Furthermore, microbial cells and associated detritus from the culture can lodge within and block the pores of the membrane, reducing its gas permeability. Cells and detritus may also accumulate in pores and be impossible to remove with cleaning, possibly contaminating subsequent cultures if the bioreactor is reused [Kishi et al. (2022) (<https://doi.org/10.1016/j.algal.2022.102959>)].

Overall, there is a need to address some of the major problems that exist in the prior art, not least the production of valuable products from biomass and cellular material and provides simple and cost-effective solutions to the problems posed by culturing large volumes of photosynthetic microorganisms within a system that facilitates effective gas exchange to enable biomass production at scale. These and other uses, features and advantages of the invention should be apparent to those skilled in the art from the teachings provided herein.

SUMMARY

5 In a first aspect, the invention provides abioreactor system for the production of biomass, the system comprising:

at least one bioreactor unit which comprises at least one liquid-containable compartment, wherein the liquid-containable compartment comprises,

- 10 (i) a first wall, wherein the first wall comprises a composite membrane that is permissible to transfer of gases therethrough, wherein the composite membrane comprises at least one barrier layer and at least one reinforcement layer; and
- (ii) a second wall, wherein the second wall comprises material that is optically transmissible to visible light and that is substantially less gas permeable than the first wall, wherein the first and second walls cooperate to define the liquid-containable compartment
- 15 within the bioreactor unit.

In a second aspect the invention provides a bioreactor unit suitable for incorporation into a bioreactor system, wherein the bioreactor unit comprises at least one liquid-containable compartment, wherein the liquid-containable compartment comprises,

- 20 (i) a first wall, wherein the first wall comprises a composite membrane layer that is permissible to transfer of gases therethrough, wherein the composite membrane comprises at least one barrier layer and at least one reinforcement layer; and
- (ii) a second wall, wherein the second wall comprises material that is optically transmissible to visible light and that is substantially less gas permeable than the first wall,
- 25 wherein the first and second walls cooperate to define the liquid-containable compartment within the bioreactor unit,

and wherein the liquid-containable compartment comprises an inlet and an outlet so as to permit circulation of liquid through the liquid-containable compartment.

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In a third aspect thie invention provides a process for the production of microbial biomass, the methods comprising providing the bioreactor system as described herein; culturing one or more biomass-producing microorganisms within the systems or bioreactor units for a period of time sufficient to generate an amount of biomass; and optionally isolating biomass.

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A fourth aspect of the invention provides a photobioreactor system for the production of microbial biomass, the system comprising:

a plurality of bioreactor units that define a circuit, wherein each bioreactor unit comprises at least one liquid-containable compartment, wherein the liquid-containable compartment comprises,

- (i) a first wall, wherein the first wall comprises a composite membrane that is permissible to transfer of gases therethrough, wherein the composite membrane comprises at least one barrier layer and at least one reinforcement layer; and
- 5 (ii) a second wall, wherein the second wall comprises material that is optically transmissible to visible light and that is substantially less gas permeable than the first wall, wherein the first and second walls cooperate to define the liquid-containable compartment within the bioreactor unit; and
- (iii) an inlet and an outlet so as to permit circulation of liquid media there-through; wherein each liquid-containable compartment encompasses a volume of at least 100 L; and
- 10 wherein each liquid-containable compartment is configured to withstand a hydraulic pressure of greater than 100 millibars.

It will be appreciated that the various embodiments and aspects of the invention as described herein may be combined as appropriate and if not inherently incompatible.

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DRAWINGS

The invention is further illustrated by reference to the accompanying drawings in which:

- 20 Figure 1a shows a schematic diagram of a system according to one embodiment of the present invention.

Figures 1b and 1c show schematic diagrams of systems according to embodiments of the present invention that are comprised of more than one bioreactor unit.

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Figures 2a and 2b show schematic diagrams of a bioreactor unit according to embodiments of the invention.

- 30 Figure 3 shows a cross section of an arrangement according to another embodiment of the invention where a linear bioreactor unit is comprised of a two-part construction, the linear unit is inserted into a channel, along direction c, to define and enclose a chamber that comprises a controllable atmosphere.

- Figure 4 shows cross sections of an arrangement according to another embodiment of the invention wherein a plurality of bioreactor units are arrayed in a panel, an enclosed atmospheric chamber is located on one side of the panel.

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Figure 5a shows cross sectional views of embodiments of the invention. Figures 5a i, 5a ii and 5a iii, demonstrate liquid-containable compartments with different percentage surface area in contact with the chamber.

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Figure 5b shows cross sectional views of embodiments of the invention. Figure 5b i shows an embodiment of a bioreactor unit where the second wall is a flat planar surface. Figure 5b ii shows an embodiment of a bioreactor unit where the second wall is comprised of a grooved surface. Figure 5b iii shows an embodiment of a bioreactor unit where the second wall is comprised of an irregular polygon.

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Figure 5c i and Figure 5c ii show cross sectional views of embodiments of the invention where the second wall is comprised of a flexible film material.

Figure 6a shows an embodiment of the invention including a system of bioreactor units connected in series.

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Figure 6b shows an embodiment of the invention including a system of bioreactor units connected in parallel.

Figure 6c shows an embodiment of the invention including reconfigurable manifolds and a system of bioreactor units connected in series and parallel.

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Figure 6d shows an embodiment of the invention including a system of bioreactor units connected in series with two chambers.

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Figures 7a and 7b show an embodiment of the invention at a larger scale with a manifold in different flow configurations.

Figure 8 shows an embodiment of the invention illustrating key dimensions.

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Figure 9a, 9b and 9c show cross sectional views of embodiments of the invention illustrating different possibilities for the construction of the chamber.

Figures 10a and 10b show schematics for different embodiments of the invention, illustrating different methods of removing biomass and adding liquid media.

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Figures 11a and 11b show an experimental apparatus that was constructed as an embodiment of the invention. Figure 11c illustrates the change in the culture pH with respect to the CO₂ concentration of the gas chamber.

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Figure 12a and 12b show an experimental apparatus that was constructed to illustrate the difference in permeance of a homogeneous polymer membrane and a composite membrane with a thin barrier layer.

Figure 13 shows cross sectional views of embodiments of the invention illustrating the percentage of the internal surface of the liquid-containable compartment that is inside the chamber.

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Figure 14 shows a partially exploded embodiment of the invention that comprises multiple bioreactors that comprise the same second wall.

5 DETAILED DESCRIPTION

All references cited herein are incorporated by reference in their entirety. Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of the ordinary skilled in the art to which this invention belongs.

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The present inventors have developed a gas permeable bioreactor system suitable for generating biomass. In alternative embodiments the bioreactor may be used to generate biomass or other bio-products from phototrophic, heterotrophic, autotrophic, chemotrophic or mixotrophic organisms. Beneficially, the system comprises one or more bioreactor units suitable for the production of biomass that comprise a liquid-containable compartment that is able to undertake gaseous exchange with a controllable atmosphere via a composite membrane or other thin film material that has a level of permeability to movement of gas molecules across it. Suitably, the atmosphere is defined within the chamber that is adjacent to all or a part of the fluid-containable compartment. The atmosphere within the chamber can be controlled in order to supply the bioreactor unit with a gaseous feed of specified composition as well as effluent gases from industrial processes. The embodiments of the invention permit the specified device to comprise an atmosphere that is optimised in order to improve or maximise organism survival, organism growth rate and/or biomass production and/or the production of specific biochemicals within the bioreactor system. In specific embodiments of the invention the bioreactor is a photobioreactor with specific application to the production of biomass or other bio-products derived from photosynthetic organisms, including photosynthetic microorganisms. It will be appreciated by the skilled reader that embodiments set out herein that refer to photobioreactors may equally be utilised, where appropriate, as bioreactors for production of biomass or other bio-products by non-phototrophic organisms.

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Prior to further setting forth the invention, a number of definitions are provided that will assist in the understanding of the invention.

As used herein, the term "comprising" means any of the recited elements are necessarily included and other elements may optionally be included as well. "Consisting essentially of" means any recited elements are necessarily included, elements that would materially affect the basic and novel characteristics of the listed elements are excluded, and other elements may optionally be included. "Consisting of" means that all elements other than those listed are excluded. Embodiments defined by each of these terms are within the scope of this invention.

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The term "photosynthesis" refers to a complex biochemical process that takes place in green plants and other photosynthetic organisms, including photosynthetic microorganisms, including (micro)algae and cyanobacteria. The phenomenon of photosynthesis harnesses the energy from light and converts carbon dioxide and water into essential metabolites and oxygen. As used herein, the term

5 "photosynthetic microorganism" refers to any organism that is capable of photosynthesis. The terms "phototroph", "phototrophy" or "phototrophic" refer to any (micro)organism or process which can capture energy from light for any purpose, in particular organisms and processes which produce energy and/or produce organic compounds using energy from electromagnetic waves (light) by photon capture. As mentioned above, the production of organic compounds by fixation of inorganic carbon using energy

10 from light is known as photosynthesis.

An "autotroph" as the term is used herein refers to an organism that synthesises complex organic compounds using carbon from simple substances such as carbon dioxide, generally using energy from light (photosynthesis) or inorganic chemical reactions (chemosynthesis).

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A "photoautotroph" as the term is used herein refers to another term for an organism that utilises light energy to synthesise organic compounds from inorganic substances such as carbon dioxide and water. Photoautotrophs are able to perform photosynthesis, which herein relates to the process of converting light energy into chemical energy that can be stored in organic molecules. As further described,

20 photosynthetic organisms and photoautotrophs are not restricted to using photosynthesis alone, and many organisms may use or be capable of photosynthesis. In addition, some organisms use light to provide cellular energy, such as in the form of adenosine triphosphate (ATP) but are not necessarily capable of fixing carbon to produce organic compounds. A "photoheterotroph", as the term is used herein, refers to an organism which can generate cellular energy from light energy to produce ATP but cannot fix (sufficient) carbon dioxide or inorganic carbon into organic compounds. They are

25 heterotrophic, meaning they require organic compounds as a source of carbon and energy. A "heterotroph" in general, refers to an organism that cannot produce its own food and therefore rely on consuming other organisms or organic compounds to obtain the carbon and energy they need. Unlike general autotrophs, they are unable to perform photosynthesis or chemosynthesis. Therefore, photoheterotrophs are able to use organic compounds such as sugars, amino acids, and fatty acids as carbon sources, along with light energy to generate ATP through a process called "photophosphorylation". The term "chemotroph" is used to refer to an organism that can obtain energy by oxidising chemical compounds rather than utilising light energy. Chemotrophs are able to derive their energy by breaking down inorganic or organic compounds such as sulphur, iron, or ammonia through

30 the process of chemosynthesis. Unlike general phototrophs, chemotrophs are able to derive energy from chemical reactions in the absence of light. The term "photomixotroph" is used to refer to organisms and processes which can use more than one source of energy, but also includes generation of cellular energy from light and/or organic compounds. They are "mixotrophic" or referred to as "mixotrophs" which means that they are able to utilise both organic and inorganic compounds as sources of energy

35 and carbon. General mixotrophs can be characterised by their ability to switch between autotrophic and

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heterotrophic modes of sustenance, depending on the availability of nutrients and their ecosystem conditions.

5 The skilled person will also be aware that references to the concentration or percentage of CO₂ (carbon dioxide) in liquid refers to the dissolved inorganic carbon (DIC) of the solution, that is, the concentration of dissolved CO₂ as well as related inorganic forms such as H₂CO₃ (carbonic acid), HCO₃⁻ (bicarbonate) and CO₃²⁻ (carbonate). Similarly, references herein to "gas concentration" and the like are intended to include any and all ionic forms or chemical compounds which form from gases in a liquid or aqueous context, for example ammonium ions (NH₄⁺) as a result of ammonia gas or sulphuric acid (H₂SO₄) as a
10 result of sulphur oxides.

As used herein, the term "dissolved oxygen" (DO) refers to the amount of gaseous oxygen (O₂) dissolved in an aqueous solution. Dissolved oxygen can be measured in mg·L⁻¹. Dissolved oxygen saturation can also be represented as a percentage of the maximum amount of O₂ that will dissolve in
15 an aqueous solution under stable equilibrium conditions. These conditions include temperature and pressure. It is possible for an aqueous solution to become supersaturated with oxygen (i.e., reach more than 100% saturation), for example due to the presence of photosynthetic aquatic oxygen producers.

As used herein, the term "translucent" has its ordinary meaning in the art, and refers to a light-pervious
20 material that allows light to pass through, resulting in the random internal scattering of light rays. The term is synonymous with "semi-transparent".

As used herein, the term "transparent" has its ordinary meaning in the art, and refers to a material that allows visible light to pass through it, such that objects can be clearly seen on the other side of the
25 material, in other words it can be described as substantially "optically clear". All membrane and non-membrane materials, chamber walls, additional components, control structures, coatings and other materials described herein can be substantially translucent or substantially transparent. Transparent materials may nonetheless comprise a tint or filter that allows certain wavelengths to pass through in preference to other wavelengths of light – e.g. a colour filter. Alternatively, the transparent material may
30 comprise a polarising filter such that it remains optically clear but only in respect of waves of polarised light that can pass therethrough.

The term "optically transmissible" encompasses materials that are translucent and/or substantially transparent.
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As used herein, the term "effluent gas" means gas produced as a waste product, by-product or intended product from a natural or human-instigated process, particularly where such gases are enriched in CO₂ and/or O₂ and/or H₂ and/or N₂ and/or CH₄; and/or depleted in CO₂ and/or O₂ and/or H₂ and/or N₂ and/or CH₄ compared to normal atmosphere. Such processes include but are not limited to combustion,
40 manufacturing, industrial processes, power and/or heat generation, vehicles such as ships, aeroplanes

and road vehicles, fermentation, biomass production, biomass treatment, fuel production, fuel treatment or conversion, refining, and waste treatment.

5 As used herein, the term "sparging" means the introduction of any gas or gases into a liquid. It may involve bubbling gas through the liquid, which can be used for various purposes such as increasing the content of gases for example CO₂, removing dissolved gases for example O₂, or adding any specific gases. Aeration is a type of sparging where air is introduced into a liquid, this is typically achieved by bubbling.

10 As used herein, the term "permeable" or "gas permeable" means a material that allows gases (referred to as "permeants"), in particular, but not limited to, oxygen (O₂), carbon dioxide (CO₂), nitrogen (N₂), methane (CH₄) and hydrogen (H₂) to be transferred from one side of the material to the other, in either a single direction or bi-directionally. As used herein, the related terms "breathable" and "semipermeable" are synonymous with "permeable" and the two terms can be interchangeably used herein. Typically,
15 the material is comprised within a sheet, film or membrane. The permeable or gas permeable material may be comprised within a composite material, such as a composite membrane.

As used herein, the term "composite membrane" refers to a gas permeable membrane comprising multiple layers and/or materials. In a composite membrane, each layer or material can perform one or
20 more specific functions. In a composite membrane individual layers may be laminated and/or conjoined to form a single composite structure.

As used herein, the term "permeant" refers to a substance and/or molecule and/or component (such as a gas/gases) that passes through a permeable material or membrane (such as a composite membrane).
25 It can be used to refer to a single component in a mixture, and/or multiple components in a mixture, that has the ability to be transported across a membrane.

As used herein, the term "permeate" refers to a substance and/or molecule and/or component (such as a gas/gases) that has passed through a permeable material or membrane (such as a composite
30 membrane). It can refer to the product obtained after a permeant has been transported through a gas permeable membrane.

As used herein, the term "reinforcement layer" refers to any layer of a composite membrane that contributes the highest mechanical strength to the composite membrane. It typically comprises a porous
35 material which may be comprised of randomly distributed fibres and/or non-woven fibres and/or woven fibres and/or any other orientation of fibres, that may be comprised of polymeric materials and/or metals/alloys and/or bio-based materials.

As used herein, the term “barrier layer” refers to any layer of a composite membrane with the lowest permeability for any specific gas. Typically, the barrier layer can be optimised to serve the purpose of a desired separation.

- 5 A barrier layer may comprise a non-porous material or a porous material. A barrier layer comprising a porous material may also be referred to as a “porous barrier layer”. A barrier layer comprising a non-porous material may also be referred to as a “non-porous barrier layer”.

- 10 In certain embodiments, the barrier layer of a composite membrane may be impermeable to liquids and/or substances in liquid phase, and/or may comprise of specific surface geometries, and/or may be hydrophobic, and/or may be hydrophilic, and/or may be comprised of a material that is food grade or rated for food-contact processing applications, and/or may have significant resistance to acidic and alkaline chemicals/substances, and/or resistance to UV light transmission.

- 15 As used herein, the term “intermediate layer” refers to any layer of a composite membrane that is not a barrier layer or a reinforcement layer. Typically, an intermediate layer has substantially negligible resistance to the transport of a desired gas and/or gases through the composite membrane with respect to any barrier layers of such composite membrane.

- 20 An intermediate layer may comprise a porous or non-porous material. An intermediate layer comprising a porous material may also be referred to as a “porous intermediate layer”. An intermediate layer comprising a non-porous material may also be referred to as a “non-porous intermediate layer”.

- 25 An intermediate layer may provide any one or more suitable functionalities to a composite membrane, for example it can reduce concentration polarisation to facilitate the permeation of gases through the composite membrane. Further to this, it may also be optimised to facilitate the fabrication of the composite membrane; for example, to facilitate the deposition of a barrier layer. An intermediate layer that facilitates fabrication of the composite membrane can prevent the percolation of the deposited/applied barrier layer material into the pores of any subsequent porous layer, which in turn facilitates the transport of permeant across the composite membrane. In certain embodiments, a composite membrane may comprise an intermediate layer or multiple intermediate layers to efficiently seal and/or join any subsequent layers, in addition to any functions priorly mentioned, without substantially hindering the permeation of permeants with respect to any barrier layers of such composite membrane. In certain embodiments, an intermediate layer may be optimised to provide additional functionalities such as, but not limited to, improving mechanical performance of the composite membrane, and/or increasing resistance to fouling (prevent formation of biofilms), and/or enhancing durability, and/or imparting additional suitable functionality (such as, but not limited to, aesthetic factors, and/or UV resistance). Furthermore, in specific embodiments, a composite membrane may comprise an intermediate layer for the purposes of protecting other layers of the composite membrane, for example a barrier layer.
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As used herein, the term “selectivity” refers to a measure of the relative ease with which different permeants or gases can permeate through a material or gas permeable membrane. The selectivity (α) of a composite membrane can be mathematically expressed as the ratio of the permeability coefficients of two gases through the composite membrane:

$$\alpha = \frac{P_{Gas\ 1}}{P_{Gas\ 2}}$$

Where $P_{Gas\ 1}$ and $P_{Gas\ 2}$ represent the permeability coefficients of gas 1 and gas 2 through the composite membrane, respectively. A higher selectivity (α) indicates a greater difference in permeability between the two gases, influencing faster gas transfer performance.

According to the Solubility-Diffusivity model which is commonly used to describe permeation behaviour of gases through a membrane, the permeability of a gas through the membrane is the product of its solubility (S) and diffusivity (D) in the membrane material. Solubility refers to the ability of a gas to interact or dissolve in the membrane material and diffusivity represents the rate at which the dissolved gas molecules pass through the membrane.

The selectivity of a barrier layer may extend to controlling the permeation of gases in a unidirectional and/or bidirectional manner while regulating the rate of permeation of different gases. In some embodiments, a barrier layer can facilitate the non-selective permeation of multiple gases but at different permeability rates and/or through different concentrated regions within the layer material.

“Barrer” is a non-SI unit of gas permeability, named after Richard Barrer. Barrer is commonly used in the field of membrane science and technology to describe the permeability of gas separation membranes and other porous materials. With respect to gas transfer membranes, Barrer is used to express the permeability of a material to gases and specifically, it quantifies the amount of gas that can permeate through a material of a given thickness and surface area, under specific conditions. The permeability coefficient in dense polymers is defined as the molar flux of the gas (rate of permeation per unit area) normalised by the film thickness and the difference between upstream and downstream partial pressures. Thus, the higher the permeability of a given membrane material, the higher the expected gas transfer across that membrane.

Hence, the Barrer unit is a measurement of the rate of a gas flow passing through an area of a membrane material with a thickness, driven by a given pressure. Barrer is defined as:

$$1\ Barrer = 10^{-10} \frac{cm^3_{STP} \cdot cm}{cm^2 \cdot s \cdot cmHg}$$

When comparing the permeability of different membrane materials typically the thickness is set at unity. Therefore, mathematically one Barrer is defined as the permeability of a material having a thickness of one centimetre, that allows 10^{-10} cubic centimetres of gas at standard temperature and pressure (0

degrees Celsius and 1 atm) to pass through a square centimetre of the material per second, under a pressure difference of one centimetre of mercury (1 cmHg).

- Similarly, another unit used to characterise the gas transport through a material or a membrane is the “Gas Permeance Unit” (GPU) and mathematically one GPU is defined as the permeability of a material that allows 10^{-6} cubic centimetres of gas at standard temperature and pressure (0 degree Celsius and 1 atm) to pass through a square centimetre of the material per second, under a pressure difference of one centimetre of mercury (1 cmHg).

$$1 \text{ GPU} = 10^{-6} \frac{\text{cm}_{STP}^3}{\text{cm}^2 \cdot \text{s} \cdot \text{cmHg}}$$

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- The GPU is commonly used in the field of polymer science and engineering to describe the permeance of gases such as oxygen, carbon dioxide, and nitrogen through various polymers. Specifically it is used in packaging and barrier applications, where the barrier properties are critical for preserving the quality and shelf life of food, pharmaceuticals, and other perishable products. The principal difference between GPU and Barrer units is that; the permeability or the permeability coefficient characterised by Barrer is an intrinsic permeation property of a gas through a material or membrane. It was an earlier introduced unit, which facilitated comparison of materials for membrane gas separation. On the other hand, permeance characterised by GPU is directly related to material or membrane thickness and is the pressure-normalised steady-state flux. It characterises gas transport through the membrane and was introduced for comparing membrane suitability for mixed gas separation.

- Gas permeability can be expressed in various units in addition to Barrer and GPU, such as, but not limited to, $\text{cm}^3 \cdot \text{cm} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, $\text{kmol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{kPa}^{-1}$, $\text{m}^3 \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{kPa}^{-1}$, and $\text{kg} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{kPa}^{-1}$, but Barrer is a more standardised and widely recognized unit in the field of materials science. It will be appreciated that the Barrer is a common measurement of gas permeability in current usage, especially through polymers and similar materials, particularly in relation to gas-permeable membranes.

- The term “gas permeability rate” refers to the measurement of the rate at which a specific gas can permeate through a material, typically expressed in units of volume per unit time per unit area. Gas permeability and gas permeability rate are often used interchangeably, but they actually have slightly different meanings, where gas permeability rate is the rate at which the amount of gas that can pass through a material, while gas permeability is a measure of the intrinsic property of a material to allow gas to pass through it. ISO 15105-1 specifies two methods for determining the gas transmission rate of single-layer plastic film or sheet and multi-layer structures under a differential pressure. One method uses a pressure sensor, the other a gas chromatograph, to measure the amount of gas which permeates through a test specimen. Other equivalent measurements of gas-permeability are known to the skilled person and would be readily equivalent to Barrer measurements described herein.

As used herein, the term "biomass" refers to any living or dead organism, including any part of an organism (including metabolites and by-products produced and/or expelled by the organism).

As used herein, a "system" refers to a configuration of modular component parts, i.e., "modules", that cooperate to provide the necessary functionality needed to perform as a bioreactor. The system may comprise one or more "units", which are modular parts that define the primary location within the system for biomass growth. The system may comprise an array or combination of a plurality of "units".

As used herein, the term "chamber" also refers to a "gas chamber" and/or to an "air-chamber" and the terms can be used interchangeably herein.

As used herein, the term "elongate" refers to a two or three-dimensional shape with a length along a primary axis greater than its length along any perpendicular axis.

As used herein, the term "fluid" refers to a flowable material, typically a liquid and suitably liquid media, which is comprised within the units, and thus the devices of the invention. As defined above, "fluid" also refers to any gas and/or mixture of gases, suitably the gaseous atmosphere comprised within the units, and thus the devices of the invention.

As used herein, the term "flow rate" refers to the volume of fluid per unit time travelling through a cross section. Flow rate can be expressed in many units such as m³/hour.

As used herein, the term "flow velocity" refers to the average velocity of a fluid, across the cross section of the passage it is passing through, in a specific direction parallel to its motion of travel averaged over a period of time great enough such that changing the length of the time period has a negligible effect on the result. Flow velocity can be expressed in many units such as m·s⁻¹.

As used herein, the term "flow regime" refers to different flow behaviours. These behaviours are defined as laminar or turbulent. In laminar flow, the fluid travels along non-intersecting streamlines. There is no mixing of the fluid and all transfer across streamlines is due to diffusion. In turbulent flow, the fluid is chaotic due to vortices, eddies and reverse flows. There is a lot of mixing in turbulent flow and transfer is no longer controlled by diffusion due to the fluid's chaotic nature. Reynolds number (Re) is a dimensionless number that is used to indicate which regime the flow is in. It is general convention that laminar flows have low Reynolds numbers (Re < 2000) and turbulent flows have high Reynolds numbers (Re >= 4000). In the transitional region (2000 <= Re < 4000) the flow could be either laminar or turbulent and it is only possible to know by physical observation."

The Reynolds number of a flow can be defined as:

$$Re = \frac{\rho u L}{\mu}$$

Where Re = Reynolds number, ρ = fluid density (kg/m^3), L = characteristic linear dimension (m) (for example hydraulic diameter in pipe flow) and μ = fluid dynamic viscosity (Pa-s).

5 As used herein, the term "liquid media" has its usual meaning in the art and is a liquid used to grow the organisms and which contains the organisms. The liquid media can comprise one or more of the following: fresh water, salty water, saline, brine, sea water, waste-water, sewage, nutrients, phosphates, nitrates, vitamins, minerals, micronutrients, macronutrients, metals, digestate, fertilisers, agricultural biomass, nutrient rich liquid derived from agricultural biomass, microorganism growth media, BG11
10 growth media, PYGV media, and organisms. The liquid media can also comprise carbon sources for the comprised organisms; often these are glucose and/or monosaccharide and/or polysaccharide sources. Suitable carbon sources of this kind can include, but are not limited to, lignin, cellulose, hemicellulose, starch, xylan, polysaccharide, xylose, galactose, sucrose, lactose, glycerol, molasses or glucose, or derivatives thereof. Other sources of suitable carbon sources can be food waste, biomass
15 waste, agricultural waste and/or industrial fluid waste. Due to the high density of organisms which is possible to support in devices of the present invention, the term liquid media is intended to encompass a wide range of viscosities, including substantially liquid, gel-like or semisolid compositions.

The term "organism" as used herein refers to a body carrying on processes of life, which has various
20 properties, such as, representatively, cellular structure, proliferation (self-reproduction), growth, regulation, metabolism, repair ability, and the like. Typically, organisms possess basic attributes, such as heredity controlled by nucleic acids and proliferation in which metabolism controlled by proteins is involved. Organisms may include natural, wild-type, artificially manipulated, genetically modified, hybridised, or other variants or isolates. Organisms suitable for use within the systems of the invention
25 typically include prokaryotic organisms, eukaryotic organisms (e.g. unicellular organisms such as yeast, etc.) and multicellular organisms (e.g. plants, animals, etc.). It will be understood that, as the term is used herein, "organism" also refers to and encompasses cells as defined herein, and that the methods of the present disclosure may be applied to any such cell or cells. In specific embodiments of the invention the organisms are microorganisms, also referred to as microbial organisms. The systems and
30 methods of the invention are not intended to encompass human embryos or totipotent stem cells derived from human embryos.

As used herein, terms relating to the orientation of the device of the invention are generally used in their commonly held meanings, but are also intended to vary as appropriate depending on the particular
35 intention or configuration of the invention. Thus, terms such as upper, top and above may refer to directions away from the Earth's centre— i.e., away from the direction of a gravitational pull. Similarly, terms such as lower, bottom and below refer to directions towards the Earth's centre – i.e., toward the direction of a gravitational pull. Similarly, vertical/vertically can be defined as parallel to the direction of the gravitational pull towards the centre of the Earth and horizontal/horizontally as perpendicular to this
40 force.

The term "mass transfer" is referring to the movement of a substance from one location to another, which is driven by a concentration difference. The phenomenon of mass transfer is driven by diffusion, which is the movement of molecules from an area of high concentration to an area of lower concentrations. The rate of mass transfer is determined by the concentration gradient, the diffusion coefficient, and the physical properties of the system, such as temperature, pressure and the presence of chemicals and other molecules. The term "mass transfer" used herein, with respect to general bioreactors, including photobioreactors, refers to movement of gases, such as carbon dioxide and oxygen and other gases, as well as nutrients and metabolic products, within the culture medium and between the culture medium and surrounding environment. The term "mass transfer" with respect to singular membrane or selective and/or non-selective membranes or composite membranes refers to the movement of molecules or particles through the respective membrane and/or the membrane's barrier layer. Mass transfer through composite membranes may be selective where certain molecules and particles are exclusively allowed to pass through, while blocking others, or it can occur non-selectively where all the molecules and particles are allowed to pass through but at varying velocities or mass transfer rate. The mass transfer rate through a membrane is determined by several factors such as, but not limited to, the material of the membrane, the thickness of the membrane, the porosity of the membrane, if it is a porous membrane, the concentration gradient across the membrane, the active surface area of the membrane, and the physicochemical properties of the molecules or particles that are being transported.

As used herein, the term "pH" refers to a scale from 0 to 14 used to specify the acidity or basicity of an aqueous solution. The pH of the liquid media is a key parameter required to be controlled. It affects the solubility of nutrients, stability of pigments and other biomolecules which can impact the quality of the final product. Optimal pH conditions are required for growth, photosynthetic activity and other metabolic processes which influence the growth rate and biomass productivity. Therefore, maintaining stable and optimal pH and temperature ranges are crucial parameters for photobioreactors and bioreactors.

Similarly, temperature also can affect the optimum growth rates, solubility and other biochemical parameters in the culture medium, which collectively can influence the kinetics of microorganisms that determine the quality and safety of the final product. Temperature plays a prominent role in photobioreactors and bioreactors by influencing the growth, metabolism, and photosynthesis efficiency of microorganisms. Each species has an optimal temperature range for maximum growth and productivity, while deviations can lead to reduced biomass production or heat stress. Temperature can also affect nutrient availability, uptake, and microbial contamination control. Proper temperature management ensures operational efficiency, energy consumption, and the desired microorganism dominance. Overall, maintaining the right temperature is crucial for optimising microorganism performance, biomass production, and the overall success of photobioreactor systems.

Specific embodiments of the present invention use gas-permeable membrane bioreactors of the general class described for the cultivation of photosynthetic and heterotrophic microorganisms in WO2017/093744, WO2018/100400, WO2020/225709 (all of which are incorporated herein by reference), but further adapted to provide application to a wider range of materials for use in construction of the bioreactor systems. This approach provides greater versatility in choice of materials and configurations for construction of bioreactor systems, as well as use of less expensive or even more advanced materials.

The configurations defined herein are particularly suitable for bioreactors that are comprised of elongate bioreactor units (e.g. based on a tubular liquid circuit as described herein in certain embodiments) because, amongst other things, maintenance of homogeneous liquid media conditions throughout the bioreactor length can be challenging.

Elongate reactors of this configuration allow key parameters of the culture to be controlled substantially evenly throughout the volume of the culture. In embodiments of the invention where the culture medium comprises photosynthetic microorganisms, the gas permeable composite membrane allows the addition of gases evenly across the entire volume of the culture medium, for example CO₂ to provide a carbon source for phototrophic growth. The colocation and orientation of the second wall and/or gas-permeable membrane layer of the bioreactor units can be suitably modified to increase or decrease the gas transfer rate between the fluid-containable compartment and the gaseous atmosphere within the adjacent chamber.

A further benefit of the technology is the ability of gases produced through the activity of the culture to pass through the gas permeable composite membrane, out of the liquid media, evenly throughout its entire volume. For example, in embodiments of the invention comprising photosynthetic microorganisms, O₂ produced during photosynthesis, which is toxic for the culture in high concentrations, can be constantly removed evenly throughout all of the liquid media in the bioreactor units via the gas permeable composite membrane.

The diffusion and dissolution of gases (for example CO₂) across the membrane into the liquid media can lower the pH of the liquid media. This mechanism for controlling the pH of the liquid media is easier and cheaper than existing alternatives that include sparging and the addition of buffers. To elaborate, when CO₂ dissolves in water, it forms carbonic acid (H₂CO₃^{*}), which dissociates into bicarbonate ions (HCO₃⁻) and hydrogen ions (H⁺). The presence of hydrogen ions leads to a decrease in pH, making the liquid media more acidic. This mechanism provides a relatively simple and cost-effective way to control the pH of the liquid media in comparison to other alternatives like sparging and the addition of buffers. The diffusion and dissolution of gases occur naturally when the liquid media and gas phase are in contact with each other through a gas permeable membrane. There is no need for complex equipment or additional processes. Compared to sparging systems that require pumps, blowers, and mixing devices, utilising gas diffusion for pH control can be more cost-effective. It eliminates the need for

energy-consuming sparging equipment and reduces operational costs associated with maintenance and power consumption. Additionally, The diffusion and dissolution of gases allow for continuous pH adjustment based on the concentration of gases present. As the gas permeates the membrane, the pH of the liquid media can be gradually lowered. This continuous adjustment can provide better control and stability of the pH compared to intermittent or batch-wise methods. The diffusion and dissolution of gases are relatively non-disruptive to the system. Unlike the addition of buffers, which can alter the chemical composition of the liquid media, gas diffusion allows for pH control without introducing additional components.

10 A benefit of the present invention relates to the high energy costs, operational costs and capital costs for controlling gas concentrations associated with sparging and compression devices of gases like CO₂ (or air mixtures) in standard photobioreactors as described previously. The present invention enables, in part, much more efficient gas-transfer control in the liquid media, including on a large scale, and provides greater versatility compared to systems that require devices for controlling sparging and compression of feed gases administered directly to the liquid media. The operational complexity and extra weight associated with compression and sparging techniques is also avoided. Gas which has been pressurised to a lower pressure than would be necessary in using other photobioreactor technologies may also be used without the need for further pressure. Due to the nature of the invention, the natural expansion properties of gas mean that supplied gas can be easily supplied and expanded to rapidly change the composition of the entire chamber. This provides a further benefit, as the gas concentration within the chamber can be relatively easily controlled on a large scale, and by extension the gas concentration in the liquid media can be controlled on the same scale. In certain embodiments of the invention, direct sparging into the liquid media, for example via bubbling, is not required for the provision of gases necessary for the growth of the culture and/or agitation and/or pH control.

25 The absence of necessary gas bubbling or sparging techniques also means that the nozzles, outlets and inlets required for such techniques will not be in contact with the liquid media or organisms, and therefore will not have to be cleaned. Such features can be difficult to clean and are frequently areas of microbial growth or debris collection, and can even be sources of contamination themselves through the introduction of contaminants with the input gas. Therefore, the invention allows for increased sterility and flexibility in process setup and shut down, as cleaning before and after use can be more effective.

Further, the nature of the device of the invention means that processes of cleaning and sterilisation can be carried out effectively and efficiently. According to one embodiment of the invention, the tubular/elongate configuration of the liquid-containable compartment of the photobioreactor or bioreactor units which comprise and contain much of the liquid media volume within the system allows for the removal of blind endings, corners, edges, seams and other crevices, by enabling a substantially uniform cross-section of the bioreactor. Since such features provide areas where unwanted microorganisms and biofilms can attach, or where debris, spent liquid media or other detritus could

accumulate, as well as being difficult to clean effectively, the present invention allows for fast and efficacious cleaning to take place.

Another benefit of the present invention is in increasing the robustness and environmental resistance of a bioreactor comprised within an assembly. The second wall of the fluid-containable compartment and walls of the chamber may be configured to provide physical protection and/or thermal insulation against external factors such as changing environmental or seasonal conditions. This insulation also decreases the energy necessary for the maintenance of the temperature of liquid media comprised with the bioreactors. Physical protection of the potentially fragile gas-permeable layers of the photobioreactor is also provided against factors such as weather, wind or hail, or animal damage. The provision of an additional barrier also acts to contain liquid spills from the bioreactor into the environment.

Another benefit of the present invention is in increasing the robustness and environmental resistance of a photobioreactor comprised within a unit. The walls of the fluid-containable compartment and/or of the chamber, may be configured to provide physical protection and/or thermal insulation against external factors such as changing environmental or seasonal conditions. This insulation also decreases the energy necessary for the maintenance of the temperature of liquid media comprised with the photobioreactors. Physical protection of the potentially fragile membrane of the photobioreactor is also provided against factors such as weather, wind or hail, or animal damage. The provision of an additional barrier also acts to contain spills from the photobioreactor into the environment.

Thermal insulation may also be provided by this invention beyond the device itself. It is envisioned that some embodiments of the invention may be configured for installation on the roofs or facades of buildings, thereby providing an added benefit of insulation to the buildings on which they are installed. For this purpose, the surface of the chamber in contact with the building can be replaced with or additionally comprise an insulating material such as a polymeric foam, insulation foam, cork, bitumen, glass fibre, or any other highly insulating material and/or coatings and/or composites for constructions.

30 The Bioreactor System

In an embodiment of the present invention, a bioreactor system is shown in Figure 1a. The bioreactor system 101 comprises at least one bioreactor unit 105. The bioreactor unit 105 comprises a liquid-containable compartment 102 and a chamber 103 that encloses an atmosphere. The liquid-containable compartment 102 is located adjacent to the chamber 103 such that exchange of gases can occur across a composite membrane 104. Gas flow is maintained continuously or intermittently through the chamber 103 via an inlet 110 and an outlet 106. The chamber 103 may be in gaseous communication with an auxiliary subsystem 121 which may have many functions including, but not limited to, optimising the circulation of gas through the chamber 103. The liquid-containable compartment 102 may be in liquid communication with an auxiliary subsystem 120, via an inlet line 108 and an outlet line 109, which may

have many functions including, but not limited to, optimising the circulation of liquid media through the liquid-containable compartment 102. The bioreactor unit 105 may function as a photobioreactor unit in which case some or all of the walls that define the chamber 103 and/or the liquid-containable compartment 102 may be translucent and/or transparent to visible light, or certain wavelengths of the electromagnetic spectrum required for photosynthetic activity to occur. Illumination 130 may come from the sun or from an artificial source. The illumination 130 may also provide a source of UV illumination (e.g. UV-C) if sterilisation of the bioreactor unit 105 is required during down time, such as during a cleaning cycle. It will be appreciated that the orientation of the bioreactor unit 105 shown in Figure 1a is not limiting, and it is equally appropriate for the liquid-containable compartment 102 to be located lowermost in the unit, or for other arrangements in which multiple liquid-containable compartments are arrayed in series or in parallel in combination with one or more chambers.

In alternative embodiments of the design, the liquid-containable compartment 102 may be a channel and/or conduit and/or hose and/or pipe and/or tube and/or duct and/or passage and/or line and/or any substantially elongate form.

In embodiments of the invention, for example the embodiment described in Figure 1b, the bioreactor system 101 may comprise a plurality of bioreactor units 105 arranged sequentially in series such that the liquid-containable compartment outlet line 109 and/or the chamber outlet 106 from one unit may serve as an inlet line into an adjacent unit or plurality of units. In this way fluid communication of the liquid-containable compartments 102 and/or chambers 103 of adjacent bioreactors 105 is maintained such that a constant flow of liquid media and/or gas can occur within a loop circuit. The supply of atmosphere to the chamber 103 may be from the same auxiliary subsystem 121 or controlled independently by separate auxiliary subsystems for each bioreactor unit 105 within the system 101. In an embodiment of the present invention, a bioreactor system is shown in Figure 1b that consists of multiple bioreactor units connected in series where the atmosphere to chamber 103 is controlled by the same auxiliary subsystem 121. Likewise, in this embodiment, the liquid in the liquid-containable compartments 102 of all of the bioreactor units is circulated through the same liquid auxiliary subsystem 120.

In alternative embodiments of the invention, for example the embodiment described in Figure 1c, the bioreactor system may comprise a plurality of bioreactor units 105 arranged in parallel such that the inlet line 108 provides a common inlet into parallel arrayed bioreactor units 105, and one or more outlet lines 109 return to the auxiliary subsystem 120. The supply of atmosphere to the chamber 103 may be the same or controlled independently for each bioreactor unit 105 by a common auxiliary subsystem 121 or a plurality of such auxiliary subsystems that provide a manifold supply via inlet 110 and return outlet 106. In alternative embodiments, each bioreactor unit 105, arranged in parallel, may also be connected to additional bioreactor units in series.

Figure 2a shows an arrangement of a bioreactor unit 205 according to an embodiment of the invention in the side-view. The bioreactor unit 205 may assume an elongate form which is divided into a liquid-
containable compartment 202 and a chamber 203 that encloses a gas filled atmosphere. In the
embodiment shown in Figure 2a, a flow of atmosphere through the chamber 203 is shown in the
5 direction of arrows b, whereas liquid media is shown flowing counter current through the liquid-
containable compartment 202 along the direction of arrows a. In alternative embodiments, it will be
appreciated that parallel flow of the liquid media and gaseous atmosphere is also provided for and/or a
mix of counter current and parallel flow is present in the same unit 205 (this can occur when the liquid-
containable compartment is configured to follow a tortuous path through a single chamber). The liquid-
10 containable compartment 202 is separated from the chamber 203 by way of a membrane or other gas
permeable material film 204. A structurally rigid enclosure 211 provides the remaining walls of the
chamber 203 thereby defining the atmospheric enclosure within. The enclosure 211 may optionally be
comprised of a translucent or transparent material. The remaining wall(s) of the liquid-containable
compartment 202 are provided by a structurally rigid second wall 207. In other embodiments the second
15 wall 207 is formed of a flexible or inflatable material. In embodiments of the invention wherein the
bioreactor unit 205 is a photobioreactor unit, natural solar or artificial illumination 230 may be provided
and the enclosure 211 may be comprised of a translucent or transparent material. Figure 2b shows an
arrangement of a bioreactor unit 205 according to an embodiment of the invention in the side-view. In
the embodiment shown in Figure 2b, a flow of atmosphere through the chamber 203 is shown in the
20 direction of arrows b, and liquid media is shown flowing in parallel through the liquid-containable
compartment 202 along the direction of arrows a. It will be appreciated that the orientation of the
bioreactor unit 205 shown in Figure 2a and Figure 2b is not limiting, and it is equally appropriate for the
liquid-containable compartment 202 to be located bottommost in the unit. In alternative embodiments
of the invention, the flow of the atmosphere comprised in the chamber may be in any direction relative
25 to the direction of flow in the liquid-containable compartment, including, but not limited to, parallel,
counter current, perpendicular and at an angle.

In Figure 3 an embodiment of the invention is shown that comprises a bioreactor system 301 that
comprises a bioreactor unit 305 that includes a single elongate liquid-containable compartment 302 and
30 a single adjacent chamber 303. The embodiment in Figure 3 is a partially exploded representation that
shows one way of assembling the bioreactor unit 305. A second wall 307 defines a semi-circular
channel upon which is applied a complementary semi-circular stretch of the gas permeable membrane
layer 304. The wall 307 may be formed of a structurally rigid material or a flexible material that assumes
its final configuration under positive hydraulic pressure exerted primarily from the contents of the liquid-
35 containable compartment 302 or the flow of the contents therethrough (Figures 5c i and 5c ii). The wall
307 and membrane layer 304 are bonded along a lateral seam to provide a fluid tight seal longitudinally
and to thereby define the liquid conduit 302 within. The liquid-containable compartment 302 may be laid
within a channel, as indicated by direction arrow C, in a strip of trunking or pipe 311. The trunking 311
cooperates with the laid-in liquid-containable compartment 302 to define an adjacent, aligned chamber
40 303 within. The chamber 303 may be substantially gas tight, or at least sufficiently non-porous such

that the atmosphere within the chamber 303 is controllable in terms of composition so as to facilitate gas exchange across the membrane layer 304 between the atmosphere within the chamber 303 and the interior of the liquid-containable compartment 302.

- 5 In embodiments where the bioreactor unit 305 is utilised as a photobioreactor unit any one or both of the materials used to manufacture the wall 307 and/or the trunking/chamber wall 311 are translucent or transparent to visible light. It is optional, but non-essential, that the membrane layer 304 is made from a light transmissible material in the event that the wall 307 is made from a translucent or transparent material. Indeed, an advantage of certain embodiments of the invention is that composite or
10 microporous materials that are not transparent to light are suitable for use in manufacture of the membrane layer 304.

Figure 4 shows an embodiment of a bioreactor system 401 of the invention which comprises a bioreactor unit 405 that includes three adjacent fluid compartments 402 that comprise liquid media and
15 a microbial culture and/or organisms growing within, to produce a biomass harvest. In the embodiment in Figure 4, the microbial culture and/or organisms comprises photosynthetic microorganisms and/or macro-algae and/or aquatic plants and the bioreactor system 401 is, therefore, a photobioreactor. However, it will be appreciated that the bioreactor systems of the invention and embodiments shown are not limited, as such, if non-photosynthesising organisms are utilised

- 20 The liquid-containable compartments 402 are longitudinal and elongated thereby allowing flow of liquid media therethrough. The compartments 402 are defined by a rigid and/or flexible second wall 407 that provides attachment points allowing a plurality of compartments 402 to be aligned substantially in parallel.

- 25 The composite membrane layer 404 is in contact with the atmosphere contained within a chamber 403 defined by structural members 411. The members 411 may cooperate with the walls 407 to provide structural integrity to the unit 405 and to enclose and provide protection to the composite membrane layers 404. The chamber 403 comprises a conduit that runs in the same direction as all or at least a substantial proportion of the liquid-containable compartments 402. This arrangement allows for an
30 atmosphere whose gaseous composition may be controlled, if necessary, by an auxiliary subsystem (not shown), and placed in contact with the composite membrane 404 thereby permitting gas exchange across the composite membrane layers 404 between the liquid-containable compartment 402 and the atmosphere within the chamber 403. In the embodiment shown in Figure 4, exemplary gaseous transfer of carbon dioxide and oxygen is shown occurring across the composite membrane layers 404.

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It will be appreciated that the shape and configuration of the walls 404 and 407 may vary depending upon the desired performance characteristics of the system 401. Hence, in certain embodiments, the channel defined by the walls 404 and 407 may be deeper, or more enclosed, non-circular in cross section (e.g. ovoid, square or polygonal), or otherwise.

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Embodiments of the invention are shown in cross section in Figure 5a that illustrate the proportion of the internal surface area of the liquid-containable compartment 502 comprising wall 504 can be varied in comparison to the internal surface area of the liquid-containable compartment comprising wall 507.

- 5 In all of these embodiments the bioreactor unit functions in a manner equivalent to that explained in the embodiments shown in Figures 1 to 4. These arrangements show how the location of the liquid-containable compartment relative to the chamber can be varied in order to maximise available surface area for gas transfer across the composite membrane in situations where atmospheric composition of the chamber is favourable, or in the alternative where there is a need to maximise the exposure of the liquid-containable compartment to the outside – e.g. to optimise illumination or to enable effective thermal regulation. It will be appreciated by the skilled reader that the positioning of the liquid-containable compartment relative to the chamber may be varied to assume co-locations that fall between or on either side of those depicted in the Figures 5a i, 5a ii and 5a iii.
- 10
- 15 Embodiments of the invention shown in cross section in Figures 5b demonstrate alternative arrangements of the bioreactor units in which the second wall (non-membrane layer) is planar (Figure 5b i), curved (Figure 5b ii) or irregular (Figure 5b iii).

- In embodiments of the invention the compartments 602 may be connected to each other with U shaped connectors to form a tortuous flow circuit in series, as in Figure 6a. Alternatively, a liquid distribution inlet manifold may be provided if the compartments 602 are to be operated in parallel, as in Figure 6b. Likewise an outlet manifold may collect out flow of media from the parallel compartments 602. Alternatively, a mix of U-shaped connectors and liquid distribution manifolds are present where liquid-containable compartments are arranged both in series and in parallel. As exemplified in Figure 6c, the manifolds can be reconfigurable to change the number of liquid-containing compartments to be in parallel or series during different modes of operation. In further embodiments of the invention, the first wall and second wall of the liquid-containable compartment can be shaped to comprise a bend in order to facilitate a change in direction, for example a u-shape, and/or curve, and/or angle. In an alternative embodiment, liquid-containable compartments 602 that are part of the same circuit can be in contact with different chambers, as illustrated in Figure 6d. In certain embodiments different chambers can have their atmospheres differently optimised, for example they can contain different compositions of gases or be under different pressures.
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- 25
- 30

- The bioreactor units described herein are particularly space-efficient, and units that comprise multiple liquid-containable compartments can be arranged within a single chamber, in series, where the outlet of one bioreactor flows into another bioreactor to which it is connected, or in parallel or a combination of these approaches. For example, in a specific embodiment, multiple bioreactor units may be arranged in series such that the flow within each bioreactor runs in an antiparallel direction to the preceding one, such that the liquid media takes a sinuous path through several bioreactor units. Where two or more bioreactor units are connected so as to be in fluid communication with each other, the connector or
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- 40

conduit which joins them can be a separate component, which does not have to comprise any gas permeable materials.

For a system consisting of a fixed number of bioreactor units that have liquid-containable compartments with the same cross-sectional area, arranging units in parallel can be advantageous as, at a fixed flow velocity, the length of the path travelled by the liquid media is less and therefore the pressure drop across the inlet and the outlet of the connected liquid-containable compartments is reduced. Alternatively, increasing the number of bioreactor units in series can reduce the capacity of the pump required to achieve the necessary flow velocity in all of the units.

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Connectors may also be used to connect the liquid-containable compartments of individual bioreactor units with a liquid tight seal to other components including the liquid-containable compartments of adjacent bioreactor units, an inlet or outlet, a manifold, a u-turn or an auxiliary subsystem. The connector may comprise a valve, typically a butterfly valve, pinch valve, solenoid valve or diaphragm valve, which acts to prevent fluid passing or allow fluid to pass through the connector, for example between one bioreactor and the next. Advantageously, this can allow for several blocking points within a system comprising multiple bioreactor units arranged in series. This enables any hydrostatic pressure stress from abruptly halting flow within the system to be shared between adjacent bioreactors, and to prevent pressure waves from propagating throughout the whole of the connected bioreactors. Otherwise, if the flow is stopped suddenly, such as due to a pump failure, with all bioreactor units remaining fluidly connected within the system, a 'water hammer' effect may put excessive stress on particular components. Any measures to mitigate such effects may be used in systems according to the invention, as appropriate, such as pressure regulators, slow-closing valves, flow diverters, shock absorbers, dampeners, and so on. Including valves throughout the liquid system also allows sections to be isolated from one another if necessary if maintenance is being carried out. Connectors may also provide ports for sensor probes or provide direct connection to in-line sensors to sense key performance parameters of the liquid media. Connectors may also comprise filters and/or meshes to capture specific particles, beads, scrubbing beads, and/or molecules present in the liquid media.

Figures 7a and 7b show a specific embodiment of the invention where the liquid-containable compartments of multiple bioreactor units are connected with connectors 771. In this embodiment a plurality of bioreactor units are arranged into four lines of bioreactor units (721, 722, 723, 724). Each line of bioreactor units is made up of four bioreactor units with the liquid-containable compartment of each connected in series. The four lines of bioreactor units are connected at each end with a manifold. In this embodiment, all of the bioreactor units share the same chamber 703.

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In specific embodiments of the inventions, connectors between bioreactors can be easy to assemble and disassemble, allowing bioreactor units to be quickly removed during maintenance either to be repaired or replaced. This would increase ease of maintenance and reduce the cost of running the system.

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In specific embodiments of the invention, the connectors may comprise structures formed into or placed upon the interior surface that promote turbulence in the liquid media flowing through the bioreactor system. Such structures may comprise one or more of fins, ribs, baffles, surface texturing, studs or beading. Encouraging fluid turbulence may serve to facilitate mixing of the liquid media - allowing organisms within the liquid-containing compartment to circulate so they can uptake light or nutrients more efficiently - as well as disrupting formation of biofilms due to settling, improved gas transfer across the membrane, and/or improved thermal regulation by removing hot or cold zones.

It is contemplated that features may be introduced that allow for improved mixing of the liquid media as it flows through the bioreactor system or bioreactor units. In this regard, static mixers can be installed in the system (either inside the bioreactor units, or inside one or more connectors between units) to increase turbulence in the liquid-containable compartments and facilitate mixing of liquid media and culture. These mixers are static and designed to mix a fluid in motion that passes through them. For instance, a static mixer can comprise a helicoidal structure which disrupts the flow of liquid media.

Improved mixing and turbulence can also be achieved by increasing the Reynolds number of the flow. Increased turbulence results in eddies and vortices in the flow that can transfer through the boundary layer of the fluid, putting all parts of the liquid more effectively in contact with the membrane. This may aid in the mechanism of mass transfer by increasing the tendency of mixing of gases and the composite membrane surface, which may increase the effective surface area available for continuous gas transfer and may improve the diffusion rate of gases through the membrane.

In certain embodiments, the flow regime of the liquid media beneficial for gas transfer comprises a Reynolds number that is no more than about 200000, about 175000, about 150000, about 125000, about 100000, about 75000, suitably no more than about 50000, about 40000, about 30000, about 20000 and typically no more than about 10000. The Reynolds number may be at least 2000, at least 4000, at least 10000, suitably at least 20000, at least 30000, at least 40000 and optionally at least 50000.

Further to increased gas permeation rate, more turbulence in the flow can improve the efficacy of cleaning processes that involve passing chemicals through the liquid-containable compartments. In a larger embodiment of the design, the turbulence in one section of the system can be increased by increasing the fluid velocity in that section, without increasing the pressure difference between the inlet and the outlet of the system. To enable this, the path of the liquid media can be changed with a reconfigurable manifold to reduce the overall path length of the fluid and the flow velocity in other parts of the system. Both of these reduce the pressure drop across the inlet and outlet. Figure 7a and 7b show an embodiment of the invention with a plurality of bioreactor units arranged in four lines (721, 722, 723 and 724). In Figure 7a the manifold is arranged so all of the liquid-containable compartments are connected in series, this means the flow velocity is the same everywhere in the system and the path

length is as long as possible. In Figure 7b 722, 723 and 724 are connected in parallel, so the flow velocity in these lines is reduced and the overall distance the fluid travels is also reduced so the pressure difference between the inlet and outlet would lower. This would allow the flow velocity at the inlet (and in line 721) to be increased until the pressure difference across the inlet and outlet in Figure 7b was the same as that in Figure 7a.

The First Wall - The Gas Permeable Composite Membrane

According to certain embodiments of the invention, the bioreactor unit comprises a first wall which comprises a composite membrane that permits gas transfer between a liquid-containable compartment and an adjacent chamber that comprises an atmosphere of controllable composition.

In certain embodiments, a composite membrane may comprise any combination of barrier layer(s), and/or intermediate layer(s), and/or reinforcement layer(s).

In certain embodiments, the number of individual layers that a composite membrane comprises may suitably be not more than about 20 layers, about 15 layers, about 12 layers, about 10 layers, about 9, about 8 layers, about 7, about 6, about 5 layers, about 4 layers, about 3 layers and typically not more than about 2 layers. The number of individual layers that a composite membrane comprises may suitably be at least about 2 layers, at least about 3 layers, at least about 4 layers, at least about 5 layers, at least about 6 layers, at least about 7 layers, at least about 8 layers, at least about 9 layers, at least about 10 layers, at least about 12 layers, and typically at least about 15 layers.

In certain embodiments, the composite membrane comprises a multi layered structure, with at least one layer being a barrier layer that is impermeable to the liquids and selectively and/or non-selectively permeable to any gas/gases. In specific embodiments, the composite membrane may exhibit a level of asymmetry in the structure that the arrangement of layers within the structure allows for the membrane to define different physical properties on either side of the membrane. By way of non-limiting example, each side of the composite membrane may have discrete properties that enhance performance in separation of permeating gases and/or hydrophobicity.

In certain embodiments, when the composite membrane is comprised of at least one layer that is porous, the individual porous layer/layers may typically be characterised by uniform pores or channels throughout the layer. By way of example, a composite membrane comprising a dense barrier layer, a porous intermediate layer and a porous reinforcement layer; the pore size of the intermediate layer may be in the range of one to tens of micrometre and the pore size of the reinforcement layer may be in the range of hundreds of micrometre. In other embodiments, the individual porous layer/layers in a composite membrane may be characterised by non uniform pore sizes that increase or reduce in pore size along the penetrant direction through the respective layers, leading to a "contracting" effect. By way of non-limiting example, a composite membrane may be comprised of a dense barrier layer, a

dense intermediate layer and a porous reinforcement layer, where the pore sizes may be larger on one side and become smaller along the thickness of the reinforcement layer. Further, this gradient in pore size can be optimised to enhance the mass transfer across the composite membrane.

- 5 Porosity, in the context of gas transfer composite membranes, refers to the measure of empty spaces or voids within the membrane structure or within the individual layers of the composite membrane. Porosity represents the ratio of the volume of the empty spaces (pores) to the total volume of the membrane and is characterised by the unit '%'. Porosity is an important parameter as it affects the permeability and/or selectivity of the composite membrane and plays a role in determining the amount
10 of gas that can pass through the composite membrane. Higher porosity generally may allow for increased gas permeation as there are more pathways available for gas molecules to move through the membrane. However, excessively high porosity may lead to reduced mechanical strength and structural integrity of the membrane and may also cause liquid permeation. The porosity of a composite membrane may be controlled through various factors, including the choice of materials, fabrication
15 techniques, and post-treatment processes. Adjusting the porosity of the composite membrane may help optimise its performance for specific gas transfer and/or separation applications, balancing the need for high permeability with sufficient mechanical strength and stability.

- In suitable embodiments, a composite membrane or any of its comprised individual porous layers can
20 have a porosity that may be suitably no more than about 60%, about 50%, about 40%, about 30%, about 20%, and typically no more than about 10% porosity. A composite membrane or any of its comprised individual porous layers can have a porosity that may be suitably at least about 1%, at least about 10%, at least about 20%, at least about 30% porosity, at least about 40%, at typically at least about 50% porosity.

- 25 Pore size, in the context of gas transfer composite membranes, refers to the average diameter or dimensions of the individual pores or openings within the composite structure or within the individual layers of the composite membrane. Pore size represents the size of the empty spaces through which gas molecules can pass and is a critical parameter as it directly influences the permeability and/or
30 selectivity of the permeants (gases) through the composite membrane. The size of the pores determines which type of gas molecules can pass through the composite membrane and to what extent. Smaller pore sizes may restrict the passage of larger gas molecules, while larger pore sizes allow for the permeation of a wider range of gas molecules. The desired pore size depends on the specific gas transfer and/or separation requirements of the application.

- 35 In suitable embodiments, a composite membrane or any of its comprised individual porous layers can have an average pore size that may be suitably no more than about 1000µm, about 500µm, about 400µm, about 300µm, about 200µm, about 100µm, about 50µm, about 40µm, about 30µm, about 20µm, about 10µm, about 1µm, about 0.1µm, and typically no more than about 0.01µm. A composite
40 membrane or any of its comprised individual porous layers can have an average pore size that may be

suitably at least about 0.001µm, at least about 0.01µm, at least about 0.1µm, at least about 1µm, at least about 10µm, at least about 20µm, at least about 30µm, at least about 40µm, at least about 50µm, at least about 100µm, at least about 200µm, at least about 300µm, at least about 400µm, and typically at least about 500 µm average pore diameter.

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In certain embodiments, the composite membrane may be designed to selectively transport specific gases through the membrane while hindering others based on their molecular size, affinity for the membrane material, and/or any other means. In alternative embodiments, a composite membrane may be designed to non-selectively allow the transfer of all gases at variable mass transfer or permeation rates and at various concentration zones within the membrane, depending on the type of gas. Such membranes can be comprised of at least one barrier layer that may be made up of a thin, dense material on the top surface and followed by subsequent individual layers, such as an intermediate layer/layers and a reinforcement layer/layers beneath it. Overall, the thickness of the individual layers and subsequently of the whole composite membrane can be tuned and optimised based on the desired performance within the embodiment of the invention. For example, in a composite membrane comprising a barrier layer, an intermediate layer and a reinforcement layer; the thickness of the intermediate layer may be about one or two times the pore size of the reinforcement layer for improved mass transfer efficiency. Furthermore, in some embodiments for a composite membrane comprised of a dense barrier layer, a non-porous intermediate layer and a porous reinforcement layer/layers, the thickness of the intermediate layer may be similar or less than that of the barrier layer for improved mass transfer efficiency.

In general, the thickness of individual layers within a composite membrane can play an important role in determining the membrane's overall performance and gas transfer and/or exchange parameters. With respect to selectivity, thinner barrier layers may allow for precise control over the composite membrane's permeability and selectivity. By adjusting the thickness of the barrier layer, it's possible to tailor the membrane's performance for specific gas permeating behaviour, achieving higher selectivity with minimal trade-offs in permeability. Conversely, a thicker barrier layer may provide higher selectivity but may reduce gas permeation rates.

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The gas permeable composite membranes, taken as a whole, may be of any overall thickness as long as they permit suitable gas transfer across them to allow for the bioreactor to function satisfactorily. Nevertheless, in certain embodiments, the first wall comprises a composite membrane that has an overall thickness that may be suitably no more than about 5000µm, about 4900µm, about 4000µm, about 3000µm, about 2000µm, about 1500µm, about 1000µm, about 800µm, about 600µm, about 500µm, about 400µm, about 200µm, about 100µm, about 50µm, about 20µm, and typically no more than 10µm. The first wall comprises a composite membrane that has an overall thickness that may be suitably at least about 5µm, at least about 10µm, at least about 20µm, at least about 50µm, at least about 100µm, at least about 200µm, at least about 400µm, at least about 500µm, at least about 600µm, at least about 800µm, at least about 1000µm, at least about 1500µm, at least 2000µm, at least 3000µm,

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at least 4000µm, and typically at least about 4900µm. In other embodiments, the thickness of the liquid-containable compartment composite membrane layer may vary across its length, for example where a photobioreactor unit is connected to another unit or another object by a connector, the thickness may be increased and/or decreased in a portion of the composite membrane proximate to the connector compared to the composite membrane distant to the connector. Composite membrane thickness can also change depending on the position of the liquid-containable compartment in the unit, for example, photobioreactor units in a lower vertical position may use composite membrane layers that are thicker, to provide more protection against swelling under increased hydrostatic pressure.

Similarly, the thickness of the reinforcement layer in a composite membrane can also impact its mechanical stability and resistance to mechanical stresses without hindering the mass transfer efficiency. In certain embodiments, the first wall comprises a composite membrane, which comprises a reinforcement layer of thickness that may be suitably no more than about 4900µm, about 4000µm, about 3000µm, about 2500µm, about 2000µm, about 1500µm, about 1200µm in thickness, about 1000µm, about 800µm, about 500µm, about 200µm, about 100µm, about 50µm, and typically no more than about 20µm. The first wall comprises a composite membrane, which comprises a reinforcement layer of thickness that may be suitably at least about 10µm, at least about 20µm, at least about 50µm, at least about 100µm, at least about 200µm, at least about 500µm, at least about 1000µm, at least about 1200µm, at least about 1500µm, at least about 2000µm, at least 2500µm, at least 3000µm and typically at least about 4000µm. Ultimately, the ideal thickness of the reinforcement layer/layers may be determined based on a careful balance between mechanical strength, impact on gas transfer performance, hydrophobicity and other specific requirements of the application. By way of non-limiting example, a thinner reinforcement layer may be preferred to applications which may not require the stronger membranes. On the other hand, in some current embodiments, a thicker reinforcement layer may be preferred to provide sufficient mechanical support and structural stability to withstand a higher liquid containable compartment pressure, and/or joining compatibility with the second wall.

Additionally, the thickness of an intermediate layer within the composite membrane can also play an important role in providing an optimised concentration profile for the efficient gas transfer to occur. In certain embodiments, the first wall comprises a composite membrane, which comprises a porous intermediate layer of thickness that may be suitably no more than about 4000µm, 3000µm, about 2000µm about 1600µm, about 1400µm, about 1200µm, about 1000µm, about 800µm, about 500µm, about 200µm, about 100µm, about 50µm, about 10µm, about 1µm, and typically no more than about 0.1µm. The first wall comprises a composite membrane, which comprises an intermediate layer of thickness that may be suitably at least about 0.01µm, at least about 0.1µm, at least about 1µm, at least about 10µm, at least about 50µm, at least about 100µm, at least about 200µm, at least about 500µm, at least about 800µm, at least about 1000µm, at least 1200µm, at least 1400µm, at least 1600µm, at least 2000µm and typically at least about 3000µm.

Further, in certain embodiments, the composite membrane comprises a non-porous intermediate layer of thickness that may be suitably no more than about 500µm, about 400µm, about 300µm, about 200µm, about 150µm, about 100µm, about 50µm, about 30µm, about 20µm, about 10µm, about 1µm and typically no more than about 0.1 µm. The composite membrane comprises a non-porous intermediate layer/layers of thickness that may be suitably at least about 0.01µm, at least about 0.1µm, at least about 1µm, at least about 10µm, at least about 20µm, at least about 30µm, at least about 50µm, at least about 100µm, at least 200µm, at least 300µm, and typically at least about 400µm. The thickness of the non-porous intermediate layer may vary depending on the specific intended use, desired performance, and the material composition in the intermediate layer. Overall, the non-porous intermediate layer in gas transfer composite membranes may be essential for the fabrication of the composite membrane (i.e. the barrier layer), reducing internal concentration polarisation, optimising concentration profile, minimising pressure drop, containing leakage, sealing the barrier layer to prevent it from delaminating, and ensuring long-term stability and performance.

Within an embodiment, for optimised permeability rates for specific gases, the thickness of a porous intermediate layer within a composite membrane may be suitably no more than about ten times, about five times, about three times, and typically no more than about two times the average pore radius of the reinforcement layer. For optimised permeability rates for specific gases, the thickness of a porous intermediate layer within a composite membrane may be suitably at least about one time, at least about two times, at least about three times, and typically at least about five times the average pore radius of the reinforcement layer.

Furthermore, in certain embodiments, the first wall comprises a composite membrane, which comprises a barrier layer, which may be of any thickness, provided it allows for suitable gas transfer and acts as a barrier for the liquid in the liquid-containable compartment. In specific embodiments, the first wall comprises a composite membrane, which comprises a barrier layer of thickness that may be suitably no more than about 1000µm, about 800µm, about 500µm, about 300µm, about 200µm, about 100µm, about 50µm, about 40µm, about 30µm, about 20µm, about 10µm, about 8µm, about 5µm, about 2µm, and typically no more than about 1µm. The first wall comprises a composite membrane, which comprises a barrier layer of thickness that may be suitably at least about 0.1µm, about 0.5µm, at least about 1µm, at least about 2µm, at least about 5µm, at least about 8µm, at least about 10µm, at least about 20µm, at least about 30µm, at least about 40µm, at least about 50µm, at least about 100µm, at least about 200µm, at least about 300µm, at least about 500µm, and typically at least about 800µm. The thickness of the barrier layer may vary depending on the specific application, desired performance, and the material composition in the barrier layer.

The thickness of a non-porous barrier layer may be determined by the intended use of the composite membrane. By way of example, composite membranes comprising thinner barrier layers may exhibit higher flux (i.e., rates of permeation), while thicker barrier layers may offer better selectivity with respect to specific permeants.

With respect to mass transfer, a composite membrane with a thinner barrier layer may minimise the mass transfer resistance, enabling faster gas permeation through the composite membrane. Due to the reduced resistance and shorter diffusion path encountered by the respective gas molecules through the barrier layer material, higher gas flux rates can be achieved and subsequently improve overall mass transfer efficiency. In certain embodiments of the invention the barrier layer thickness is leveraged to tailor the composite membrane to enhance mass transfer efficiency to and from the liquid-containable compartment.

As used herein the term "hydrophobicity" refers to the parameter used to describe the degree to which a surface or a material repels water. As used herein, the term "contact angle" or "water contact angle" refers to the angle formed between a water droplet and the surface of a material. This angle measures the hydrophobicity of a surface; a high contact angle indicates a hydrophobic surface that repels water, while a low contact angle indicates a hydrophilic surface that attracts water. Furthermore, a surface is generally considered to be hydrophobic if it has a contact angle with water that is larger than 90°, indicating that it repels water and is resistant to wetting.

In some embodiments of the invention, with respect to composite membranes, hydrophobicity refers also to the ability of the membrane surface, both as a whole composite membrane and/or respective individual layers, to resist the passage of water molecules to pass through it. In certain embodiments of the invention, gas transfer membranes are designed to be highly hydrophobic to prevent the accumulation of liquid phase on the composite membrane surface and/or within the composite membrane structure, which can block the pores and reduce the composite membrane's gas permeation rate. In other words, a hydrophobic surface refers to a material or surface which has a low affinity for water or other liquids, meaning that water molecules tend to bead up and roll off the surface of the membrane. Hydrophobic membranes can also be optimised to prevent the transport of water vapour, which can also interfere with the transfer of gases or lead to unwanted condensation. Hydrophobicity may be achieved by modifying and/treating the surface of the composite membrane with hydrophobic materials or by selecting a material with inherent hydrophobic properties to form the composite structure. Some the examples of such materials include, but not limited to, ethylene tetrafluoroethylene (ETFE), polytetrafluoroethylene (PTFE) and polydimethylsiloxane (PDMS), which are inherently hydrophobic due to their low surface energy and lack of polar groups. In some cases excessive hydrophobicity can also be detrimental to composite membrane performance, as it can prevent the passage of other substances, such as gases, through the membrane. Therefore, the degree of hydrophobicity may be carefully controlled and optimised for the composite membrane's intended use within the embodiment of the invention to prevent formation and/or accumulation of biofilms without hindering the mass transfer of desired gas/gases. The contact angle of a hydrophobic composite membrane can vary depending on its surface properties and the measurement method used, along with other factors.

In certain embodiments of this invention, any layer of a composite membrane can be hydrophilic. For example any barrier layers of a composite membrane can be hydrophilic, the reinforcement layer of a composite membrane can be hydrophilic, any intermediate layer of a composite membrane can be hydrophilic.

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In certain embodiments, the contact angle of the surface of the first wall in contact with the liquid media and/or or the surface of the first wall in contact with the atmosphere within the chamber may be suitably no more than about 170 degrees, about 160 degrees, about 150 degrees, about 140 degrees, about 130 degrees, about 120 degrees, about 110 degrees, about 100 degrees, about 90 degrees, about 80
10 degrees, about 70 degrees, and typically no more than about 60 degrees, about 50 degrees, about 40 degrees, about 30 degrees. The contact angle of the surface of the first wall in contact with the liquid media and/or or the surface of the first wall in contact with the atmosphere within the chamber may be suitably at least about 0 degrees, about 10 degrees, about 20 degrees, about 30 degrees, about 40
15 degrees, about 50 degrees, at least about 60 degrees, at least about 70 degrees, at least about 80 degrees, at least about 90 degrees, at least about 100 degrees, at least about 110 degrees, at least about 120 degrees, at least about 130 degrees, at least about 140 degrees, and typically at least about 150 degrees.

In certain embodiments, the contact angle of any surface of a composite membrane and/or any surface
20 of its comprised individual layers may be suitably no more than about 170 degrees, about 160 degrees, about 150 degrees, about 140 degrees, about 130 degrees, about 120 degrees, about 110 degrees, about 100 degrees, about 90 degrees, about 80 degrees, about 70 degrees, and typically no more than about 60 degrees, about 50 degrees, about 40 degrees, about 30 degrees. The contact angle of any
25 surface of a composite membrane and/or any surface of its comprised individual layers may be suitably at least about 0 degrees, about 10 degrees, about 20 degrees, about 30 degrees, about 40 degrees, about 50 degrees, at least about 60 degrees, at least about 70 degrees, at least about 80 degrees, at least about 90 degrees, at least about 100 degrees, at least about 110 degrees, at least about 120
degrees, at least about 130 degrees, at least about 140 degrees, and typically at least about 150 degrees.

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In certain embodiments of this invention, any layer of a composite membrane can be hydrophilic. For example any barrier layers of a composite membrane can be hydrophilic, the reinforcement layer of a composite membrane can be hydrophilic, any intermediate layer of a composite membrane can be hydrophilic. In another embodiment, the composite membrane comprises a barrier layer or any layer,
35 whose surface or the material itself may feature hydrophilic properties. In such embodiments, the composite membrane may be designed to enhance the interaction with liquid molecules (such as a liquid media), which may influence the prevention of formation and/or accumulation of unwanted biofilms without hindering the mass transfer efficiency of the composite membrane. The degree of hydrophilicity can also be precisely adjusted to improve permeability and/or selectivity and/or durability
40 of the composite membrane. facilitating efficient separation and purification processes.

At least a part of the composite membrane is permeable to transmission of gases across the membrane. As used in this context, the phrase "at least a part" means an area of the composite membrane that is of a sufficient size to allow a gas/gases to pass through the outer surface (i.e., chamber atmosphere-facing side of the liquid-containable compartment). The gas may typically comprise of but is not limited to oxygen, carbon dioxide and water vapour, and may also comprise nitrogen, nitrogen oxides, sulphur oxides, hydrogen, hydrogen sulphides and/or methane. The permeability or permeability coefficient, as used herein, refers to the permeability of the least permeable individual layer of a composite membrane. Within an embodiment of the invention, for a composite membrane and/or for any individual layers of the composite membrane, the interpretation of the permeability is defined by the Barrer unit value, suitably ascribed to the least gas permeable layer.

The Barrer can be expressed in SI units as:

$$1 \text{ barrer} = 3.35 \times 10^{-16} \frac{\text{mol} \cdot \text{m}}{\text{m}^2 \cdot \text{s} \cdot \text{Pa}}$$

Further, the Barrer can also be expressed in CGS unit as:

$$1 \text{ barrer} = M \times 3.35 \times 10^{-13} \frac{\text{g} \cdot \text{cm}}{\text{cm}^2 \cdot \text{s} \cdot \text{bar}}$$

Where M is the molecular weight of the penetrant gas in $\text{g} \cdot \text{mol}^{-1}$.

Reference herein to the permeability or permeability coefficient of the composite membrane may also be taken to refer to the permeability of the composite membrane's least gas permeable layer within the embodiments of the invention. The permeability is directly related to the concentration gradient of the permeant (such as gas), a material's intrinsic permeability, and the diffusivity of the permeated gas in the membrane material, including through the individual layers of the composite material and the composite membrane material as a whole.

The permeability coefficient of oxygen through the composite membrane may be suitably no more than about 2500 Barrer, about 2000 Barrer, about 1500 Barrer, about 1250 Barrer, about 1000 Barrer, about 900 Barrer, about 800 Barrer, about 700 Barrer, about 600 Barrer, about 400 Barrer, about 300 Barrer, about 200 Barrer, and typically no more than about 100 Barrer. The permeability coefficient of oxygen through the composite membrane may be suitably at least 50 Barrer, at least 100 Barrer, at least 200 Barrer, at least 300 Barrer, at least 400 Barrer, at least 500 Barrer, at least 600 Barrer, at least 700 Barrer, at least 800 Barrer, at least 900 Barrer, at least 1000 Barrer, at least 1250 Barrer, at least 1500 Barrer, and typically at least 2000 Barrer.

The permeability coefficient of oxygen in SI units through the composite membrane may be suitably no more than about $8375 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $6700 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $5025 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $4187.5 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $3350 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $3015 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $2680 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $2345 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$.

$2 \cdot s^{-1} \cdot Pa^{-1}$, about $2010 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $1340 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $1005 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $670 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, and typically no more than about $335 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$. The permeability coefficient of oxygen through the composite membrane may be suitably at least $167.5 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $335 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $670 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $1005 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $1340 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $1675 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $2010 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $2345 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $2680 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $3015 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $3350 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $4187.5 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, at least $5025 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, and typically at least $6700 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$.

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The permeability rate can be measured using the unit $m^3 \cdot m^{-2} \cdot s^{-1}$. Depending on the specific conditions (such as, but not limited to, barrier layer composition and formulation, temperature, pressure differential, relative humidity, concentration gradient, and the thickness of the barrier layer), the permeability rate of oxygen through the composite membrane may be suitably no more than about $10^{-2} m^3 \cdot m^{-2} \cdot s^{-1}$, about $10^{-3} m^3 \cdot m^{-2} \cdot s^{-1}$, $10^{-4} m^3 \cdot m^{-2} \cdot s^{-1}$, $10^{-5} m^3 \cdot m^{-2} \cdot s^{-1}$, $10^{-6} m^3 \cdot m^{-2} \cdot s^{-1}$, $10^{-7} m^3 \cdot m^{-2} \cdot s^{-1}$, $10^{-8} m^3 \cdot m^{-2} \cdot s^{-1}$, about $10^{-9} m^3 \cdot m^{-2} \cdot s^{-1}$, about $10^{-10} m^3 \cdot m^{-2} \cdot s^{-1}$, about $10^{-11} m^3 \cdot m^{-2} \cdot s^{-1}$, about $10^{-12} m^3 \cdot m^{-2} \cdot s^{-1}$, about $10^{-13} m^3 \cdot m^{-2} \cdot s^{-1}$, and typically no more than about $10^{-14} m^3 \cdot m^{-2} \cdot s^{-1}$. Depending on the specific conditions, the permeability rate of oxygen through the composite membrane may be at least $10^{-15} m^3 \cdot m^{-2} \cdot s^{-1}$, suitably at least $10^{-14} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-13} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-12} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-11} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-10} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-9} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-8} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-7} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-6} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-5} m^3 \cdot m^{-2} \cdot s^{-1}$, at least $10^{-4} m^3 \cdot m^{-2} \cdot s^{-1}$, and typically at least $10^{-3} m^3 \cdot m^{-2} \cdot s^{-1}$.

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The permeability coefficient of carbon dioxide through the composite membrane may be suitably no more than about 10000 Barrer, about 7500, about 5000 Barrer, about 4500 Barrer, about 4000 Barrer, about 3500 Barrer, about 3000 Barrer, about 2500 Barrer, about 2000 Barrer, about 1500 Barrer, about 1000 Barrer, about 800 Barrer, about 600 Barrer, about 400 Barrer, and typically no more than about 200 Barrer. The permeability coefficient of carbon dioxide through the composite membrane may be suitably at least 100 Barrer, at least 200 Barrer, at least 400 Barrer, at least 600 Barrer, at least 800 Barrer, at least 1000 Barrer, at least 1500 Barrer, at least 2000 Barrer, at least 2500 Barrer, at least 3000 Barrer, at least 3500 Barrer, at least 4000 Barrer, at least 4500 Barrer, at least 5000 Barrer, and typically at least 7500 Barrer.

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The permeability coefficient of carbon dioxide in SI units through the composite membrane may be suitably no more than about $33500 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $25125 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $16750 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $15075 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $13400 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $11725 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $10050 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $8375 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $6700 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $5025 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $3350 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $2680 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $2010 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$, about $1340 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$ and typically no more than about $670 \times 10^{-16} \text{ mol} \cdot m \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$. The permeability coefficient of carbon dioxide in SI units through the composite

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at least $10^{-9} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-2} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

Additionally, water vapour permeability can also be measured in $\text{g} \cdot \text{m}^{-2} \cdot 24\text{h}^{-1}$. In these terms, suitable water vapour permeability through the composite membrane may be around $3200 \text{ g} \cdot \text{m}^{-2} \cdot 24\text{h}^{-1}$ at a thickness of $20\mu\text{m}$, around $1200 \text{ g} \cdot \text{m}^{-2} \cdot 24\text{h}^{-1}$ at a thickness of $50\mu\text{m}$ and around $800 \text{ g} \cdot \text{m}^{-2} \cdot 24\text{h}^{-1}$ at a thickness of $100\mu\text{m}$. In composite membranes within the embodiments, the barrier layer may have a much lower thickness, even as low as around $1\mu\text{m}$. In such composite membranes, the water vapour permeability in $\text{g} \cdot \text{m}^{-2} \cdot 24\text{h}^{-1}$ may be much higher than that described above.

10

When the composite membrane is permeable to sulphur dioxide (SO_2), the permeability coefficient of sulphur dioxide may be suitably no more than about 16000 Barrer, about 14000 Barrer, about 12000 Barrer, about 10000 Barrer, about 9000 Barrer, about 8000 Barrer, about 7000 Barrer, about 6000 Barrer, about 5000 Barrer, about 2500 Barrer, and typically no more than about 1000 Barrer. The permeability coefficient of sulphur dioxide may be suitably at least 500 Barrer, at least 1000 Barrer, at least 2500 Barrer, at least 5000 Barrer, at least 6000 Barrer, at least 7000 Barrer, at least 8000 Barrer, at least 9000 Barrer, at least 10000 Barrer, at least 12000, and typically at least 14000 Barrer.

When the composite membrane is permeable to sulphur dioxide, the permeability coefficient of sulphur dioxide in SI units may be suitably no more than about $53600 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $46900 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $40200 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $33500 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $30150 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $26800 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $23450 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $20100 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $16750 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $8375 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, and typically no more than about $3350 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$. The permeability coefficient of sulphur dioxide in SI units may be suitably at least $1675 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $3350 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $8375 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $16750 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $20100 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $23450 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $26800 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $30150 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $33500 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $40200 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, and typically at least $46900 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$.

When the composite membrane is permeable to sulphur dioxide and depending on the specific conditions, the permeability rate of sulphur dioxide may be suitably no more than about $10^{-1} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-2} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, typically no more than about $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The permeability rate of sulphur dioxide may be suitably at least $10^{-9} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-2} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

35

When the composite membrane is permeable to hydrogen sulphide (H_2S), the permeability coefficient of hydrogen sulphide may be suitably no more than about 12000 Barrer, about 10000 Barrer, about 9000 Barrer, about 8000 Barrer, about 7000 Barrer, about 6000 Barrer, about 5000 Barrer, about 2500 Barrer, about 1000 Barrer, and typically no more than about 500 Barrer. The permeability coefficient of hydrogen sulphide may be suitably at least 100 Barrer, at least 500 Barrer, at least 1000, at least 2500 at least 5000 Barrer, at least 6000 Barrer, at least 7000 Barrer, at least 8000 Barrer, at least 9000 Barrer, and typically at least 10000 Barrer.

When the composite membrane is permeable to hydrogen sulphide, the permeability coefficient of hydrogen sulphide in SI units through the composite membrane may be not more than about $40200 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, suitably no more than about $33500 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $30150 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $26800 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $23450 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $20100 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $16750 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $8375 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $3350 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ and typically no more than about $1675 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$. The permeability coefficient of hydrogen sulphide in SI units through the membrane may be at least $335 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, suitably at least $1675 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $3350 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $8375 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $16750 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $20100 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $23450 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $26800 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $30150 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, and typically at least $33500 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$.

When the composite membrane is permeable to hydrogen sulphide and depending of specific conditions, the permeability rate of hydrogen sulphide may be suitably no more than about $10^{-2} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, about $10^{-3} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, about $10^{-4} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, about $10^{-5} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, about $10^{-6} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, about $10^{-7} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and typically no more than about $10^{-8} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The permeability rate of sulphur dioxide may be suitably at least $10^{-9} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, at least $10^{-8} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, at least $10^{-7} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, at least $10^{-6} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, at least $10^{-5} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, at least $10^{-4} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and typically at least $10^{-3} \text{ m}^3\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

When the composite membrane is permeable to molecular hydrogen (H_2), the permeability coefficient of molecular hydrogen may be suitably no more than about 1600 Barrer, about 1400 Barrer, about 1200 Barrer, about 1000 Barrer, about 900 Barrer, about 800 Barrer, about 700 Barrer, about 600 Barrer, about 500 Barrer, about 250 Barrer, about 150 Barrer, and typically no more than about 100 Barrer. The permeability coefficient of molecular hydrogen may be suitably at least 50 Barrer, at least 100, at least 150, at least 250 Barrer, at least 500 Barrer, at least 600 Barrer, at least 700 Barrer, at least 800 Barrer, at least 900 Barrer, at least 1000 Barrer, at least 1200 Barrer, and typically at least 1400 Barrer.

When the composite membrane is permeable to molecular hydrogen, the permeability coefficient of molecular hydrogen in SI units may be suitably no more than about $5360 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $4690 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $4020 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $3350 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $3015 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $2680 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $2345 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, and typically at least $1675 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$.

1, at least $268 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $301.5 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $335 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $502.5 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $837.5 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $1675 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $2010 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $2345 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $2680 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $3015 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $3350 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $4020 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, and typically at least $4690 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$.

When the composite membrane is permeable to molecular nitrogen and depending on specific conditions, the permeability rate of molecular nitrogen may be suitably no more than about $10^{-2} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically no more than about $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The permeability rate of molecular nitrogen may be suitably at least $10^{-9} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

15 When the composite membrane is permeable to methane (CH_4), the permeability coefficient of methane may be suitably no more than about 3500 Barrer, about 3000 Barrer, about 2500 Barrer, about 2000 Barrer, about 1800 Barrer, about 1500 Barrer, about 1200 Barrer, about 1000 Barrer, about 900 Barrer, about 800 Barrer, about 600 Barrer, about 400 Barrer, about 200 Barrer, and typically no more than about 100 Barrer. The permeability coefficient of methane may be suitably at least 50 Barrer, at least 100 Barrer, at least 200 Barrer, at least 400 Barrer, at least 600 Barrer, at least 800 Barrer, at least 900 Barrer, at least 1000 Barrer, at least 1200, at least 1500 Barrer, at least 1800 Barrer, at least 2000 Barrer, at least 2500 Barrer, and typically at least 3000 Barrer.

When the composite membrane is permeable to methane, the permeability coefficient of methane in SI units may be suitably no more than about $11725 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $10050 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $8375 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $6700 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $6030 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $5025 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $4020 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $3350 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $3015 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $2010 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $1340 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, about $670 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, and typically no more than about $335 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$. The permeability coefficient of methane in SI units may be suitably at least $167.5 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $335 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, $670 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $1340 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $2010 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $3015 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $3350 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $4020 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $5025 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $6030 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $6700 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, at least $8375 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$, and typically at least $10050 \times 10^{-16} \text{ mol}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$.

When the composite membrane is permeable to methane and depending on specific conditions, the permeability rate of methane may be suitably no more than about $10^{-3} \text{ m}^3 \cdot \text{m}^2 \cdot \text{s}^{-1}$, about $10^{-4} \text{ m}^3 \cdot \text{m}^2 \cdot \text{s}^{-1}$,
40 about $10^{-5} \text{ m}^3 \cdot \text{m}^2 \cdot \text{s}^{-1}$, about $10^{-6} \text{ m}^3 \cdot \text{m}^2 \cdot \text{s}^{-1}$, and typically no more than about $10^{-7} \text{ m}^3 \cdot \text{m}^2 \cdot \text{s}^{-1}$. The

permeability rate of molecular methane may be suitably at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

In certain embodiments, the composite membrane may be comprised of all porous individual layers, which may be attributed to have any pore sizes, and/or any porosities, and/or any kind of pore structure distribution. In such embodiments, the permeability coefficient of any gas

through a composite membrane where all of its individual layers are porous may be suitably no more than about 100,000,000 Barrer, 10,000,000 Barrer, about 9,000,000 Barrer, about 8,000,000 Barrer, about 7,000,000 Barrer, about 6,000,000 Barrer, about 5,000,000 Barrer, about 4,000,000 Barrer, about 3,000,000 Barrer, and 2,000,000 Barrer, about 1,000,000 Barrer, about 500,000 Barrer, about 100,000 Barrer, about 10,000 Barrer, about 5,000 Barrer, about 1,000 Barrer, and typically no more than about 100 Barrer. The permeability coefficient of any gas through a composite membrane where all of its individual layers are porous may be suitably at least 10 Barrer, at least 100 Barrer, at least 1000 Barrer, at least 10,000 Barrer, at least 100,000 Barrer, at least 500,000 Barrer, at least 1,000,000 Barrer, at least 2,000,000 Barrer, at least 3,000,000 Barrer, at least 4,000,000 Barrer, at least 5,000,000 Barrer, at least 6,000,000 Barrer, at least 7,000,000 Barrer, at least 8,000,000 Barrer, at least and typically at least 10,000,000 Barrer.

In suitable embodiments, the permeability coefficient of any gas through a composite membrane where all of its individual layers are porous in SI units may be suitably no more than about $335,000,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $33,500,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $30,150,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $26,800,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $23,450,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $20,100,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $16,750,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $13,400,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $6,700,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $3,350,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $1,675,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $335,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $33,500 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, about $16,750 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, and no more than about $3,350 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$. The permeability coefficient of any gas through a composite membrane where all of its individual layers are porous in SI units may be suitably be at least $33.5 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $335 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $3,350 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $16,750 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $33,500 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $335,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $1,675,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $3,350,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $6,700,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $13,400,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $16,750,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $20,100,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $23,450,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $26,800,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, at least $30,150,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$, and typically at least about $33,500,000 \times 10^{-16} \text{ mol} \cdot \text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$.

In other embodiments, depending on specific conditions, the permeability rate for any gas through a composite membrane where all of its individual layers are porous may be suitably no more than $10^3 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^2 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^1 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-1} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, $10^{-2} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

$2 \cdot s^{-1}$, about $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, about $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically no more than about $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The permeability rate for any gas through a composite membrane where all of its individual layers are porous may be suitably be at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, $10^{-2} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-1} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^1 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically $10^2 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

In some embodiments, it is important that the gas permeable material of the barrier layer is not permeable to passage of liquids to prevent liquid media within the bioreactor from leaking to the outside. Loss of liquid media resulting in flooding of the chamber would result in depletion of the volume of the liquid in the liquid-containable compartment as well as hindering effective gas transfer from the chamber to the liquid-containable compartment. In some embodiments, any gas permeable material and/or layers that make a composite membrane can be porous (including microporous or nanoporous structures) or non-porous. Gas permeable materials are referred to as porous if the gas particles can migrate through direct movement through the porous structure. In some embodiments, when the gas permeable material is porous, it is important that it is substantially impermeable to liquids for the reasons given above. It is a particular advantage of the present invention that a wider range of gas permeable membrane materials can be utilised than hitherto thought possible because there is no corresponding requirement that the composite membrane is optically transmissible (i.e. translucent or transparent).

Any layer of a gas permeable composite membrane may be a polymer, such as a chemically-optimised gas permeable polymer. Chemically-optimised polymers may be advantageous over corresponding unmodified polymers because they may be cheaper, more resistant to tear, stronger, more hydrophobic, ultrahydrophobic/superhydrophobic, antistatic, easier to fabricate with, less brittle, more elastic, more permeable to gases and selectively permeable to specific gases. Chemical modifications on polymers may be performed in any way a skilled person will know such as by modifying the chemical composition of the monomer, the back bone chain, side chains, end groups, and/or the use of different curing agents, crosslinkers, fillers, processes of vulcanisation, manufacture, fabrication, and/or the use of coatings and other methods.

Polymer chemical modifications can improve the gas separation and/or permeability and enhance the overall performance of any individual layers within a composite membrane or simply the composite membrane as a whole. Some of the chemical modifications that can be imparted on polymers for their use in gas transfer composite membranes may include, but not limited to:

1. Cross-linking: The term "cross-linking" of polymers refers to the formation of chemical bonds between polymer chains, creating a three-dimensional network of interconnected polymer molecules. These bonds can be covalent or ionic and can be formed through various methods such as chemical reactions, irradiation, or physical means such as heat or pressure. Crosslinking may improve the mechanical strength and thermal stability of the polymer matrix.

In specific embodiments of the present invention, cross-linking may be used to reduce the polymer chain mobility of the barrier layer or the least permeable layer and increase desired specific gas selectivity.

2. Functionalization: The term "functionalization" of polymers refers to a process of introducing new functional groups or chemical moieties onto the polymer backbone. This modification can alter the physical, chemical, and mechanical properties of the polymer, including its solubility, reactivity, thermal stability, and surface properties. Functionalization can be achieved through various methods, such as grafting, copolymerization, crosslinking, and chemical modification. It can be used to improve the compatibility of the polymer with other materials, enhance its adhesion to surfaces, increase its biocompatibility, or introduce new functionalities for specific applications. In specific embodiments of the present invention, adding functional groups to the polymer structure of the barrier layer or the least permeating layer may alter its surface properties and enhance its selectivity and thus improve permeability of the composite membrane for desired specific gases (such as carbon dioxide and/or nitrogen and/or oxygen).
3. Blending: The term "blending" with respect to polymers refers to a process of combining two or more different polymers to create a new material with properties that combine from those of the individual polymers. In this process, the polymers can be physically mixed together to form a homogeneous blend. In specific embodiments of the present invention, blending the polymer material of any of the composite membrane's layers with another polymer or a suitable compatible substance may enhance its overall functionality for the intended use. For example, blending the polymer of the barrier layer with substances (such as, but not limited to, zeolite and/or zinc based compounds) may improve its selectivity, permeability and/or its resistance to biofilms. Additionally, by way of an example, blending the polymer of the reinforcement layer with substances (such as, but not limited to, another polymer, and/or reinforcing agent, and/or compatibility agent) may improve the composite membrane's overall mechanical strength and/or joining compatibility with the second wall and/or thereof.
4. Incorporating nanoparticles: In specific embodiments of the present invention, certain nanoparticles may be incorporated into a polymer matrix of any of the composite membrane's layers that may alter its structure and/or composition and/or surface morphology and enhance its overall functionality for the intended use. By way of non-limiting example, nanoparticles (such as, but not limited to, silica-based, and/or graphene oxide-based, and/or titanium dioxide-based nanoparticles) may be carefully incorporated within the polymer matrix of the barrier layer to ensure sustainable performance and/or longevity and/or impart surface geometries and/or thereof.
5. Copolymerization: The term "copolymerization" refers to a process of combining two or more different monomers (building blocks of polymers) to form a single polymer chain. In this process, the monomers may react with each other in different ways, such as alternating, block, or random copolymerization, resulting in a copolymer with unique properties and characteristics. The copolymerization may also be achieved through different methods such as radical polymerization, anionic polymerization, cationic polymerization, or coordination polymerization,

depending on the nature of monomers and reaction conditions. In specific embodiments of the present invention, copolymerization of any of the composite membrane's layers may introduce different monomers into the respective layer's polymer structure and alter its properties which may improve its overall functionality for the intended use. By way of non-limiting example, the polymer matrix of a non-porous intermediate layer within a composite membrane may be copolymerised with a fluoropolymer (such as PTFE) which can significantly enhance the mass transfer efficiency across the composite membrane and/or thereof.

For a composite membrane comprising a porous barrier layer, it may be comprised of a 'highly hydrophobic' or 'superhydrophobic' coating or treatment or surface. This highly hydrophobic surface can restrict the passage of liquids, such as water or any liquid or other liquid contaminants, while allowing the transmission of gases, such as oxygen and carbon dioxide. The suitability of porous barrier layer materials as a liquid barrier with gas permeating properties depends on various factors, including, but not limited to, the specific application requirements, desired gas permeability, liquid barrier performance, and/or compatibility with the environment. The term 'highly hydrophobic' refers to surfaces that are treated to take the concept of hydrophobicity to an extreme level, exhibiting extremely high water-repellent or liquid-repellent properties. These treatments can result in surfaces that have self-cleaning capabilities and can repel water droplets effectively. Superhydrophobic coatings, treatments or surfaces can provide remarkable water-repellent and/or liquid-repellent properties to porous surfaces, making them highly desirable for applications utilising embodiments of the invention that comprise self-cleaning and/or anti-fouling surfaces. Some of the commonly used methods for superhydrophobic treatments of porous polymer surfaces include, but are not limited to:

1. Surface Roughening: One such approach to achieving superhydrophobicity is to create a rough surface texture on the porous material. This may involve techniques such as, but not limited to, etching, sandblasting, or electrochemical deposition. The rough surface traps air pockets, reducing the contact area with water/liquid and enhancing the water and/or liquid repellency.
2. Coating with Superhydrophobic Materials: Superhydrophobic coatings may be applied to porous polymer surfaces to impart high liquid-repellent properties. These coatings typically consist of, but are not limited to low-surface-energy materials, such as fluoropolymers or nanoparticles, which create a rough surface texture. The combination of surface roughness and low surface energy leads to superhydrophobic behaviour.
3. Chemical Modification: Surface chemical modifications may be employed to make porous materials superhydrophobic. This may involve functionalizing the surface with specific chemical compounds or altering the surface chemistry through reactions. For example, the introduction of perfluorinated groups to the surface can significantly enhance its liquid repellency within certain embodiments of the invention.
4. Hierarchical Structures: Creating hierarchical structures by combining microscale and nanoscale features on the porous surface can contribute to superhydrophobicity. This may be achieved through techniques such as, but not limited to, photolithography, nanoimprinting, or

self-assembly methods. The hierarchical structure enhances the surface roughness and air-trapping capabilities, leading to excellent liquid repellency.

- 5 5. Self-Assembly: Self-assembly techniques may be utilised to create superhydrophobic surfaces on porous materials and may involve the spontaneous arrangement of molecules or nanoparticles into ordered structures on the surface. Self-assembled monolayers or nanoparticle coatings can create superhydrophobicity by altering the surface energy and structure.

10 In certain embodiments, a composite membrane comprising a porous barrier layer may be comprised of a highly hydrophobic surface. Furthermore, increasing the hydrophobicity of the porous barrier layer can elevate the liquid entry pressure of the composite membrane. These may include but are not limited to materials such as: Polytetrafluoroethylene (PTFE), Expanded Polytetrafluoroethylene (ePTFE), Polyurethane (PU), Polyethylene (PE), Polypropylene (PP), Polyethylene (PE)-Polypropylene (PP) Blends, Polyvinylidene Fluoride (PVDF), Polyvinyl Alcohol (PVA), Polyethylene Terephthalate (PET),
 15 Polyamide (PA), Polyimides, Cellulose Acetate, Polycarbonate (PC), Polystyrene (PS), Polyethersulfone (PES), Polysulfone (PSU), Polyacrylonitrile (PAN), Polyethylene Oxide (PEO), Polyether Ether Ketone (PEEK), Silicone Rubber, Fluorinated Ethylene Propylene (FEP), Polydimethylsiloxane (PDMS), Nylon 6,6 (PA6,6), Nylon 6 (PA6), Polybutylene Terephthalate (PBT), Ethylene Vinyl Acetate (EVA), Polyvinyl Chloride (PVC), Chitosan-Based Polymers, Cellulose-Based
 20 Polymers, Polyhydroxyalkanoates (PHA), Polyvinylpyrrolidone (PVP), Polybenzimidazole (PBI), Polyvinyl Chloride (PVC), Polyoxyethylene (POE), Polysulfide (PS), Polyphenylene Sulfide (PPS), Polyethylene Naphthalate (PEN), Polyvinyl Fluoride (PVF), Polyvinylpyrrolidone (PVP), Polyvinyl Butyral (PVB), Polyacrylamide (PAM), Polypropylene Carbonate (PPC), Polyphthalamide (PPA), Polybenzoxazole (PBO), Polycaprolactone (PCL), Polyoxyethylene (POE), Polyvinyl Acetate (PVA),
 25 Polyvinylidene Chloride (PVDC), Polyvinyl Formal (PVF), Polyvinyl Methyl Ether (PVME), Polyvinyl Methyl Ketone (PVMK), Polystyrene Sulfonate (PSS), Polytriazole (PTA), Polyoxymethylene (POM), Polybenzimidazole (PBI), Graphene-based additives/materials, Metal-Organic Frameworks (MOFs), Carbon nanotubes.

30 In other embodiments, a composite membrane comprising a porous barrier layer may be comprised of the porous silicon-based materials and/or a particular nanoporous silicon and/or porous silicon nanostructures such as, but not limited to: nanoporous Polydimethylsiloxane (PDMS), nanoporous Polyphenylmethylsiloxane (PPMS), nanoporous Polymethylphenylsiloxane (PMPS), nanoporous Polydiphenylsiloxane (PDPS), nanoporous Polymethylhydrosiloxane (PMHS), nanoporous
 35 Polytrifluoropropylmethylsiloxane (PTFPMS), nanoporous Polydiphenylsiloxane (PDPS), nanoporous Polymethylvinylsiloxane (PMVS), nanoporous Polyoctylmethylsiloxane (POMS), nanoporous Poly(dimethylsiloxane-co-ethylene oxide) (PDMS-PEO), nanoporous Polysiloxane-Polyimide block copolymers, nanoporous Polysiloxane-Polycarbonate block copolymers, and/or nanoporous Polysiloxane-Polyether block copolymers can also be contemplated for use.

In certain embodiments, the gas permeable polymer is characterised by a rigid, contorted or twisted macromolecular backbone that gives rise to a plurality of microvoids within the material structure. In specific embodiments, the porous barrier layer may comprise a polymer of intrinsic microporosity (PIM), featuring a continuous network of interconnected voids with widths in the range of one to tens of
 5 nanometers. These voids are typically formed by contorted fused ring sequences interrupted by spirocentres.

In specific embodiment, increasing the hydrophobicity of any porous layer of a composite membrane can increase the liquid entry pressure of the composite membrane and/or the individual layer of the
 10 composite membrane. The liquid entry pressure denotes the pressure needed to compel liquid into the pores and through the material.

In certain embodiments, a composite membrane comprising a non-porous or dense barrier layer may comprise of any suitable gas permeable material including, but not limited to: Poly(ethylene oxide),
 15 Poly(butylene terephthalate), or Poly(ethylene oxide), Poly(butylene terephthalate) block copolymers (PEO-PBT), for example 1000PEO40PBT60; Silicones, Polysiloxanes, for example Polydimethylsiloxanes (PDMS); Fluorosilicone, Organo-silicones, SiOX-modified polymers, Vinyl methyl siloxane (VMQ), Phenyl vinyl methyl siloxane (PVMQ), Silicon-oxide polymers, Sulfonated Polyetheretherketone (SPEEK), Amino-organosilanes such as, but not limited to, gamma-
 20 Aminopropyltriethoxysilane (γ -APS), Cellulose (including plant-based cellulose and bacterial cellulose), Polyimides, Polyamides, Cellulose acetate (celluloid), Nitrocellulose, and Cellulose esters. Additionally, Polycarbonate (PC), Polyphenylene oxides (PPO), Polymethyl pentenes (PMP), Polytetrafluoroethylene (PTFE), Ethylene tetrafluoroethylene (ETFE), Polyethylene terephthalate (PET), Polyvinylidene fluoride (PVDF), Polyurethane (PU), Polyvinyl chloride (PVC), Polyetherimide
 25 (PEI), Polyethersulfone (PES), Polyacrylonitrile (PAN), Polyvinyl alcohol (PVA), Ethylene vinyl alcohol (EVOH), Thermoplastic elastomers (TPE), Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), Polycaprolactone (PCL), Thermoplastic starch blends, Polyethylene (PE), Polypropylene (PP), Polybenzimidazole (PBI), Polyetheretherketone (PEEK), Polysulfone (PSU), Polymethyl methacrylate (PMMA), Polyoxymethylene (POM), Polyisobutylene (PIB), Polyisoprene (PI), Polyacrylate (PA),
 30 Polyvinyl acetate (PVAc), Polybutadiene (PB), Polychloroprene (CR), Polyvinyl butyral (PVB), Fluoroelastomers (FKM), Hydrogenated nitrile butadiene rubber (HNBR), Ethylene propylene diene monomer (EPDM), Acrylonitrile butadiene styrene (ABS), Polyphenylene oxide (PPO), Polyphenylene sulfide (PPS), Liquid crystal polymers (LCP), Chlorinated polyethylene (CPE), Poly(1-butene) (PB-1), Polytetramethylene ether glycol (PTMEG) may also be contemplated for use.

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In certain embodiments, the non-porous barrier layer within a composite membrane may be comprised of Polysiloxanes-based materials. Polysiloxanes can further be optimised by means of chemical modifications and/or machine modifications to enhance the composite membrane's performance. Such modifications can be used to improve gas selectivity and/or gas permeation rates of desired gases such
 40 as carbon dioxide and/or oxygen among others. It has been found that polysiloxanes are good

candidates for gas permeable membranes thanks to the Si-O bonds in the polymer structure which facilitates higher bond rotation, increasing chain mobility, and thereby increasing levels of permeability. Polysiloxane elastomers (such as silicone rubber) are also flexible, tolerant to UV radiation and resilient materials.

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Further, in suitable embodiments, a composite membrane comprising a non-porous barrier layer may comprise polysiloxanes, optionally optimised polysiloxanes. These materials may include, but are not limited to polysiloxanes such as Polytrifluoropropylmethylsiloxane (PTFPMS), Polydiphenylsiloxane (PDPS), Polymethylvinylsiloxane (PMVS), Polydimethylsiloxane (PDMS), Polyphenylmethylsiloxane (PPMS), Polymethylphenylsiloxane (PMPS), Polydiphenylsiloxane (PDPS), Polymethylhydrosiloxane (PMHS), Polyoctylmethylsiloxane (POMS), Poly(dimethylsiloxane-co-ethylene oxide) (PDMS-PEO), Polysiloxane-Polyimide block copolymers, Polysiloxane-Polycarbonate block copolymers, Polysiloxane-Polyether block copolymers, Polyurethane-Siloxane copolymers, Polysiloxane-Polystyrene copolymers, Polysiloxane-Acrylic copolymers, Polysiloxane-Epoxy copolymers, Polysiloxane-Polyamide copolymers, Polysiloxane-Polyurea copolymers, Polysiloxane-Polyester copolymers, Polysiloxane-Polyaniline copolymers, Polysiloxane-Polypyrrole copolymers, Fluorosilicone rubber (FVMQ), Silicone-Polypropylene glycol block copolymers, Silicone-Polyacrylate block copolymers, Amino-functionalized Polysiloxanes, Carboxy-functionalized Polysiloxanes, Hydroxy-functionalized Polysiloxanes, Alkoxy-functionalized Polysiloxanes, Vinyl-functionalized Polysiloxanes, Phenyl-functionalized Polysiloxanes, Silanol-terminated Polysiloxanes, Epoxy-functionalized Polysiloxanes, Methacrylate-functionalized Polysiloxanes, Ethyl Acrylate-functionalized Polysiloxanes, Poly (dimethylsiloxane-co-phenylsiloxane), Poly (dimethylsiloxane-co-methylphenylsiloxane), Poly (dimethylsiloxane-co-methylhydrosiloxane), Poly (dimethylsiloxane-co-trifluoropropylmethylsiloxane), Poly (dimethylsiloxane-co-diphenylsiloxane), Polysiloxane-Elastomer blends, Polysiloxane-Thermoplastic blends, Silica-reinforced Polysiloxanes, and/or other polysiloxane elastomers, Graphene-based membranes, Metal-Organic Frameworks (MOFs), Carbon nanotube and/or thereof.

Furthermore, the properties of the polysiloxane elastomers used in certain embodiments of this invention can be optimised through chemical, mechanical and process-driven interventions related to, but not limited to, the molar mass (M_m) of polymer chains, the dispersity in the polymer (dispersity in the ratio of the weight average molar mass to number average molar mass), the temperature and duration of the heat treatment during curing, the ratio of the cross-linking agent to polysiloxane elastomers, the cross-linking agent chemical composition, different end groups (such as, but not limited to, methyl-, hydroxy- and vinyl- terminated elastomers) which can influence the way in which end-linked polysiloxane structures form during cross-linking, and/or with coatings.

In an embodiment, the composite membrane or the any layer of the composite membrane comprises polysiloxanes, suitably optimised polysiloxanes that may be optically transparent or translucent or opaque, and/or high tolerance to UV radiation, without hindering the permeability of desired gases across the composite membrane.

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In specific embodiments, a non-porous barrier layer within a composite membrane may be more effective at remaining impermeable to liquids compared to a porous layer. In such embodiments, after prolonged use, where the liquid is under pressure, the continuous structure and/or surface of the non-porous layer provides a robust barrier that prevents liquid infiltration more effectively than a porous layer. Additionally, In other embodiments, in environments prone to biofilm formation, a non-porous barrier layer may offer significant advantages with respect to biofilms. Further, biofilms can develop within the pores of a porous membrane, potentially compromising its integrity and increasing the risk of leakage. The non-porous barrier layer, by contrast, does not provide the same foothold for biofilms, maintaining its impermeability and ensuring consistent gas permeable performance.

In certain embodiments, a composite membrane may comprise an intermediate layer which may comprise a non-porous material and/or a porous material to facilitate the permeation of desired gases. In suitable embodiments, a composite membrane comprising a porous intermediate layer may comprise polymers such as, but not limited to; any Polyolefins such as Polyethylene (PE), Polypropylene (PP), Polybutene-1 (PB-1), Polyisobutylene (PIB); any Fluoropolymers such as Polytetrafluoroethylene (PTFE), Ethylene tetrafluoroethylene (ETFE), Polyvinylidene fluoride (PVDF), Fluoroelastomers (FKM), Fluorinated ethylene propylene (FEP); any Polyesters such as Polyethylene terephthalate (PET), Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), Polycaprolactone (PCL); any Polyamides such as nylon 6,6 (PA6,6), nylon 6 (PA6), nylon 11 (PA11); any Polyimides (PI) such as thermoplastic PI; any Polycarbonates and Polyphenylene compounds such as Polycarbonate (PC), Polyphenylene oxides (PPO), Polyphenylene sulfide (PPS); any Polyurethanes such as thermoplastic Polyurethane (TPU); any Polyethers such as Polyether Ether Ketone (PEEK), Polyoxymethylene (POM), Polytetramethylene ether glycol (PTMEG); any Polyacrylates such as Polyacrylonitrile (PAN); any Vinyl polymers such as Polyvinyl Chloride (PVC), Polyvinyl Alcohol (PVA), Polyvinyl acetate (PVAc), Polyvinyl butyral (PVB); any Styrenics such as Polystyrene (PSy), Acrylonitrile butadiene styrene (ABS); any Cellulose derivatives such as Cellulose acetate (celluloid), Nitrocellulose, Cellulose esters; any Polyethers such as Polyethersulfone (PES), Polyetherimide (PEI); any Elastomers such as Thermoplastic elastomers (TPE), Polychloroprene (CR), Hydrogenated nitrile butadiene rubber (HNBR), Ethylene propylene diene monomer (EPDM); any other polymers such as Polymethyl methacrylate (PMMA), Polymethyl pentenes (PMP), Polyvinylidene chloride (PVDC), Polyisoprene (Pyl), Polyacrylamide (PAM), Polyethylene oxide (PEO), Polystyrene sulfonate (PSS), Polyoxymethylene (POM), Poly(1-butene) (PB-1), Polyvinyl Formal (PVF), Polyvinyl Methyl Ether (PVME), Polyvinyl Methyl Ketone (PVMK), Polytriazole (PTA), Polyvinylpyrrolidone (PVP), Polybenzimidazole (PBI), Liquid crystal polymers (LCP), Chlorinated polyethylene (CPE), Polyvinylidene Fluoride (PVDF), Ethylene vinyl alcohol (EVOH), Polyvinylpyrrolidone (PVP), Polyethylene Naphthalate (PEN), Polyvinyl Fluoride (PVF), Polyvinyl Butyral (PVB), Polypropylene Carbonate (PPC), Polyphthalamide (PPA), Polybenzoxazole (PBO), Polyoxymethylene (POE), Polyvinylidene Chloride (PVDC), Polychlorotrifluoroethylene (PCTFE), Ethylene chlorotrifluoroethylene (ECTFE), Perfluoroalkoxy (PFA), Tetrafluoroethylene-hexafluoropropylene-vinylidene (THV); and thereof.

In specific embodiments, a composite membrane comprising a porous intermediate layer may comprise thin metal foils, such as, but not limited to, aluminium or stainless steel, which may provide excellent barrier properties, mechanical strength, and resistance to high temperatures and corrosive environments. In certain embodiments, a porous intermediate layer may comprise glass fibre mats, which may offer high chemical resistance, anti-channeling and can act as an additional or sole reinforcement layer for a membrane. In suitable embodiment, a porous intermediate layer may comprise nonwoven fabrics made of synthetic fibres (such as, but not limited to, polyester, rayon, spandex or acrylic fibres) or natural fibres (such as, but not limited to, cotton, jute, hemp, linen, wool, or silk) which may provide better mass transfer management capabilities while maintaining structural integrity. In an embodiment, a porous intermediate layer may comprise a combination of any of the above mentioned materials. For example, a combination of polymer and fabric, or a combination of polymer and metal foil, which may offer enhanced performance and enhanced specific functionalities.

Further, in certain embodiments, a composite membrane comprising a non-porous intermediate layer may comprise polysiloxanes, optionally optimised polysiloxanes. These materials may include, but are not limited to polysiloxanes such as Polytrifluoropropylmethylsiloxane (PTFPMS), Polydiphenylsiloxane (PDPS), Polymethylvinylsiloxane (PMVS), Polydimethylsiloxane (PDMS), Polyphenylmethylsiloxane (PPMS), Polymethylphenylsiloxane (PMPS), Polydiphenylsiloxane (PDPS), Polymethylhydrosiloxane (PMHS), Polyoctylmethylsiloxane (POMS), Poly(dimethylsiloxane-co-ethylene oxide) (PDMS-PEO), Polysiloxane-Polyimide block copolymers, Polysiloxane-Polycarbonate block copolymers, Polysiloxane-Polyether block copolymers, Polyurethane-Siloxane copolymers, Polysiloxane-Polystyrene copolymers, Polysiloxane-Acrylic copolymers, Polysiloxane-Epoxy copolymers, Polysiloxane-Polyamide copolymers, Polysiloxane-Polyurea copolymers, Polysiloxane-Polyester copolymers, Polysiloxane-Polyaniline copolymers, Polysiloxane-Polypyrrole copolymers, Fluorosilicone rubber (FVMQ), Silicone-Polypropylene glycol block copolymers, Silicone-Polyacrylate block copolymers, Amino-functionalized Polysiloxanes, Carboxy-functionalized Polysiloxanes, Hydroxy-functionalized Polysiloxanes, Alkoxy-functionalized Polysiloxanes, Vinyl-functionalized Polysiloxanes, Phenyl-functionalized Polysiloxanes, Silanol-terminated Polysiloxanes, Epoxy-functionalized Polysiloxanes, Methacrylate-functionalized Polysiloxanes, Ethyl Acrylate-functionalized Polysiloxanes, Poly (dimethylsiloxane-co-phenylsiloxane), Poly (dimethylsiloxane-co-methylphenylsiloxane), Poly (dimethylsiloxane-co-methylhydrosiloxane), Poly (dimethylsiloxane-co-trifluoropropylmethylsiloxane), Poly (dimethylsiloxane-co-diphenylsiloxane), Polysiloxane-Elastomer blends, Polysiloxane-Thermoplastic blends, Silica-reinforced Polysiloxanes, and/or other polysiloxane elastomers thereof. In other embodiments, the non-porous intermediate layer may comprise of chemically-modified and/or machine-modified materials, including, but not limited to, those mentioned above.

The properties of a composite membrane can be tailored by adjusting the composition, thickness, and morphology of the different layers, making it a versatile and effective tool for permeation applications. Due to its composite structure, such membranes may often be only partially transmissive to light (e.g.

translucent or semi-transparent) and not considered completely transparent, which is why they have not generally been considered favourable for use with photobioreactor systems previously. However, advancements in material science and engineering have opened up the feasibility of developing gas permeable composite membranes that can be highly translucent and/or nearly transparent. In certain
 5 embodiments, by optimising the material choice, arrangement and physical properties of the composite membrane's individual layers, composite membranes can be fabricated to maintain or more so enhance their functional performance while allowing significant light transmission.

In certain embodiments, a composite membrane comprises a reinforcement layer (generally porous)
 10 that may be comprised of polymers such as, but not limited to; any Polyolefins such as Polyethylene (PE), Polypropylene (PP), Polybutene-1 (PB-1), Polyisobutylene (PIB); any Fluoropolymers such as Polytetrafluoroethylene (PTFE), Ethylene tetrafluoroethylene (ETFE), Polyvinylidene fluoride (PVDF), Fluoroelastomers (FKM); any Polyesters such as Polyethylene terephthalate (PET), Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), Polycaprolactone (PCL); any Polyamides such as nylon 6,6
 15 (PA6,6), nylon 6 (PA6), nylon 11 (PA11); any Polyimides (PI) such as thermoplastic PI; any Polycarbonates and Polyphenylene compounds such as Polycarbonate (PC), Polyphenylene oxides (PPO), Polyphenylene sulfide (PPS); any Polyurethanes such as thermoplastic Polyurethane (TPU); any Polyethers such as Polyether Ether Ketone (PEEK), Polyoxymethylene (POM), Polytetramethylene ether glycol (PTMEG); any Polyacrylates such as Polyacrylonitrile (PAN); any Vinyl polymers such as
 20 Polyvinyl Chloride (PVC), Polyvinyl Alcohol (PVA), Polyvinyl acetate (PVAc), Polyvinyl butyral (PVB); any Styrenics such as Polystyrene (PSy), Acrylonitrile butadiene styrene (ABS); any Cellulose derivatives such as Cellulose acetate (celluloid), Nitrocellulose, Cellulose esters; any Polyethers such as Polyethersulfone (PES), Polyetherimide (PEI); any Elastomers such as Thermoplastic elastomers (TPE), Polychloroprene (CR), Hydrogenated nitrile butadiene rubber (HNBR), Ethylene propylene diene monomer (EPDM); any other polymers such as Polymethyl methacrylate (PMMA), Polymethyl pentenes (PMP), Polyvinylidene chloride (PVDC), Polyisoprene (Pyl), Polyacrylamide (PAM), Polyethylene oxide (PEO), Polystyrene sulfonate (PSS), Polyoxymethylene (POM), Poly(1-butene) (PB-1), Polyvinyl Formal (PVF), Polyvinyl Methyl Ether (PVME), Polyvinyl Methyl Ketone (PVMK), Polytriazole (PTA), Polyvinylpyrrolidone (PVP), Polybenzimidazole (PBI), Liquid crystal polymers (LCP), Chlorinated
 25 polyethylene (CPE), Polyvinylidene Fluoride (PVDF), Ethylene vinyl alcohol (EVOH), Polyvinylpyrrolidone (PVP), Polyethylene Naphthalate (PEN), Polyvinyl Fluoride (PVF), Polyvinyl Butyral (PVB), Polypropylene Carbonate (PPC), Polyphthalamide (PPA), Polybenzoxazole (PBO), Polyoxyethylene (POE), Polyvinylidene Chloride (PVDC), and thereof.

35 In specific embodiments, a reinforcement layer of a composite membrane may comprise porous ceramic materials, such as, but not limited to, alumina (Al_2O_3) or zirconia (ZrO_2), which may serve as a high-temperature resistant, chemically stable, and mechanically strong reinforcement layer. In certain embodiments, a reinforcement layer may comprise metal/alloy screens or meshes made of materials such as, but not limited to, aluminium or stainless steel or other corrosion-resistant metals, or carbon
 40 fibre or glass fibre (fabric) mats which may provide robust support, good gas transfer distribution,

dimensional stability, chemical resistance and high mechanical strength. Furthermore, a reinforcement layer may comprise of synthetic (man-made) and/or natural fibres or filaments mats of the non-woven and/or woven orientations. In other embodiment, a reinforcement layer may comprise nonwoven fabrics made of synthetic fibres (such as, but not limited to, polyester, rayon, spandex or acrylic fibres) or
5 natural fibres (such as, but not limited to, cotton, jute, hemp, linen, wool, or silk). In an embodiment, a reinforcement layer may comprise a combination of any of the above mentioned materials which may offer enhanced mechanical performance and specific functionalities.

10 In certain embodiments, the composite membrane may be flexible, that is, it may comprise a durable material that is capable of bending or deforming without breaking or creasing. Flexibility determines the ability to withstand deformation under different harsh conditions. For example, some polymers, such as silicone rubber, have high elasticity and can be stretched or compressed without permanent deformation, making them particularly durable.

15 Further, in suitable embodiments, a reinforcement layer may offer adaptability in context to sufficient mechanical properties, material compatibilities, and/or ease of fabrication of the liquid containing compartment. Similarly, a reinforcement layer within a composite membrane may be comprised of materials that may comprise a combination of strength, pore size, porosity, and uniformity of pore distribution.

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In certain embodiments, a composite membrane and/or a reinforcement layer comprised within a composite membrane may have a yield strength that may be suitably no more than about 10000 MPa, about 1000 MPa, 500 MPa, about 250 MPa, about 200 MPa, about 150 MPa, about 100 MPa, about 50 MPa, about 40 MPa, about 30 MPa, about 20 MPa, about 10 MPa, about 5 MPa, about 4 MPa, about
25 3 MPa, about 2 MPa, about 1 MPa, about 0.5 MPa, and typically no more than about 0.1 MPa. The composite membrane and/or a reinforcement layer comprised within a composite membrane may have a yield strength that may be suitably of at least 0.01 MPa, at least 0.1 MPa, at least 0.5 MPa, at least 1 MPa, at least 2 MPa, at least 3 MPa, at least 4 MPa, at least 5 MPa, at least 10 MPa, at least 20 MPa, at least 30 MPa, at least 40 MPa, at least 50 MPa, at least 60 MPa, at least 70 MPa, at least 80 MPa,
30 at least 90 MPa, at least 100 MPa, at least 200 MPa, at least 500 MPa, and typically at least 1000 MPa.

In specific embodiments, any layers of a composite membrane may comprise additives and/or combinations of additives incorporated into various compositions tailored to meet specific antibiofilm needs. Some of these additives encompass materials like, but not limited to, zinc (Zn), silver (Ag),
35 copper (Cu), ammonium compounds, natural essential oil compounds, chitosan, bismuth subsalicylate and thereof.

A membrane, or a composite membrane, can be made by any methods known in the art. Typically, they can be manufactured through a multi-step process that depends on the specific manufacturing
40 processes which can vary depending on the type of gas transfer or mass transfer composite membrane,

the materials used, and the intended application. Optimization and customization of the manufacturing process are often required to achieve the desired membrane properties and performance. Typically, a composite membrane manufacturing process can involve the following steps:

- 5 1. Material selection: Selecting appropriate materials for a barrier layer, reinforcement layer, intermediate layer and any additional layers such as, but not limited to, protective intermediate layers or coatings is crucial for the overall stability and performance of the membrane. The materials may have the desired gas transfer or mass transfer properties, liquid barrier properties, mechanical strength, chemical resistance, and bio-compatibility.
- 10 2. Substrate preparation: Preparing the substrate or a reinforcement layer, which provides structural support to the membrane and may also form a base upon which additional layers can be coated upon. This may involve surface cleaning, treatment, or modification to enhance adhesion and compatibility with other layers.
- 15 3. Layer deposition: This step involves depositing the additional layers (such as, but not limited to, intermediate layer, or barrier layer) onto the prepared substrate. This may be achieved through various techniques such as casting, solution casting, coating, spin-coating, dip coating, deposition, vapour deposition, or electrochemical deposition. The barrier layer material is typically applied in liquid form and then cured or solidified to form a thin film or dense film, or an ultra-thin dense coating.
- 20 4. Additional layer deposition: If required, additional layers such as additional intermediate layers or protective intermediate layers or coatings may be applied to enhance the membrane's performance or functionality. These layers may be deposited using similar techniques as mentioned in the previous step.
- 25 5. Layer bonding: If the composite membrane consists of multiple layers, the different layers may be bonded together using appropriate methods such as lamination, heat pressing, or adhesive bonding. This may ensure the integrity and stability of the composite structure and/or individual layers.
- 30 6. Post-treatment: After the layers are assembled, the membrane may undergo post-treatment processes such as curing, drying, annealing, or surface modification, or chemical modification treatments to improve its properties, or to enumerate specific functionality, or durability, or performance.
- 35 7. Quality control: The manufactured membranes may undergo quality control checks to ensure their dimensional stability, accuracy, gas transfer performance, mechanical strength, and other desired characteristics. This may involve testing the membranes under specific operating conditions to assess their gas permeability, selectivity, and durability.

In certain embodiments, solution-coating techniques such as dip coating can be employed to manufacture composite membranes with an ultra-thin layer or layers on to any suitable layer (such as a reinforcement layer or an intermediate layer). Dip coating involves immersing the suitable layer which acts as a 'substrate' into a polymer solution, allowing it to coat the surface uniformly. Generally, the

selected polymer is diluted into a polymer solution which is homogenised in a water-insoluble solvent. As the substrate is withdrawn, a thin film/layer forms, and subsequently solvent evaporation solidifies the layer, creating a thin polymer layer on the substrate. This method is versatile and can be tailored to achieve specific properties by adjusting the polymer concentration in the solution and coating parameters. Post-treatment steps like crosslinking or surface modification can further enhance the mechanical, chemical, and functional properties of the coated layers, optimising the composite membrane for various applications.

In certain embodiments, dip coating may be used to manufacture composite membranes, including, but not limited to, ultra-thin barrier layer composite membranes. Dip coating is particularly advantageous for creating ultra-thin barrier layers due to its ability to produce consistent and precise coatings with a high degree of permeability. In some embodiments, post-treatment methods, such as, but not limited to, crosslinking, annealing, or surface modification, can be applied to the dip-coated layer to further enhance their mechanical strength, chemical resistance, and functional properties, thereby improving the performance and durability of the composite membrane.

Further, techniques like solution casting can be used to manufacture porous or micro/nano porous barrier layer membranes and/or any intermediate layers and/or any other layers that facilitates the functionality of the overall composite membrane in its intended use. This technique involves preparing a polymer solution by dissolving the polymer in a suitable solvent and then casting the solution onto a flat substrate (for example, onto any layer constituting the composite membrane) to form a uniform film. As it is subjected to drying the solvent evaporates, the polymer solidifies, resulting in a membrane with a porous structure. The pore size and pore distribution can be finely tuned by adjusting the concentration of the polymer solution, the casting speed, and the solvent evaporation rate, among others.

In certain embodiments, solution casting methods may be used to manufacture composite membranes, including, but not limited to, micro/nanoporous barrier layer composite membranes. In some embodiments post-treatment steps, such as thermal annealing, solvent vapour exposure, or surface modification, may be applied to the cast polymer layer to further enhance their mechanical strength, chemical resistance, and functional properties, thereby improving overall performance of the composite membrane.

Additionally, techniques such as "Electrospinning" may also be used to manufacture membranes, and/or any individual layers comprised within a composite membrane in specific embodiments. The term electrospinning refers to a versatile technique which can produce porous films or layers with fine fibres (both nanofiber and microfiber dimensions). The process begins with the preparation of a polymer solution by dissolving a polymer in a suitable solvent with respect to the composite membrane's compatibility. This solution is then loaded into a syringe connected to a metallic needle or spinneret. By applying a high voltage to the needle, an electric field is created. As the voltage is increased, a droplet

of the polymer solution forms at the needle's tip, eventually elongating into a cone shape known as the "Taylor cone". Once the electric field strength reaches a critical point, a charged jet of the polymer solution is ejected from the Taylor cone, and the jet undergoes elongation and whipping motions, resulting in the formation of ultra-thin polymer fibres. These fibres are collected on a grounded or oppositely charged collector, forming a nonwoven mat or film or layer. During the process, the solvent in the polymer solution evaporates, allowing the fibres to solidify and form a porous structure. The resulting electrospun porous film or layer possesses a high surface area-to-volume ratio and an interconnected pore structure, making it suitable for a wide range of applications such as the one in the current invention (mass transfer, gas transfer). Optimization of the electrospinning parameters and material selection is often necessary to achieve desired morphology, porosity, and performance for specific applications.

Within certain embodiments, post-treatment steps, such as crosslinking, or annealing, or surface modification, may be applied to the electrospun porous film structure to enhance its mechanical, and/or chemical, and/or functional properties (for example, hydrophobicity). These additional treatments can further tailor the performance and characteristics of the specific individual layers or the composite membrane as a whole. In specific embodiments, electrospinning may be used to initially manufacture a reinforcement layer (for example, comprising of materials such as, but not limited to, PMMA, ETFE, and PPy microporous structures) and later any intermediate layer can be similarly electrospun (for example, comprising of materials such as, but not limited to, PVDF, PTFE and micro/nano porous structures) onto this already electrospun reinforcement layer. Further, in suitable embodiments, the combined electrospun intermediate and reinforcement layer can be coated and/or casted, and/or sprayed, and/or treated and/or thereby, to deposit a layer/layers of a suitable material with a desired thickness to form the barrier layer for the composite membrane.

In certain embodiments, nanocomposites could be used for making highly gas-permeable membrane materials and/or any layers of a composite membrane. Nano-materials and nano-structures mixed together with a membrane material can be used to increase the permeability of that membrane material, for example nano-clay filled siloxanes. It was found that nanoclay (nanoparticles of layered mineral silicates) provides substantial polymer reinforcement, though the gas permeability of the nanocomposite remains high, despite the large nanolayer aspect ratio. The random orientation of the clay nanolayers in the polymer matrix is responsible for the lack of an effective gas barrier property, thereby increasing its gas permeability properties.

Cellulose in general, or plant-based cellulose, or bacterial cellulose can be used to make membranes or any layers of a composite membrane. These materials are inherently hydrophilic, meaning it has a high affinity for water. However, it can be possible to modify cellulose to make it hydrophobic by introducing hydrophobic groups or coatings onto its surface. Some of the methods used to make cellulose hydrophobic can be as follows. These may include chemical modification, which may involve treating cellulose with hydrophobic agents or functional groups. This can be achieved by using reagents

that react with the hydroxyl groups on cellulose and introduce hydrophobic substituents. For example, within the specific embodiments of the invention, reactions with alkyl halides or silanes can introduce hydrophobic alkyl chains or silane groups onto the cellulose surface, and may lead to hydrophobic surfaces. Another approach may be to apply a hydrophobic coating onto the surface of cellulose. This may be done by using hydrophobic polymers or coatings that repel water. Techniques such as dip coating, spray coating, or electrostatic deposition may be employed to apply the hydrophobic coating onto the cellulose surface within specific embodiments of the invention. Further, plasma treatment may also be used, which may involve exposing cellulose to a low-pressure plasma environment. This may modify the surface properties of the cellulose, including making it more hydrophobic. Plasma treatment may also introduce functional groups or rearrange the surface structure, resulting in increased hydrophobicity. Additionally, vapour-phase deposition techniques, such as chemical vapour deposition (CVD) or plasma-enhanced chemical vapour deposition (PECVD), may be utilised to deposit a thin hydrophobic layer onto the cellulose surface. This method may allow for precise control over the thickness and composition of the hydrophobic layer.

In another embodiment, the composite membrane comprises bacterial cellulose. While bacterial cellulose has the same molecular formula as plant cellulose, it has significantly different macromolecular properties and characteristics. In general, bacterial cellulose is more chemically pure, containing no hemicellulose or lignin. Furthermore, bacterial cellulose can be produced on a variety of substrates and can be grown to virtually any shape, due to the high moldability during formation. Additionally, bacterial cellulose has a more crystalline structure compared to plant cellulose and forms characteristic thin ribbon-like microfibrils, which are significantly smaller than those in plant cellulose, making bacterial cellulose much more porous. The skilled person will be aware of a number of bacterial systems that are engineered to optimise cellulose production, such as the cellulose biosynthetic system of *Acetobacter sp.*, *Azotobacter sp.*, *Rhizobium sp.*, *Pseudomonas sp.*, *Salmonella sp.*, and *Alcaligenes sp.*, which can be expressed in *E. coli*, for example. Bacterial cellulose can be treated such that its surface provides a chemical interface to enable bonding with molecules.

In suitable embodiments, the liquid-containable compartment is comprised in form of a tube, pipe, hose or any other appropriate elongate form, comprising a length of continuous composite membrane of gas permeable material fused to the second wall. Typically, in certain embodiments, such an elongate tube or hose arrangement has a substantially uniform cross-section bore across at least the majority of its length, optionally for the entirety of its length. This cross-section profile may be (but does not have to be) round or circular, or may be elliptical, ovoid, or in the shape of a rounded off polygon, such as a square or rectangle. Suitably, the cross-section lacks internal blind endings, sharp corners, edges and other crevices. In other words, in certain embodiments, for at least the majority of the length of the bioreactor unit, the interior profile of the bore of the liquid-containable compartment is substantially uniform with a substantially smooth surface. The interface between bioreactor units and connectors may comprise some minor crevices and gaps without compromising the overall uniformity of the liquid-containable compartments in a bioreactor system. End-reinforcements can be used to reinforce the

terminal portions of the liquid-containable compartment by having a thicker wall or stronger material attached to reinforce the areas where the composite membrane layer, in particular, comes into contact with a connector to connect it to adjacent inlet/outlet lines or other bioreactor units. Similar reinforcements can be applied along the underside of the composite membrane layers if needed. This reinforcement can be done in any suitable way, for example by attaching thicker layers of the same composite membrane material (for example by using adhesive methods), or attaching a stronger and/or thicker material for example a flexible non-elastic polymer or a thicker mesh, or by using more layers of thermo curing silicone adhesive tapes, or by using more layers of self-curing (or UV curing) silicone glue to make a thicker layer, or by adding a microporous material sheet and/or film to the outside of the composite membrane layer (i.e., the side in communication with the chamber's atmosphere).

In certain embodiments, the first and the second walls may be joined or bonded to form the liquid-containable compartment. The areas where the walls are joined, as well as in specific sections of the first wall (i.e. the composite membrane), the individual layers of the composite membrane may be fused to close the pores of any porous layer of the composite, for example, the intermediate layer and/or the barrier layer. This process is carried out to prevent any loss of liquid from the liquid-containable compartment through porous layers of the composite, ensuring a completely liquid-tight seal. In suitable embodiments, the process can also strengthen the connection between the individual layers of the composite, reinforcing these areas and reducing the possibility of delamination over time. This fusing can be achieved through the application of adhesives and/or thermal treatment and/or pressure treatment.

The first and second walls, i.e. composite membrane layer and second wall, may be bonded and/or joined by any of the following methods, but are not limited to:

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1. Adhesion: The first and the second walls may be bonded together using adhesives that can be completely food-grade or at least biocompatible within the embodiments of the invention. Similarly, such adhesive interfaces may also exist in the form of adhesive tapes or double-sided adhesive tapes at the interphase of the first and second walls. In certain embodiments of the invention, pressure-sensitive adhesive (PSA) tapes may be used between the first and second walls, PSA are tapes which have an adhesive coating on one side that allows them to adhere to films or surfaces or materials, when pressure is applied. These tapes can provide a simple and effective method of joining membranes, as they can be easily applied and removed without leaving residue or requiring additional curing time. Additionally, post application, the interface can be cured utilising heat pressing techniques, or can cure spontaneously at room temperature, or can cure spontaneously at specific temperatures, or can cure after being irradiated with UV light (a light comprising of ultraviolet wavelengths) or other suitable wavelengths of light, or can cure using heat or pressure alone. In certain embodiments of the invention, epoxy, either single-part or two-part based epoxies may be used between the first and second walls. Further, epoxies may be tailored to cure at different rates and under various

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conditions, allowing for flexibility in the manufacturing and application processes. As used herein, the term “adhesive interface” or “glue interface”, also includes the use of non-crystallised (non-vulcanised) polymers that can bond the two walls with heat or humid pressing. As used herein, the related terms, “glue interface”, “adhesive” and “adhesive interface” are synonymous, and the three terms can be used interchangeably.

2. Heat pressing: The term “heat pressing” or “hot press” or “thermal welding” or “thermosealing” within the embodiments refers to a process of bonding two materials, i.e. the first and second walls by the application of heat, pressure, and temperature. The skilled person in the art will be familiar with suitable heat pressing techniques for this application. The precise temperature, pressure, surface preparation methods, duration (time) of heat applied and followed by cooling and solidification, required to bond portions of the first and second walls together will depend on the specific materials comprised in the two components.

3. Mechanical joining: In specific embodiments, the first and the second walls may be mechanically clamped and/or crimped together using particular devices such as, but not limited to, clamps, clips, rails, crimps, or frames. Such methods apply pressure to hold the walls tightly in place, creating a temporary or a permanent joint depending on the configuration. Further, the walls can be designed with interlocking mechanisms, such as hooks, loops, or tabs, that allow them to be mechanically joined together. The skilled person in the art will be familiar with such interlocking features which may provide a secure, cost-effective connection and may include attributes such as, but not limited to, closures, fasteners, or attachment points. In certain embodiments, attachment points may be applied manually or using specialised tools or equipment which provide a secure and/or reversible method of joining or sealing the walls, allowing for facile disassembly, when or if needed. Additionally, gaskets which are typically made of elastomeric materials such as rubber or silicone, which can provide a compressible and flexible sealing interface between the two walls can be utilised. In the context of mechanically clamping, gaskets may be used to create a tight seal and secure the seal in place. In specific embodiments, the gasket material may be selected based on compatibility with the first and second walls and the specific applications of the invention. The gasket may be soft enough to conform to the irregularities of the two wall surfaces and provide a reliable seal, while also having sufficient strength and resilience to maintain the clamping force. In specific embodiments of the invention, clamping or fixing means may be integrated into one or more walls of the chamber. In these embodiments the chamber may provide a surface or support onto which to secure the liquid-containable compartment and may, in the same joining assembly, seal the first wall to the second wall of the liquid-containable compartment and seal the liquid-containable compartment to the chamber.

4. Ultrasonic welding (USW): The term “ultrasonic welding” refers to a process or a technique used to join the two walls (within the embodiments) together using high-frequency vibrations.

5 Ultrasonic welding offers several advantages for joining polymer materials, or films, or surfaces, or porous membranes, which can enable fast welding speeds, precise control over the welding process and geometries, and the ability to create strong and consistent bonds. It is a non-contact method that does not require the use of adhesives or additional materials, resulting in
10 clean and visually aesthetic welds. However, the suitability of ultrasonic welding depends on the specific polymer or materials which are comprised within the two walls respectively, and their compatibility with the process parameters such as frequency, amplitude, and pressure. Several parameters play a crucial role in the ultrasonic welding process and impact the welding outcome. Proper parameter selection and control ensure consistent and reliable welds in ultrasonic welding processes. Some of the important parameters are described as follows:

- 15 • Frequency: The term "frequency" refers to the number of vibrations per second and is typically in the range of 20 to 70 kHz. Higher frequencies can provide finer vibrations, resulting in better precision and smaller weld sizes between the two walls. However, higher frequencies may require lower amplitudes and can be more sensitive to variations in material thickness.
- 20 • Amplitude: The term "amplitude" refers to the maximum displacement of the vibrating tool or sonotrode. It can directly affect the energy delivered to the first and second walls during welding. Higher amplitudes may generally result in stronger welds, but excessive amplitudes may cause material damage or inconsistent welds. The amplitude may be selected based on the material properties and desired welding strength between the two walls.
- 25 • Pressure: The term "pressure" with respect to ultrasonic welding refers to the force applied between the materials or the two walls during welding. It can ensure proper contact and promotes molecular interdiffusion for effective bonding. Optimal pressure depends on the material type, thickness, and surface condition and insufficient pressure may result in weak or incomplete welds, while excessive pressure can lead to material deformation or damage.
- 30 • Welding Time: The term "welding time" refers to the duration of applying vibrations and pressure to create the bond between the two walls. It depends on factors such as material type, thickness, and desired welding strength. The welding time may be decided based on having a sufficient window for proper energy transfer, melting, and bonding of the material surfaces. Too short welding time may result in weak welds, while longer than necessary welding time may cause excessive heating and degradation of materials comprised within the two walls or each respective wall, as a
35 whole.
- 40 • Tool Design and Contact Area: The shape and design of the sonotrode or actuator or vibrating tool that applies the vibrations onto the respective wall, affects the distribution of energy and pressure during welding. The contact area between the tool and the materials should be optimised for effective energy transfer and uniform bonding.

- Cooling and Solidification: Once the desired bond is formed between the two walls, a certain value of pressure is maintained for a short period to allow the bonded interface to cool and solidify.
- Material Properties: The material properties of the two walls, including melting temperature, thermal conductivity, and viscoelastic behaviour, influence the ultrasonic welding process. Different or dissimilar materials require different process parameters to achieve optimal weld strength and quality.

It is important to consider these parameters and optimise them for each specific application and material combination within the embodiments of the invention.

5. Non-conventional welding techniques: Other non conventional welding methods such as, but not limited to, "radio frequency welding" and "solvent welding" may be used to bond the first and second wall in certain embodiments of the invention. "Radiofrequency (RF) welding", also known as "high-frequency welding" or "dielectric welding", refers to a process that joins or bonds thermoplastic materials using electromagnetic energy. It involves generating a high-frequency electric field between two electrodes, causing polar molecules in the thermoplastic materials to rapidly oscillate and generate heat. This heat softens and melts the contacting surfaces, which are then pressed together to form a strong bond. The materials cool and solidify, resulting in a durable and consistent bond. RF welding may offer fast cycle times, strong bonds, and is suitable for joining large or irregularly shaped components or surfaces, or the walls in certain embodiments of the invention. Specific equipment and parameters may vary based on the comprised materials within the two walls and the desired bond strength. Additionally, "solvent welding (SW)" refers to a process or technique used to join thermoplastic materials by applying a chemical solvent that softens the surfaces, allowing them to fuse together. The process involves surface preparation, selecting a compatible solvent, applying the solvent to the surfaces, aligning and applying pressure to the softened parts, and allowing the solvent to evaporate and the joint to solidify. Solvent welding can create strong and seamless bonds in materials like acrylics, polyvinyl chloride (PVC), and polystyrene. Factors such as solvent selection, surface preparation, and proper assembly techniques contribute to the success of solvent welding between two walls within specific embodiments. Aspects such as clean working space, safety precautions and proper ventilation are also important when working with solvents.

Making dissimilar polymers compatible for processes such as adhesive bonding and/or ultrasonic welding and/or other described bonding techniques can be challenging, as the processes may require or rely on molecular interdiffusion and chain entanglement between the polymer materials comprised within both the walls. However, there are a few strategies that can help improve compatibility and enhance the bonding between dissimilar polymers. Elementarily, in certain embodiments, material compatibility can be achieved between the two walls for bonding by choosing polymers or materials that are chemically similar or microstructurally similar (i.e. crystalline, semi-crystalline or amorphous). For

example, in certain embodiments, the first wall may be comprised of acrylic/polymethyl methacrylate (PMMA) and the second wall (i.e. the composite membrane and/or any of the individual layers of the composite membrane) can be comprised of similar PMMA or micro structurally similar acrylonitrile butadiene styrene (ABS) and/or polystyrene (PSy), so that the tendency to form a strong bonded interface is high. In certain embodiments, the first wall and second wall, or any suitably compatible constituent layer thereof, may be subjected to additional treatment with certain materials that increase their bond strengths during adhesive bonding. Such methods may include flame treatment, or plasma treatment, or surface polishing. In certain embodiments, other techniques can be used including copolymerization or creating polymer blends/copolymers which are homogeneous that combine the dissimilar polymers and improve compatibility and bonding. Moreover, specific compatibilizer agents, that can improve the compatibility of dissimilar polymers, may also be used as an additive. Compatibilizers work by reducing interfacial tension and promoting molecular interactions between the polymers and they may be added to one or more of the walls prior to the bonding process. In certain embodiments, surface treatments or preparing the surfaces of the two walls may be crucial to promote bonding. Surface treatments such as plasma treatment or corona treatment can increase surface energy and enhance the wettability between the two walls, allowing for better intermolecular interactions. In specific embodiments, in the context of ultrasonic welding, process optimization or adjusting the welding parameters, such as amplitude, pressure, and welding time, may help optimise the bonding between the two walls. Fine-tuning these parameters based on the specific material combination may enhance the intermolecular interactions and improve the quality of the weld. Additionally, in certain embodiments, the application of a thin interfacial layer or adhesive layer on one or more of the walls may improve compatibility and bonding. The interfacial layer can be carefully selected to have good adhesion to both walls and act as a "bridge" between them. For example, the composite membrane may be coated with an additional adhesive thin layer to make it more compatible for it to be joined with the second wall.

More specifically, if the first wall comprises a composite membrane layer of polysiloxanes, where it could be bonded to the second wall by using silicone adhesives which can be in liquid form, viscous liquid gel form, a layer form, a layer tape form, and/or may comprise all types of silicone adhesive which can cure below or above 22°C or can cure with pressure, or can cure after being irradiated with UV light (a light comprising of ultraviolet wavelengths) or other suitable light wavelengths.

In alternative embodiments, the silicon adhesive interface between the first and the second wall can be composed of a thin layer of un-cured polysiloxane and/or dimethylpolysiloxane (PDMS), which can be mixed with its cross-linking agent, and quickly applied on the intended bonding regions on the walls, then pressed and heated to cure, bonding the composite membrane layer to the second wall.

A composite membrane may comprise various combinations of layers depending on factors such as required permeability, rate of permeability, mechanical strength, anti-biofilm capacity, chemical resistance, durability and other parameters or properties. A specific embodiment of the invention may

comprise a composite membrane which comprises a combination of layers that may include but are not limited to:

- 5 1. Porous Barrier Layer + Porous Reinforcement Layer: In this embodiment of the invention, the porous barrier layer may act as an impermeable layer for the liquid phase up to a certain hydraulic pressure, and/or other related functions. The porous reinforcement layer may substantially provide the mechanical strength of the composite membrane, and/or joining compatibility with the second wall, and/or other related functions.
- 10 2. Non-porous Barrier Layer I + Non-porous Barrier Layer II + Porous Intermediate Layer + Porous Reinforcement Layer: In this embodiment of the invention, the non-porous barrier layer I may act as an impermeable layer for the liquid phase, and/or a selective layer optimised to block undesired gases and/or a selective layer optimised to enhance the rate of permeability for desired gases, and/or other related functions. The non-porous barrier layer II may act as a
15 selective layer, and/or reduce the concentration gradient across the composite membrane, and/or other related functions. The porous intermediate layer may facilitate the fabrication of the barrier layer by acting as a suitable substrate, and/or other related functions. The porous reinforcement layer may substantially provide the mechanical strength of the composite membrane, and/or joining compatibility with the second wall, and/or other related functions.
- 20 3. Non-porous Barrier Layer + Porous Intermediate Layer + Porous Reinforcement Layer: In this embodiment of the invention, the non-porous barrier layer may act as an impermeable layer for the liquid phase, and/or a selective layer optimised to block undesired gases, and/or a selective layer optimised to enhance the rate of permeability for desired gases, and/or other related
25 functions. The porous intermediate layer may facilitate the transport of desired gases across the composite membrane, and/or facilitate the fabrication of the barrier layer by acting as a suitable substrate, and/or protect other layers of the composite membrane by absorbing UV radiation, and/or other related functions. The porous reinforcement layer may substantially provide the mechanical strength of the composite membrane, and/or joining compatibility with
30 the second wall, and/or other related functions.
- 35 4. Non-porous Barrier Layer + Porous Reinforcement Layer: In this embodiment of the invention, the non-porous barrier layer may act as an impermeable layer for the liquid phase, and/or a hydrophobic layer. The porous reinforcement layer may substantially provide the mechanical strength of the composite membrane, and/or joining compatibility with the second wall, and/or other related functions.
- 40 5. Porous Intermediate Layer I + Non-porous Barrier Layer + Porous Intermediate Layer II + Porous Reinforcement Layer: In this embodiment, the porous intermediate layer I may perform as a protective layer. The non-porous barrier layer may act as an impermeable layer for the

liquid phase, and/or a selective layer optimised to block undesired gases and/or a selective layer optimised to enhance the rate of permeability for desired gases, and/or other related functions. The porous intermediate layer II may facilitate the fabrication of the barrier layer by acting as a suitable substrate. The porous reinforcement layer may substantially provide the mechanical strength of the composite membrane, and/or joining compatibility with the second wall, and/or other related functions.

A composite membrane may have numerous advantages over a gas permeable membrane comprising a single layer intended for the same use. These advantages can include, but are not limited to, higher permeance, advantageous mechanical properties, lower elasticity, reduced material usage and easier handling.

In certain embodiments, a composite membrane may comprise a barrier layer that is significantly thinner than an equivalent single layer gas permeable membrane that needs to be of a certain thickness in order for it to be suitably used in the same application as the composite membrane. In such embodiments, as a result, the significant reduction of the thickness of the barrier layer in the composite membrane minimises the length of the diffusion pathways which allows for faster permeation of gases, enhancing its permeance compared to an equivalent single layer gas permeable membrane.

In certain embodiments, a composite membrane may comprise a reinforcement layer with advantageous mechanical characteristics over a single layer gas permeable membrane such as, but not limited to, higher strength and/or lower elasticity. In specific embodiments, the desired gas permeability may be solely defined by the composite membrane's least permeable layer (such as a barrier layer), allowing the material and construction of other layers (such as a reinforcement layer) to be optimised for its mechanical properties. In such embodiments, the reinforcement layer can comprise a strong material and potentially include additional reinforcement to further enhance its mechanical strength. Further, within these embodiments, as long as the reinforcement layer remains substantially porous, it may have a negligible effect on the overall gas permeability of the composite membrane. In contrast, the mechanical properties of a single layer gas permeable membrane are defined entirely by its single layer. A single layer gas permeable membrane may typically require additional separate supporting layers, and/or components, and/or structures in order to withstand the required hydraulic pressure.

In suitable embodiments, a liquid-containable compartment can comprise a composite membrane which has low elasticity. This is advantageous as it minimises the deformation or expansion of the liquid containable compartment under hydraulic pressure, reducing its change in volume. Additionally, composite membranes with high mechanical strength will increase the capacity of the liquid-containable compartment to withhold a higher internal hydraulic pressure. Therefore, a composite membrane can have superior mechanical properties alongside higher permeance compared to a single layer gas permeable membrane.

In certain embodiments, a composite membrane may comprise a suitable reinforcement layer and/or any layer that can protect the barrier layer, which does not hinder the composite membrane's permeability, to facilitate its handling during the fabrication of the liquid containable compartment. This can enable safer handling of the composite membrane, thereby reducing the risk of any damage that might occur in its absence. In contrast, typical single layer gas permeable membranes may comprise a soft, homogenous, unreinforced, rubber-like material, that can be very difficult to handle and susceptible to damage.

10 The Second Wall

According to certain embodiments of the invention, the bioreactor unit comprises a liquid-containable compartment, assembled using a first wall comprising a composite membrane, and a second wall that may serve singular or multiple functions. The second wall may provide optical transmission into the interior of the liquid-containable compartment and, optionally, may also provide structural integrity .

In one embodiment, the second wall may be constructed from a rigid material that possesses the necessary strength to bear a load and ensure the structural integrity of both the bioreactor unit and the liquid-containable compartment. This choice of material guarantees the stability and robustness of the bioreactor system. Alternatively, the second wall may be made from a flexible material which is capable of withstanding the hydraulic pressure load generated by the flow inside the liquid-containable compartment. This flexibility may allow for the second wall to adapt and accommodate changes in pressure within the bioreactor unit without compromising the overall integrity of the bioreactor system.

In the case of a photobioreactor, where the unit incorporates light for photosynthetic processes, the second wall may comprise an optically transmissible and/or translucent and/or substantially transparent material. This choice enables efficient transmission of light into the liquid-containable compartment, promoting optimal growth conditions for the organisms or processes within. In certain embodiments, the only barrier to light entering the liquid media is the second wall, substantially increasing the amount of light that can reach the liquid media over some alternative technologies known in the art. In specific embodiments, it is typical for the second wall to comprise a material that is impermeable to the ingress of liquid and resistant to oxidation, particularly when exposed to substances present within the liquid media and cleaning fluids. This ensures the durability and longevity of the bioreactor unit.

Overall, the choice of material for the second wall depends on the specific requirements of the bioreactor unit, including structural integrity, optical transmission, gas transfer, manufacturability, impermeability or relatively low permeability when compared to the membrane wall, and resistance to oxidation. Selecting the appropriate material can play a vital role in ensuring the efficient and reliable operation of the bioreactor system.

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In suitable embodiments, the second wall of a bioreactor unit may be comprised of lightweight, rigid, structural materials such as, but not limited to:

- 5 • Metals and metal alloys, such as, but not limited to, aluminium, stainless steel, titanium, copper and alloys thereof;
- Glass, including, but not limited to, soda glass, laminated glass, toughened glass, borosilicate glass, reinforced glass or glass polymer composite materials;
- 10 • Commodity or engineering polymers, including but not limited to, acrylics such as polymethyl methacrylate (PMMA), polyethylene (For example, HDPE), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), polyethylene (PE), polypropylene (PP), polycarbonates (PC), polyethylene terephthalate (PET), polystyrene (PSy), nylon (PA), polyethylene terephthalate glycol (PETG), polyether ether ketone (PEEK), epoxy and urea-formaldehyde (UF) resins and blends of the mentioned materials thereof;
- 15 • Fibre reinforced composites (FRP), including, but not limited to, carbon fibre reinforced polymers (CFRP), glass fibre reinforced polymers (GFRP), aramid fibre reinforced polymer (AFRP) such as Kevlar®, which may be combined with a polymer matrix, such as epoxy, to create AFRP composites, or ceramic fibre (Cr-FRP) reinforced composites and thereof;
- 20 • Wood and natural fibre based materials, including marine ply and wood/plant fibre reinforced materials (For example, MhyDF) and polymers. Natural fibres, such as, but not limited to, jute, hemp, bamboo, or flax, can be combined with various polymer matrices to create sustainable and environmentally friendly composites. Similarly, natural fibres, such as cellulose or sisal, may be incorporated into a cementitious matrix
- 25 to create natural fibre cement composites.

In suitable embodiments, the second wall of a bioreactor unit may be comprised of lightweight, flexible materials such as, but not limited to:

- 30 • Polyvinyl chloride (PVC), PVC films are transparent and flexible, which can offer good durability and chemical resistance;
- Polyvinylidene Chloride (PVDC), which is known for its excellent barrier properties and clarity;
- Polyvinylidene Fluoride (PVDF), which offers good weatherability, UV resistance, and thermal stability;
- 35 • Polyimide (PI), PI films can offer exceptional thermal stability, chemical resistance, and excellent mechanical properties combined with high transparency and flexibility;
- Polycarbonate (PC), PC films are transparent, lightweight, and can offer high impact-resistance;

- Polymethyl methacrylate (PMMA), PMMA films can offer excellent optical clarity, and sections can be easily thermoformed into various semi rigid shapes;
- Polyethylene (PE), such as, but not limited to, high-density polyethylene (HDPE), low-density polyethylene (LDPE) or linear low-density polyethylene (LLDPE), which can exhibit excellent transparency and flexibility;
- Ethylene tetrafluoroethylene (ETFE), polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP). Fluoropolymers such as ETFE, PTFE and FEP are notable for their unique properties and find diverse applications in various use cases. ETFE films are particularly valued for their thermal resistance, optical clarity and strength, while PTFE and FEP films are renowned for their chemical resistance and low-friction characteristics;
- Polyethylene terephthalate (PET), which can offer good optical clarity, high tensile strength, and excellent dimensional stability;
- Polyethylene naphthalate (PEN), PEN films provide high transparency, heat resistance, and dimensional stability. They can offer excellent performance in applications that require excellent barrier properties against gases and moisture;
- Thermoplastic polyurethane (TPU), which combines flexibility, transparency, and durability;
- Ethylene Vinyl Acetate (EVA), which offers good flexibility, transparency, and impact resistance;
- Polyether Ether Ketone (PEEK), a high-performance material with good transparency and mechanical properties;
- Nano cellulose, or cellulosic materials, derived from wood pulp or plant fibres or bacterial sources, can be transparent and flexible. Additionally, these films are biodegradable and eco-friendly;
- Silicone rubber elastomers;
- Any of the above mentioned materials or a combination of materials comprising additives or combinations of additives incorporated into various compositions tailored to meet specific antibiofilm needs without affecting visible light transmissibility. Some of these additives encompass materials like, but not limited to, zinc (Zn), silver (Ag), copper (Cu), ammonium compounds, natural essential oil compounds, chitosan, bismuth subsalicylate and thereof.

The materials the second wall is comprised of may be un-reinforced or comprise structural reinforcement such as fibre, fabric, mesh or metal wire.

In certain embodiments, the second wall may comprise a composite material comprising one or more materials and/or material layers and/or adhesive layers and/or joining layers and/or reinforcing structures. These materials, layers and structures can have multiple advantages including, but not limited to, UV resistance/reflectance/absorption, IR resistance/reflectance/absorption, mechanical

strength, chemical resistance, being safe for food contact, hydrophobicity and surface roughness. The layers of the composite membrane may be joined and/or laminated by any method known in the art. For example, in certain embodiments, individual layers can be laminated using an additional layer located in between that acts as simple or as functional adhesive that provides high levels of resistance to weathering, insulation and additional properties. In certain embodiments, a composite second wall may comprise any rigid or flexible possible second wall material included above.

In certain embodiments, the composite material can be designed to include layers with special coatings or treatments that enhance its resistance to UV radiation, UV reflection and/or absorption, corrosion, hydrophobicity, and chemical exposure, thereby extending the lifespan of the second wall in harsh conditions. The specific arrangement and composition of the layers can be tailored to meet the unique requirements of different applications, ensuring optimal performance for a wide range of structural and environmental conditions.

Within certain embodiments, the second wall may comprise reinforcing structures within the composite material including embedded metal grids, woven fabric, or mesh made from high-strength materials such as, but not limited to, Kevlar or aramid fibres. These reinforcing elements may be strategically placed to maximise the load-bearing capacity and resistance to deformation under stress. The combination of these various layers and reinforcements results in a supporting second wall that offers superior mechanical performance, durability, and resistance to environmental factors. In other embodiments, these reinforcing structures may also be placed or fitted externally to the second wall.

In certain embodiments, the composite material may comprise an outer layer made of a durable and weather-resistant polymer such as, but not limited to, polyethylene or polypropylene and/or fluoropolymers such as, but not limited to, ethylene tetrafluoroethylene (ETFE) or fluorinated ethylene propylene (FEP). Beneath the outer layer, there could be one or more layers of reinforcement material, for example, fibreglass or carbon fibre or bio-based fibres to provide strength and rigidity to the supporting second wall. Additionally, an inner layer might consist of a foam core or honeycomb structure to enhance the supporting second wall's overall strength while maintaining a lightweight profile. In certain embodiments, the inner layer of a composite second wall may comprise a material that is safe for food contact. This material would be in direct contact with the liquid in the liquid-containable compartment.

In various embodiments, the second wall may comprise a composite material that comprises numerous layers. The second wall composite material may comprise no more than about 10 layers, about 9 layers, about 8 layers, optionally no more than about 7 layers, about 6 layers, about 5 layers, suitably no more than about 4 layers, about 3 layers. The second wall composite material may comprise at least about 2 layers, about 3 layers, about 4 layers, about 5 layers, about 6 layers, about 7 layers.

In certain embodiments, the second wall and/or a layer comprised within a composite second wall may have a yield strength that may be suitably no more than about 10000 MPa, about 1000 MPa, 500 MPa, about 250 MPa, about 200 MPa, about 150 MPa, about 100 MPa, about 50 MPa, about 40 MPa, about 30 MPa, about 20 MPa, about 10 MPa, about 5 MPa, about 4 MPa, about 3 MPa, about 2 MPa, about 1 MPa, about 0.5 MPa, and typically no more than about 0.1 MPa. The second wall and/or a layer comprised within a composite second wall may have a yield strength that may be suitably of at least about 0.01 MPa, at least about 0.1 MPa, at least about 0.5 MPa, at least about 1 MPa, at least about 2 MPa, at least about 3 MPa, at least about 4 MPa, at least about 5 MPa, at least about 10 MPa, at least about 20 MPa, at least about 30 MPa, at least about 40 MPa, at least about 50 MPa, at least about 60 MPa, at least about 70 MPa, at least about 80 MPa, at least about 90 MPa, at least about 100 MPa, at least about 200 MPa, at least about 500 MPa, and typically at least about 1000 MPa.

In certain embodiments, the surface of the second wall in contact with the liquid media and/or the opposite surface of the second wall may have a contact angle of no more than about 160 degrees, about 150 degrees, about 140 degrees, about 130 degrees, about 120 degrees, about 110 degrees, about 100 degrees, about 90 degrees, about 80 degrees, about 70 degrees, and typically no more than about 60 degrees. The contact angle may be suitably at least about 30 degrees, at least about 40 degrees, about 50 degrees, at least about 60 degrees, at least about 70 degrees, at least about 80 degrees, at least about 90 degrees, at least about 100 degrees, at least about 110 degrees, at least about 120 degrees, at least about 130 degrees, at least about 140 degrees, and typically at least about 150 degrees.

In certain embodiments, the invention may comprise a second wall with an overall thickness that may be suitably no more than about 100mm, about 50mm, about 20mm, about 10mm, about 5mm, about 4mm, about 3mm, about 2mm, about 1.5mm, about 1mm, about 800µm, about 600µm, about 500µm, about 400µm, about 200µm, about 100µm, about 50µm, about 20µm, and typically no more than 10µm. A second wall with an overall thickness that may be suitably at least about 5µm, at least about 10µm, at least about 20µm, at least about 50µm, at least about 100µm, at least about 200µm, at least about 400µm, at least about 500µm, at least about 600µm, at least about 800µm, at least about 1mm, at least about 1.5mm, and optionally at least about 2mm, about 4mm, about 5mm, about 6mm, about 8mm, about 10mm.

In certain embodiments, the invention may comprise a second wall comprising a composite material with an overall thickness that may be suitably no more than about 10mm, about 5mm, about 4mm, about 3mm, about 2mm, about 1.5mm, about 1mm, about 800µm, about 600µm, about 500µm, about 400µm, about 200µm, about 100µm, about 50µm, about 20µm, and typically no more than 10µm. A second wall with an overall thickness that may be suitably at least about 5µm, at least about 10µm, at least about 20µm, at least about 50µm, at least about 100µm, at least about 200µm, at least about 400µm, at least about 500µm, at least about 600µm, at least about 800µm, at least about 1mm, at least

about 1.5mm, and optionally at least about 2mm, about 4mm, about 5mm, about 6mm, about 8mm, about 10mm.

In certain embodiments, the invention may comprise a second wall comprising a composite material .

- 5 The thickness of a layer of the composite material may be suitably no more than about 10mm, about 5mm, about 4mm, about 3mm, about 2mm, about 1.5mm, about 1mm, about 800µm, about 600µm, about 500µm, about 400µm, about 200µm, about 100µm, about 50µm, about 20µm, and typically no more than 10µm. The thickness of a layer of the composite material may be suitably at least about 0.1µm, about 0.5µm, at least about 1µm, at least about 5µm, at least about 10µm, at least about 20µm,
- 10 at least about 50µm, at least about 100µm, at least about 200µm, at least about 400µm, at least about 500µm, at least about 600µm, at least about 800µm, at least about 1mm, at least about 1.5mm, and optionally at least about 2mm, about 4mm, about 5mm, about 6mm, about 8mm, about 10mm.

- In certain embodiments, at least a portion of the material used to manufacture the second wall will be
- 15 optically transmissible, such that it is transparent and/or translucent, to allow the effective transmission of light such that when the organisms comprised within the bioreactor unit are phototrophic or mixotrophic, they can use the light to perform photosynthesis for the production of energy and/or the fixation of carbon. Such transparency may also be useful even where the cells do not require light, for example to enable straightforward inspection of the liquid-containable compartment interior by an
- 20 operator. In some embodiments, the proportion of the area of one or more of the second walls that is optically transmissible may be no more than 100%, about 90%, about 80%, about 70%, about 60%, about 50%, about 40%, about 30%, or about 20%. The portion of the area permissible to visible light may be at least about 0%, at least about 10%, at least about 20%, at least about 30%, at least about 40%, at least about 50%, at least about 60%, at least about 70%, at least about 80% or at least about
- 25 90%

- 'Switchable glass', 'Smart glass' or 'Electrochromic glass' or similar materials may be used in the manufacture of second walls of the invention. These are materials (which can be but are not limited to being rigid like glass, flexible like a polymer film or a coating) whose light transmission properties are
- 30 altered when voltage, light or heat is applied. These may be of particular use in areas with high light exposure, for example to reduce damage to the materials or the microorganisms within the liquid-containable compartment as a result of especially high light exposure, for example photobleaching. Typically, the smart glass material changes from substantially translucent, and/or with a reflective optical property (similar to a mirror finish) to substantially transparent, changing from blocking some (or
- 35 all) wavelengths of light to letting light pass through. Examples of technologies that may be used in pursuit of the above include but are not limited to electrochromic, photochromic, UV transition glass, thermochromic, suspended particle, micro-blind, prism-integrated glass, nanoparticles or minerals-integrated glass, and polymer dispersed liquid crystal devices.

In specific embodiments, the second wall may comprise additional and specific treatments to optimise their performance and maintain their transparency. Some common treatments or coatings for the second wall with respect to photobioreactors include, but are not limited to:

- 5 1. Anti-fouling coatings: To prevent fouling or biofilm formation on the inner surface of the second wall or a tube or the liquid chamber, anti-fouling coatings are applied. These coatings can be hydrophilic or hydrophobic or have low surface energy to discourage the adhesion of microorganisms or other particles, making it easier to clean the chamber and maintain their optical clarity.
- 10 2. UV stabilisation: Transparent second walls in photobioreactor units are often exposed to ultraviolet (UV) radiation from light sources. UV stabilisers or additives can be incorporated into the material composition to enhance UV resistance and prevent degradation, discoloration, or embrittlement caused by prolonged exposure to UV rays.
- 15 3. Chemical resistance: Depending on the specific application and the nature of the substances being processed, transparent second walls may require chemical resistance to withstand exposure to various chemicals or cleaning agents. Choosing tube materials with inherent chemical resistance or applying chemical-resistant coatings can help protect the transparency and structural integrity of the second wall.
- 20 4. Optical transparency enhancement: Transparent second walls are designed to transmit light efficiently to support photosynthetic processes. Surface treatments or coatings can be applied to improve the optical transmission properties, reducing light scattering and enhancing light transmission through the second wall's section.
- 25 5. Wavelength modification: Filters can be applied to the second wall to modify or convert wavelengths of light entering the bioreactor. These filters can be used to block harmful wavelengths, and/or enhance specific wavelengths beneficial for the biological processes inside the reactor, or convert wavelengths to optimise the efficiency of light utilisation by the organisms or processes within the bioreactor.
- 30 6. Thermal stability: Photobioreactor units may operate under elevated temperatures, particularly in certain industrial or research settings. The second walls can be coated with a more thermally stable material to have adequate thermal stability and to withstand the temperature fluctuations while maintaining their transparency and structural integrity without warping or melting.
- 35 7. Surface smoothness: Smooth inner and/or outer surfaces of the second wall can minimise light scattering and reduce the potential for fouling or the accumulation of particles, improving the overall performance and longevity of the photobioreactor system. Surface treatments or polishing can be applied to achieve the desired smoothness.
8. Hydrophobic coatings: Applying hydrophobic coatings to the second wall can help repel water and reduce moisture buildup, thereby maintaining the optical clarity of the wall and reducing the risk of contamination and biofilm formation.

It is important to note that, in certain embodiments, the specific treatments required for transparent second walls in bioreactor units can vary depending on the materials used, the operating conditions, and the nature of the (micro)organisms or substances being processed.

5 The Photobioreactor Unit

The geometry of the chamber will vary depending upon the overall configuration of the bioreactor unit, for example, in certain embodiments, the unit may comprise a plurality of liquid-containable compartments aligned in parallel (as shown in Figures 3 and 5) or a single liquid-containable compartment (as shown in Figure 4). Typically the chamber will be of a suitable size and volume to enable effective gas flow throughout the chamber and/or chambers, where connected with more bioreactor units, to enable effective gas exchange to occur across the first wall of the liquid-containable compartment(s) and to promote the production of microbial biomass within the liquid-containable compartment(s).

In certain embodiments of the invention, multiple liquid containable compartments may comprise the same first wall and/or second wall (see Figure 14).

In certain embodiments, the length of a liquid-containable compartment, being the distance between the inlet and outlet of a liquid-containable compartment of a single bioreactor unit, may be no more than about 4000m, about 2000m, about 1000m, about 500m, about 300m, optionally no more than about 250m, about 200m, about 100m, about 75m, about 50m, about 25m, about 10m, about 9m, about 8m, about 7m, about 6m, about 5m, about 4m, about 3m, typically no more than about 2m. The length of a liquid-containable compartment of a single bioreactor unit may be at least 0.1m, at least about 0.3m, about 0.5m, about 1m, suitably at least about 2m, about 3m, about 4m, about 5m, about 6m, about 7m, about 8m, about 9m, about 10m, about 25m, about 50m, and optionally at least about 75m. In the embodiment illustrated in Figure 8, the length is indicated by dimension D.

In certain embodiments, the width of a liquid-containable compartment of a single bioreactor unit may be no more than about 5m, about 2m, about 1m, about 0.5m, about 0.2m, about 0.1m, about 0.09m, about 0.08m, about 0.07m, about 0.06m, about 0.05m, about 0.04m, about 0.03m, about 0.02m, about 0.01m, about 0.005m, typically no more than about 0.001m. The width of a liquid-containable compartment may be at least about 0.001m, about 0.005m, about 0.01m, about 0.02m, about 0.03m, about 0.04m, suitably at least about 0.05m, about 0.06m, about 0.07m, about 0.08m, about 0.09m, about 0.1m, about 0.2m and optionally at least about 0.5m. In the embodiment illustrated in Figure 8, the width is indicated by dimension B.

In certain embodiments, the cross sectional area of a liquid-containable compartment perpendicular to the direction of flow of liquid media through it may be no more than about 20m², about 10m², about 3m², about 1m², about 1x10⁻¹m², about 5x10⁻²m² about 1x10⁻²m², typically no more than about 8x10⁻³m²,

about $6 \times 10^{-3} \text{m}^2$, about $4 \times 10^{-3} \text{m}^2$, about $2 \times 10^{-3} \text{m}^2$, about $1 \times 10^{-3} \text{m}^2$, about $7 \times 10^{-4} \text{m}^2$, about $3 \times 10^{-4} \text{m}^2$, about $8 \times 10^{-5} \text{m}^2$. The cross sectional area of a liquid-containable compartment perpendicular to the direction of flow of liquid media through it may be at least about $5 \times 10^{-7} \text{m}^2$, about $1 \times 10^{-6} \text{m}^2$, about $1 \times 10^{-5} \text{m}^2$, about $8 \times 10^{-5} \text{m}^2$, about $1 \times 10^{-4} \text{m}^2$, about $3 \times 10^{-4} \text{m}^2$, about $7 \times 10^{-4} \text{m}^2$, suitably at least about $1 \times 10^{-3} \text{m}^2$, about $2 \times 10^{-3} \text{m}^2$, about $4 \times 10^{-3} \text{m}^2$, about $6 \times 10^{-3} \text{m}^2$, about $8 \times 10^{-3} \text{m}^2$, about $1 \times 10^{-2} \text{m}^2$, about $1 \times 10^{-1} \text{m}^2$ and optionally at least about 1m^2 . In the embodiment illustrated in Figure 8, cross sectional area is indicated by A.

In certain embodiments, the volume of a liquid-containable compartment of a single bioreactor unit may be no more than about $40 \times 10^3 \text{L}$, optionally no more than about $750 \times 10^3 \text{L}$, about $100 \times 10^3 \text{L}$, about $5 \times 10^3 \text{L}$, about 5000L , about 1000L , about 500L , about 250L , about 100L , about 50L , about 40L , about 30L , about 20L , about 10L , about 8L , about 6L , about 5L , about 4L , about 3L , about 2L , about 1.5L , about 1.2L , about 1L , typically no more than about 0.8L . The volume of the liquid-containable compartment of a single bioreactor unit may be at least about 0.0001L , about 0.001L , about 0.005L , about 0.01L , about 0.02L , about 0.03L , about 0.05L , about 0.1L , about 0.2L , about 0.5L , about 1L , about 2L , about 5L , about 8L , about 10L , about 20L , about 30L , about 40L , about 50L , optionally at least about 100L , about 250L , about 500L .

As discussed, in certain embodiments, multiple bioreactor units can be connected in series, and can be arranged such that the flow direction of one liquid-containable compartment is opposite to the flow direction of the preceding compartment, creating a tortuous path through the unit. The length for which consecutive liquid-containable compartments can be arranged to run before such a change of flow direction occurs can be no more than about 4000m , about 2000m , about 1500m , about 1000m , about 750m , about 500m , about 400m , about 300m , about 200m , about 100m , about 80m , about 60m , about 40m , about 20m , about 10m , about 5m , about 1m . The length for which consecutive liquid-containable compartments can be arranged to run without such a change in flow direction may be at least about 1m , about 5m , about 10m , about 20m , about 40m , about 60m , about 80m , suitably at least about 100m , about 200m , about 300m , about 400m , optionally at least about 500m . In the embodiment illustrated in Figure 8, the length is indicated by dimension E. All of the liquid-containable compartments of the bioreactor units connected in series with no change of direction do not have to share the same chamber. Generally, this length is selected to be as long as possible before a change in direction occurs but without causing undue difficulties in maintenance or an excessive difference in pressure across the inlet and outlet of the system. At a set flow velocity, the longer the path of the fluid through the system, the higher the pressure will be at the inlet. This increases the maximum pressure the liquid-containable compartments and connectors would have to withstand. The pressure is also proportional to the flow velocity, so this problem is exacerbated if the flow velocity during cleaning is greater than the flow velocity during normal operation.

In certain embodiments, a photobioreactor system comprising a liquid media circuit may comprise of multiple photobioreactor units arranged horizontally in an array, comprising series of units connected in

series and changing in direction, multiple units being arranged in parallel, or otherwise. The horizontal (width) dimensions of the array of bioreactors, measured perpendicular to the direction of flow of the liquid media, may be no more than about 4000m, about 2000m, about 1500m, about 1000m, about 750m, about 500m, about 400m, about 300m, about 200m, about 150m, about 100m, about 75m, about 50m, about 40m, about 30m, about 25m, about 20m, about 15m, about 10m, suitably no more than about 5m. The width of the array may be at least about 0.5m, about 1m, about 2m, about 5m, about 10m, suitably at least about 15m, about 20m, about 25m, optionally at least about 30, about 40m, about 50m, about 100m, about 200m. In the embodiment illustrated in Figure 8, the width is indicated by dimension F. However, the liquid-containable compartments of the bioreactor units included in the array do not all have to share the same chamber. The minimum horizontal dimension can evidently be no less than the horizontal width of a single bioreactor. This width dimension of the array should be chosen to allow sufficient volume of liquid media to be contained, but not to be so wide that excessive pressure is created through the need for multiple changes of flow direction.

Similarly, in certain embodiments, a liquid media circuit may comprise of multiple photobioreactor units arranged or 'stacked' vertically. The minimum height of an array of bioreactors can evidently be no less than the height of a single bioreactor. The total height of an array may be no more than about 100m, about 50m, about 25m, about 20m, about 10m, about 9m, about 8m, about 7m, about 6m, about 5m, about 4m, about 3m, about 2m, typically no more than about 1m. The total height of an array may be at least about 0.15m, about 0.2m, about 0.3m, about 0.4m, about 0.5m, suitably at least about 1m, about 2m, about 3m, about 4m, about 5m, optionally at least about 6m, about 7m, about 8m, about 9m, about 10m. Height should be chosen to allow sufficient volume of liquid media to be contained, but not to be so high that excessive pressure is created, and/or to cause difficulties in maintenance.

In certain embodiments, a liquid media circuit may comprise of multiple photobioreactor units arranged side-by-side or vertically. The gaps left between them, vertically or horizontally, may be no more than about 1000mm, about 500mm, about 250mm, about 100mm, suitably no more than about 50mm, typically no more than about 10mm. The gaps between bioreactor units may be at least about 1mm, about 5mm, about 10mm, about 50mm, or at least about 100mm. In embodiments where multiple liquid-containable compartments share the same chamber, this dimension can be taken to mean the gap between the liquid-containable compartments. In some embodiments, no gap may be left (that is, neighbouring bioreactors may touch). In general, gap size is chosen to allow gas to circulate effectively between photobioreactors. In the embodiment illustrated in Figure 8, the gap is indicated by dimension C.

In certain embodiments, the volume of the liquid-containable compartments of the photobioreactor system as a whole, during normal operation, is not intended to be particularly limited except by the capacity of the bioreactor units and other parts of the system. In embodiments of the invention the volumetric capacity of the liquid-containable compartment(s) comprised within the photobioreactor system may be no more than about 200x10⁶L, 20x10⁶L, about 1x10⁶L, about 500,000L, about 100,000L,

suitably not more than about 50,000L, about 20,000L, about 10,000L, about 5000L, typically not more than 1000L. The volume of liquid media comprised within the liquid-containable compartments of the photobioreactor system as a whole may be at least about 50L, about 100L, about 200L, about 500L, about 1000L, about 5000L, about 10,000L, suitably at least about 20,000L, about 50,000L, about 100,000L, optionally at least about 500,000L, about 1,000,000 L.

In certain embodiments of the invention, the volumetric capacity of the entire liquid media circuit, which comprises of the liquid-containable compartments of the photobioreactor units, and may also comprise an auxiliary subsystem, a pump, opaque conduits, tanks, valves and any other additional equipment/components, during normal operation, may be no more than about 400×10^6 L, 200×10^6 L, 200×10^6 L, 20×10^6 L, about 1×10^6 L, about 500,000L, about 100,000L, suitably not more than about 50,000L, about 20,000L, about 10,000L, about 5000L, typically not more than 1000L. The volumetric capacity of the entire liquid media circuit, during normal operation, may be at least about 50L, about 100L, about 200L, about 500L, about 1000L, about 5000L, about 10,000L, suitably at least about 20,000L, about 50,000L, about 100,000L, optionally at least about 500,000L, about 1,000,000 L.

As discussed, in certain embodiments, multiple bioreactor units can be connected in series, and can be arranged such that the flow direction of one liquid-containable compartment is substantially opposite to the flow direction of the preceding compartment. The number of bioreactor units that can be connected together before such a change of direction occurs may be no more than about 20,000, about 10,000, about 5000, about 2000, about 1000 about 500, suitably no more than about 100, about 50, optionally no more than about 25. The number of connected bioreactor units may be at least about 2, about 5, about 10, about 50, about 100, suitably at least about 500, about 1000, about 2000, about 5000, optionally at least 10,000.

As discussed, in certain embodiments, multiple bioreactor units can be positioned such that the first wall of each liquid-containable compartment is exposed to the same chamber. In certain embodiments, the number of bioreactor units that can share the same chamber may be no more than about 5,000,000, about 1,000,000, about 100,000, about 50,000, suitably no more than about 20,000, about 10,000, about 5000, optionally no more than 2500. The number of bioreactor units may be at least about 2, about 10, about 100, about 500, about 1000, about 2500, suitably at least about 5000, about 10,000, about 20,000, optionally at least about 50,000, about 100,000.

The Chamber

In certain embodiments, the chamber is typically defined by a housing that may comprise one or more walls that may provide structural definition and support to the bioreactor unit. The chamber may be further defined by the collocation of the liquid-containable compartment with the housing such that together they cooperate to enclose a volume of space adjacent to, and in gaseous communication with, the gas exchange composite membrane layer (the first wall). Suitably, the housing accommodates a

portion of the liquid-containable compartment with at least one liquid-containable compartment oriented such that the first wall is exposed to the atmosphere within the chamber and the second wall is positioned to be outwardly facing. In specific embodiments, the second wall is oriented to face toward a source of illumination.

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In certain embodiments of the invention, the liquid-containable compartment is partially enclosed within the chamber. The internal or inwardly facing surface area of the liquid-containable compartment is taken to mean the area on the inside of the liquid-containable compartment that is directly in contact with the liquid media. Suitably, this is not taken to include any area that is left open to form the inlet and/or the outlet of the liquid-containable compartment. The external or outwardly facing surface of the liquid-containable compartment is taken to mean the opposite surface.

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In some embodiments, the percentage of the internal surface area of the liquid-containable compartment located inside the chamber may be no more than about 100%, about 95%, about 90%, about 80%, about 70%, about 60%, about 50%, about 40%, about 30%, about 20%, typically not more than 10%. The percentage of the internal surface area of the liquid-containable compartment located inside the chamber may be at least about 1%, about 10%, about 20%, about 30%, about 40%, about 50%, about 60%, about 70%, suitably at least about 80%, optionally at least about 90%. Inside the chamber housing is taken to mean anything inside of the points of the liquid-containable compartment, that are in direct contact with the atmosphere in the chamber, that are closest to the external environment. Figure 13 illustrates embodiments of the invention in cross section, annotating the percentages of the internal surface area inside the chamber. As the cross section of these embodiments is substantially uniform, this percentage is represented as the percentage of the length A of the total circumference of the internal surface of the liquid containable compartment (length A + length B).

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In certain embodiments of the invention, the internal surface area of the liquid containable compartment comprising the first wall may be no more than about 99%, about 95%, about 90%, about 80%, about 70%, about 60%, about 50%, about 40%, about 30%, about 20%, typically not more than about 10%, about 5% of the total internal surface area of the liquid containable compartment. The internal surface area of the liquid containable compartment comprising the first wall may be at least about 1%, about 5%, about 10%, about 20%, about 30%, about 40%, about 50%, about 60%, about 70%, suitably at least about 80%, optionally at least about 90% of the total internal surface area of the liquid containable compartment.

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In certain embodiments of the invention, the internal surface area of the liquid containable compartment comprising the second wall may be no more than about 99%, about 95%, about 90%, about 80%, about 70%, about 60%, about 50%, about 40%, about 30%, about 20%, typically not more than about 10%, about 5% of the total internal surface area of the liquid containable compartment. The internal surface area of the liquid containable compartment comprising the second wall may be at least about 1%, about 5%, about 10%, about 20%, about 30%, about 40%, about 50%, about 60%, about 70%, suitably at

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least about 80%, optionally at least about 90% of the total internal surface area of the liquid containable compartment.

5 In certain embodiments, the percentage of the external surface of the first wall that is in direct contact with the atmosphere contained within the chamber may be no more than about 99%, about 95%, about 90%, about 80%, about 70%, about 60%, about 50%, about 40%, about 30%, about 20%, typically not more than about 10%, about 5%. The percentage of the external surface of the first wall that is in direct contact with the atmosphere contained within in the chamber may be at least about 1%, about 5%, about 10%, about 20%, about 30%, about 40%, about 50%, about 60%, about 70%, suitably at least
10 about 80%, optionally at least about 90%.

In certain embodiments of the invention, irrespective of the number of liquid-containable compartments it is in gaseous communication with, or how it may be connected to other chambers in the system, the width of the chamber may be no more than about 200m, about 150m, about 100m, about 75m, about
15 50m, about 25m, about 10m, about 5m, about 2m, about 1m, typically no more than about 0.5m. The width of the chamber may be at least about 0.001m, about 0.005m, about 0.01m, about 0.05m, about 0.1m, suitably at least about 1m, about 2m, about 5m, optionally at least about 10m.

In certain embodiments, the height of the chamber may be no more than about 200m, about 150m,
20 about 100m, about 75m, about 50m, about 25m, about 10m, about 5m, about 2m, about 1m, typically no more than about 0.5m. The height of the chamber may be at least about 0.001m, about 0.005m, about 0.01m, about 0.02m, about 0.05m, about 0.1m, typically at least about 1m, about 2m, about 5m, optionally at least about 10m.

25 In certain embodiments, the length of the chamber may be no more than about 4000m, about 2000m, about 1500m, about 1000m, about 750m, about 500m, about 400m, about 300m, about 200m, about 100m, about 80m, about 60m, about 40m, about 20m, about 10m, typically no more than about 5m. The length of the chamber may be at least about 0.5m, about 1m, about 2m, about 5m, about 10m, suitably at least about 20m, about 40m, about 60m, about 80m, about 100m, optionally at least about
30 200m, about 300m about 400m, about 500m.

In certain embodiments, the volume of the chamber may be no more than about $200 \times 10^6 \text{m}^3$, about $100 \times 10^6 \text{m}^3$, about $50 \times 10^6 \text{m}^3$, about $10 \times 10^6 \text{m}^3$, about $5000 \times 10^3 \text{m}^3$, about $600 \times 10^3 \text{m}^3$, about $50 \times 10^3 \text{m}^3$, about $7.5 \times 10^3 \text{m}^3$, suitably no more than about 800m^3 , about 80m^3 , typically no more than about
35 10m^3 . The volume of the chamber may be at least about $1 \times 10^{-7} \text{m}^3$, about $5 \times 10^{-7} \text{m}^3$, about $1 \times 10^{-6} \text{m}^3$, about $5 \times 10^{-6} \text{m}^3$, about $1 \times 10^{-5} \text{m}^3$, about $5 \times 10^{-5} \text{m}^3$, about $0.1 \times 10^{-3} \text{m}^3$, about $12.5 \times 10^{-3} \text{m}^3$, suitably at least about 0.1m^3 , about 10m^3 , about 80m^3 , about $7.5 \times 10^3 \text{m}^3$, optionally at least about 800m^3 .

According to a specific embodiment, the chamber is filled with a gas mixture comprising CO_2 in higher
40 concentration to that of the liquid media within the fluid-containable compartment, increasing the

concentration differential between the liquid media and the surrounding atmosphere. In this way the gas-transfer rate of CO₂ through the composite membrane into the liquid media is increased. Supply and control of the gaseous atmosphere within the chamber is maintained by gaseous connection to one or more auxiliary subsystems and/or atmospheric control modules within the system.

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As the CO₂ (in all its possible forms that can be taken up by photosynthesising microorganisms) in the liquid media is consumed by the photosynthetic microorganisms comprised within, and more CO₂ passes across the composite membrane of the first wall from the atmosphere within the chamber to the liquid media, the CO₂ gas transfer rate will decrease over time as the concentration differential stabilises towards an equilibrium state. To overcome the tendency toward equilibrium, the gas mixture comprising CO₂ can be continuously or intermittently delivered through a gas chamber inlet, and a similar volume of gas can be removed through an outlet, typically using a valve or a controlled valve such as a solenoid valve and/or butterfly valve and/or pressure sensitive valve. Optionally the outlet valve can be closed when the gas mixture is delivered, to pressurise the gas chamber above ambient standard atmospheric pressure and so further increase gas transfer rate across the gas-permeable membrane. Should the concentration of CO₂ in the chamber be too high and above the CO₂ concentration of normal atmospheric air, normal atmospheric air can be introduced to the chamber in the same way as described above in order to lower the CO₂ concentration in the chamber.

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In further embodiments, the concentration of CO₂ in the chamber can be maintained at the CO₂ concentration of normal atmospheric air by continually adding normal atmospheric air to the chamber, as described above.

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In certain embodiments, the CO₂ concentration of the gas in the chamber may be controlled to be no more than about 100%, about 90%, about 80%, about 70%, about 60%, suitably no more than about 50%, about 40%, about 30%, about 20%, about 10%, about 5%, optionally no more than about 4.8%, about 4.6%, about 4.4%, about 4.2%, about 4%, about 3.8%, about 3.6%, about 3.4%, about 3.2%, about 3%, about 2.8%, about 2.6%, about 2.4%, about 2.2%, typically about 2%, about 1.9%, about 1.8%, about 1.7%, about 1.6%, about 1.5%, about 1.4%, about 1.3%, about 1.2%, about 1.1%. The CO₂ concentration may be controlled to be at least about 0%, about 0.01%, about 0.04%, about 0.1%, about 0.2%, about 0.3%, about 0.4%, about 0.5%, about 0.6%, about 0.7%, about 0.8%, about 0.9%, about 1%, suitably at least about 1.1%, about 1.2%, about 1.3%, about 1.4%, about 1.5%, about 1.6%, about 1.7%, about 1.8%, about 1.9%, typically at least about 2%, about 2.2%, about 2.4%, about 2.6%, about 2.8%, about 3%, about 3.2%, about 3.4%, about 3.6%, about 3.8%, about 4%, about 4.2%, about 4.4%, about 4.6%, about 4.8%, about 5%, typically at least about 6%, about 7%, about 8%, about 9%, optionally at least about 10%.

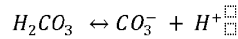
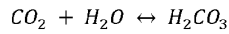
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In certain embodiments of the invention, the concentration of carbon dioxide (CO₂) within the chamber is controlled in order to control the pH of the culture in the bioreactor units. A CO₂ source is introduced into or removed from the bioreactor units through a control subsystem. If the pH of the culture is too

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high, the controlled chamber inlet and outlet valves add a controlled amount of CO₂ into the chamber, which is then absorbed by the microalgae culture through the composite membrane of the liquid-containable compartment. Typically, when CO₂ is dissolved into the culture medium, it forms carbonic acid (H₂CO₃). The carbonic acid then dissociates into bicarbonate (HCO₃⁻) and hydrogen ions (H⁺) as shown in the following reactions:



The release of hydrogen ions (H⁺) lowers the pH of the culture medium. A pH probe and controller continuously measure and monitor the pH of the culture medium. The controller is programmed to maintain the pH within a predefined optimal range. The pH control system operates as an automated feedback loop, where the continuous pH measurements ensure real-time adjustments to the CO₂ being introduced into the chamber, providing a consistent and optimal pH environment for the culture. This is advantageous over traditional methods of pH control, which can involve chemical additives, as the materials for these traditional methods can be costly and the process of adding the chemicals to the culture can introduce impurities.

In certain embodiments, in addition to providing CO₂ to be consumed by photosynthetic microorganisms, any CO₂ source can be added to the chamber to control the pH of the fluid. CO₂ source can be added to the chamber to maintain the pH of the liquid at no more than about 14, about 13, about 12, about 11, about 10.5, about 10, suitably no more than about 9.5, about 9, about 8, about 7, typically no more than about 6. The pH may be maintained at at least about 3, suitably at least about 4, about 5, about 6, about 7, about 8, about 9, typically at least about 10.

The gas mixture introduced into the gas chamber may also comprise a lower concentration of O₂ than that found in the liquid media and/or than atmospheric O₂ levels, in order to increase the O₂ depletion rate from the liquid media. This could be achieved in an auxiliary subsystem using an oxygen depleting system. Alternatively, the rate of O₂ transfer from the liquid media to the chamber via the composite membrane can be increased by the introduction into the gas chamber of inert gases such as nitrogen, helium, argon or methane and/or CO₂ in order to increase the O₂ concentration differential between the atmosphere in the chamber and the liquid media.

In certain embodiments, the O₂ concentration of the gas in the chamber may be no more than about 50%, about 30%, about 25%, about 20%, about 15%, about 10%, typically no more than about 5%, about 4%, about 3%, about 2%, about 1%, suitably no more than about 0.5%, about 0.4%, about 0.3%, about 0.2%, about 0.1%. The O₂ concentration may be at least about 0%, about 0.01%, about 0.05%, about 0.1%, about 0.2%, about 0.4%, about 0.6%, about 0.8%, about 1%, about 2%, about 3%, about 4%, about 5%, suitably at least about 6%, about 7%, about 8%, about 9%, about 10% optionally at least about 15%.

The gas can be moved inside the chamber passively by gas expansion, or by using a low energy method which reduces CO₂ feed delivery costs such as a fan, blower, turbine or other impeller comprised within the system, such as for example within a feed line, supply/exhaust manifold or within the auxiliary subsystem comprising atmospheric control. Alternatively, the gas can be compressed prior to
5 introduction into the gas chamber.

In certain embodiments, the internal environment of the chamber can be controlled internally or by controlling the gas supply and/or the gas discharge to and from the chamber respectively. For example, the humidity of the atmosphere within the chamber can be controlled by the presence of a desiccating
10 agent installed in a feed line, supply/exhaust manifold or within the auxiliary subsystem comprising atmospheric control, or by a desiccating agent or material or coating placed inside the chamber itself or within an attached system. For example the chamber atmosphere can be circulated to a desiccant for drying, before being returned to the chamber; typically the desiccant can be in the form of a honeycomb wheel. The humidity of the gas in the chamber could also be controlled by passing it over chilled coils,
15 forcing water vapour to condense and collect before being removed. A supply/exhaust manifold could be used to control humidity in the chamber by removing higher humidity air and replacing it with a gas mixture with lower humidity.

In certain embodiments, the temperature of the chamber atmosphere can be controlled by the one or
20 more auxiliary subsystems by introducing a gas mixture with reduced or increased temperature compared to the ambient chamber atmosphere, or by the presence of a cooling or heating component installed in the chamber and/or gas inlet and/or before the gas inlet. By controlling the temperature of the chamber atmosphere, it is possible to also control the temperature of the liquid media inside the liquid-containable compartment. For example, the chamber atmosphere can be circulated to an air
25 conditioning unit and/or an air heating unit, before being returned to the chamber. Alternatively, heating and/or cooling units can be comprised by or contained within the chamber itself, which can control the temperature of the atmosphere already within the chamber more directly. In some cases, the gas mixture in the chamber may be recirculated in the same chamber or passed to a chamber in an adjacent bioreactor unit. Before returning a gas mixture to a chamber, the gas can be desiccated, cooled, heated,
30 filtered, cleaned and/or replenished with a suitable amount of desired gas to adjust its composition and/or be cooled, heated, and/or desiccated further.

In certain embodiments, the support structures that define the housing of the chamber are typically constructed of a rigid material that is able to bear a load and provide structural integrity to the bioreactor
35 unit. In certain embodiments, suitable materials are also relatively impermeable to gas diffusion so as to allow for the maintenance of the atmosphere within the chamber volume. Suitably, the walls of the chamber are substantially gas-impermeable and the chamber as a whole is substantially air-tight, to prevent loss or contamination of the controlled atmosphere comprised within. Suitable materials may also be relatively impermeable to gas diffusion so as to allow for the maintenance of the atmosphere
40 within the chamber volume. It is not necessary for the chamber to be entirely air-tight and/or for the

materials to be relatively impermeable, as long as it fulfils the purpose of allowing the atmosphere within to be controlled to some extent either in terms of gas composition, temperature, humidity, pressure or otherwise. The chamber can also be made by solely flexible materials or a combination of flexible materials and/or semi rigid support members and/or inflatable structures (that could be inflated to provide additional structural support).

Materials of the support members and chamber walls may include:

1. Metals and metal alloys, such as aluminium, steel, stainless steel, titanium, copper;
2. Glass, including laminated glass or glass polymer composite materials;
3. Polymers, including acrylics, polyethylene (e.g. LDPE, HDPE), PVC, polypropylene, polycarbonates, polystyrene, nylon, epoxy, PVDF, PET, PETG, ETFE and UF resins;
4. Fibre reinforced composites, including carbon fibre reinforced polymers (CFRP), glass fibre reinforced polymers (GFRP);
5. Concrete, geological based materials such as rocks;
6. Wood and natural fibre-based materials, including marine ply and wood fibre reinforced materials (e.g. MDF).

The support members and/or chamber walls may be formed by rotational moulding, injection moulding, thermo-forming, extrusion, casting, cutting, bending, welding, printing or modular assembly and typically assume a pipe or box-like configuration in cross section. In embodiments of the invention, the support members may be formed as conduits, trunking or piping, with channels in an upper surface to accommodate placement of the liquid-containable compartment thereupon. The walls of the chamber can also be composed or defined by the structures or body assemblies of vehicles, industrial machines, ships, spaceships or spacecraft, submersible vehicles, wall cavities, containers, greenhouses, underground or partially underground chambers, semi-underground chambers, architectural structures, building rooms and/or houses.

In certain embodiments, UV additives and/ UV coating or UV-based chemical compounds may be used in the fabrication of the chamber and/or its components. These UV additives are chemical compounds that can be incorporated into the materials to enhance their resistance to UV radiation. These additives work by absorbing or reflecting harmful UV rays, thereby preventing the degradation and discoloration of materials, thus extending the lifespan.

In some embodiments of the invention, the bioreactor system may comprise an array of liquid-containable compartment(s) and chamber(s) that are substantially suspended above the ground and/or mounting surface, and/or substantially resting on the ground and/or mounting surface, and/or substantially anchored to the ground and/or mounting surface.

Figure 9a illustrates an embodiment of the invention that comprises sheet metal that is cut and bent to construct the walls of the chamber 911. The ribs in the middle of the chamber serve to stiffen the structure and could be secured with bolts, welding, adhesives or other suitable methods of joining. The structure forms channels for the liquid-containable compartments 902 to sit in with the composite
5 membrane layer facing downwards into the chamber 903.

Figure 9b illustrates an embodiment of the invention that comprises a chamber made up of a combination of rigid and flexible materials. A pair of U-beams run down either side of the chamber with beams intermittently spanning the gap between them. I-beams are supported on the cross beams and
10 thereon the liquid-containable compartments 902 are mounted. Along the bottom of the U-beams a seamless flexible substantially less gas permeable film material 911 is secured such that it hangs between the two U-beams, creating a chamber between it and the bottom of the liquid continuing compartments 903.

Figure 9c illustrates an embodiment of the invention where the main body of the chamber has been constructed from rotationally moulded polymer, for example LDPE with UV stabilising additives. The top surface of the component would then be finished and machined to include the final mounting locations for the liquid-containable compartments 902. Sections of the top of the component would also be removed to allow the composite membrane layer of the liquid-containable compartment to be in
15 20 contact with the atmosphere within the chamber 903. The internal geometry of the rotational moulded chamber would also include features that would ensure it was adequately stiff to support the assembly while maintaining a single connected chamber 903.

In some embodiments, at least a portion of the material used to define the walls of the chamber may
25 be transparent or translucent, to allow the effective transmission of light therethrough. The translucent/transparent portion which permits transmission of light into the chamber can be composed of any suitable translucent/transparent material. The chambers can be comprised entirely of the translucent/transparent material, or can be supported on a support structure such as a scaffold or frame, as discussed below. Suitably the material is substantially gas-impermeable, strong, light, and
30 possesses good thermal insulation properties. Optionally the material is provided in sheets and/or films. In some embodiments the material is non-flexible, non-elastic, transparent and strong, for example comprising glass, high performance glass, low iron glass with very high solar energy transmittance (Pilkington Sunplus™), glass composites, reinforced glass composites with increased strength, impact proof glass composites, low reflectance glass, high light transmittance glass, double glazing style glass
35 and/or triple glazing with or without vacuum/argon/air in between, or glass composites made of several layers of different materials to increase strength and/or light transmittance, or electrically switchable smart glass.

Photobioreactor Operation

In embodiments of the invention the photobioreactor unit may be connected to an auxiliary subsystem which controls the supply and condition of the liquid media used. Depending on the application of the device, the auxiliary subsystem can be of any degree of complexity and composed by any kind of auxiliary components. In a suitable embodiment of this invention, the photobioreactor unit is connected to an auxiliary subsystem mainly composed of, but not limited to, conduits for supply of gas and/or of liquid media, reservoirs, tanks for liquids and tanks for gases, pressure vessels, low-pressure gas vessels/tanks, canisters, pumps for liquid media, biomass-separators, sieves, vibrating sieves, centrifuges, any kind of impeller for gases, gas and/or liquid filters, dehumidification devices, heat exchangers for liquid and/or gas, artificial illumination systems (especially if natural sunlight is not present), liquid and/or gas temperature control systems, sensors, probes, housings for sensors and computer processors. The conduits and reservoirs (liquid and/or gas tanks) can be of any type and of any suitable material. The different features of the auxiliary subsystem do not have to be all comprised together but may be dispersed in different parts of the system as a whole. For example, biomass separators, gas outlets and/or inlets for nutrients may be included in connectors between individual bioreactors.

The pumps can also be of any type; typically the liquid pumps are positive displacement pumps, for example peristaltic pumps, which can reduce the contamination risk of the liquid media and the breakage of the cells used due to the peristaltic tube being the only component in contact with the liquid media. In some embodiments diaphragm pumps (also known as membrane pumps) can be used. Diaphragm pumps create relatively little friction with the liquid media and so can have advantages in the reduction of cell breakage and the risk of contamination. In some other embodiments disk pumps, hollow rotary disk pumps, screw pumps, progressive cavity pumps and gear pumps can be used. Progressive cavity pumps create relatively little friction with the liquid media and so can have advantages in the reduction of cell breakage while being able to pump liquid at high flow rates. In some other embodiments centrifuge pumps can be used. Centrifuge pumps are known to cause high shear stress to the organism grown in the bioreactor units, however, they could be over-sized and/or modified to decrease the shear stress down to acceptable levels.

Some embodiments of the invention can comprise an auxiliary subsystem that may constantly and/or intermittently circulate the liquid media and/or fluids through the liquid-containable compartment(s) during normal operation for any advantageous purpose which may include mixing and/or reducing biofilm formation and/or avoiding sedimentation of the organisms in the liquid media and/or facilitating higher permeance of gases through the first wall. The average fluid velocity of the liquid media and/or fluid in the liquid-containable compartment during normal operation may be no more than about $10 \text{ m}\cdot\text{s}^{-1}$, about $5 \text{ m}\cdot\text{s}^{-1}$, about $4 \text{ m}\cdot\text{s}^{-1}$, about $3 \text{ m}\cdot\text{s}^{-1}$, about $2.5 \text{ m}\cdot\text{s}^{-1}$, about $2 \text{ m}\cdot\text{s}^{-1}$, about $1.5 \text{ m}\cdot\text{s}^{-1}$, typically no more than about $1 \text{ m}\cdot\text{s}^{-1}$. The average flow velocity may be at least about $0.01 \text{ m}\cdot\text{s}^{-1}$, about $0.05 \text{ m}\cdot\text{s}^{-1}$, about $0.1 \text{ m}\cdot\text{s}^{-1}$, about $0.2 \text{ m}\cdot\text{s}^{-1}$, about $0.3 \text{ m}\cdot\text{s}^{-1}$, about $0.4 \text{ m}\cdot\text{s}^{-1}$, about $0.5 \text{ m}\cdot\text{s}^{-1}$, about $0.6 \text{ m}\cdot\text{s}^{-1}$,

about $0.7 \text{ m}\cdot\text{s}^{-1}$, about $0.8 \text{ m}\cdot\text{s}^{-1}$, about $0.9 \text{ m}\cdot\text{s}^{-1}$, about $1 \text{ m}\cdot\text{s}^{-1}$, about $1.5 \text{ m}\cdot\text{s}^{-1}$, suitably at least about $2 \text{ m}\cdot\text{s}^{-1}$, about $2.5 \text{ m}\cdot\text{s}^{-1}$, optionally at least about $3 \text{ m}\cdot\text{s}^{-1}$.

5 The maximum hydraulic pressure the liquid-containable compartment can withstand is a key performance characteristic that contributes to the maximum possible average flow velocity of liquid media. It also contributes to the maximum possible circuit length of the liquid media system comprising liquid-containable compartment(s). The higher the hydraulic pressure the liquid-containable compartment can withstand, the more photobioreactor units that can be connected and operated in series. Embodiments with a longer circuit length and/or more liquid containable compartments
10 connected in series allow for more efficient pumping as a system of the same volume, but with more units in parallel would require a higher liquid media volumetric flow rate to maintain the same flow velocity in the liquid-containable compartments. Furthermore, embodiments with a longer liquid circuit and/or more units connected in series would also have a larger proportion of the total volume of the liquid media circuit contained within the liquid-containable compartments. This would result in a higher
15 proportion of the volume of the circuit being exposed to light at any time, improving the efficiency of the system. The ability of embodiments of this invention to withstand hydraulic pressure is fundamental for utilising the advantages above and enabling a system that is large enough to feasibly operate at an industrial scale.

20 In certain embodiments, the maximum operating hydraulic pressure in the circuit of liquid-containing compartments may be up to about 10 bar, about 9 bar, about 8 bar, about 7, bar, about 6 bar, about 5 bar, about 4 bar, about 3 bar, about 2.5 bar, about 2 bar, about 1.5 bar, typically no more than about 1 bar. The maximum operating hydraulic pressure may be at least about 0.01 bar, about 0.05 bar, about 0.1 bar, about 0.2 bar, about 0.5 bar, about 1 bar, about 1.5 bar, suitably at least about 2 bar. Suitably
25 the hydraulic pressure may be at least 0.01 bar and up to 10 bar. Typically, the hydraulic pressure may be at least 0.05 bar and up to 7 bar. Optionally the hydraulic pressure may be at least 0.1 bar and up to 5 bar.

In certain embodiments, the maximum hydraulic pressure the liquid-containing compartment can withstand may be up to about 10 bar, about 9 bar, about 8 bar, about 7, bar, about 6 bar, about 5 bar, about 4 bar, about 3 bar, about 2.5 bar, about 2 bar, about 1.5 bar, typically no more than about 1 bar. The maximum hydraulic pressure the liquid-containing compartment can withstand may be at least about 0.01 bar, about 0.05 bar, about 0.1 bar, about 0.2 bar, about 0.5 bar, about 1 bar, about 1.5 bar, suitably at least about 2 bar. Suitably the hydraulic pressure may be at least 0.01 bar and up to 10 bar.
30 Typically, the hydraulic pressure may be at least 0.05 bar and up to 7 bar. Optionally the hydraulic pressure may be at least 0.1 bar and up to 5 bar.

Some embodiments of the invention can comprise an auxiliary subsystem that may constantly and/or intermittently circulate gas through the chamber(s) of the bioreactor unit(s) during normal operation for
40 any advantageous purpose which may include mixing and/or facilitating higher permeance of gases

through the first wall. The average gas velocity of the gas in the chamber(s) of the bioreactor unit(s) during normal operation may be no more than about $10\text{m}\cdot\text{s}^{-1}$, about $5\text{m}\cdot\text{s}^{-1}$, about $4\text{m}\cdot\text{s}^{-1}$, about $3\text{m}\cdot\text{s}^{-1}$, about $2.5\text{m}\cdot\text{s}^{-1}$, about $2\text{m}\cdot\text{s}^{-1}$, about $1.5\text{m}\cdot\text{s}^{-1}$, typically no more than about $1\text{m}\cdot\text{s}^{-1}$. The average flow velocity may be at least about $0.01\text{m}\cdot\text{s}^{-1}$, about $0.05\text{m}\cdot\text{s}^{-1}$, about $0.1\text{m}\cdot\text{s}^{-1}$, about $0.2\text{m}\cdot\text{s}^{-1}$, about $0.3\text{m}\cdot\text{s}^{-1}$, about $0.4\text{m}\cdot\text{s}^{-1}$, about $0.5\text{m}\cdot\text{s}^{-1}$, about $0.6\text{m}\cdot\text{s}^{-1}$, about $0.7\text{m}\cdot\text{s}^{-1}$, about $0.8\text{m}\cdot\text{s}^{-1}$, about $0.9\text{m}\cdot\text{s}^{-1}$, about $1\text{m}\cdot\text{s}^{-1}$, about $1.5\text{m}\cdot\text{s}^{-1}$, suitably at least about $2\text{m}\cdot\text{s}^{-1}$, about $2.5\text{m}\cdot\text{s}^{-1}$, optionally at least about $3\text{m}\cdot\text{s}^{-1}$.

In certain embodiments pressure within the chamber(s) comprised within the bioreactor system may be controlled to be no more than about 10 bar, about 8 bar, about 6 bar, about 4 bar, about 2 bar, about 1 bar, about 0.5 bar, about 0.2 bar, about 0.1 bar, about 0 bar, about -0.1 bar, typically no more than about -0.2 bar. The pressure within the chamber may be at least about -1 bar, about -0.5 bar, about -0.2 bar, about -0.1 bar, about 0 bar, about 0.1 bar, about 0.2 bar, suitably at least about 0.5 bar, about 1 bar, about 2 bar, about 5 bar.

In certain embodiments, the maximum pressure the chamber is be able to withstand may be no more than about 10 bar, about 8 bar, about 6 bar, about 4 bar, about 2 bar, about 1 bar, about 0.5 bar, about 0.2 bar, about 0.1 bar, about 0 bar, about -0.1 bar, typically no more than about -0.2 bar. The maximum pressure the chamber is be able to withstand may be at least about -1 bar, about -0.5 bar, about -0.2 bar, about -0.1 bar, about 0 bar, about 0.1 bar, about 0.2 bar, suitably at least about 0.5 bar, about 1 bar, about 2 bar, about 5 bar.

The organisms contained within the liquid-containable compartments of the photobioreactor systems described in specific embodiments are typically capable of performing photosynthesis or other reactions that are dependent upon the presence of an electromagnetic energy source. Any microorganism that is capable of photosynthesis is referred to herein as a photosynthetic microorganism. In a suitable embodiment, the photosynthetic microorganism is selected from micro-algae (such as green, blue-green, golden and red algae), phytoplankton, dinoflagellates, diatoms, bacteria and cyanobacteria, such as *Spirulina* sp. The microorganism may be a wild-type or genetically-modified and/or genetically-engineered strain. A single device according to embodiments of the invention may comprise one or more different types of organisms.

Typically, at least one microorganism is a *Haematococcus* sp., *Haematococcus pluvialis*, *Chlorella* sp., *Chlorella autotrophica*, *Chlorella vulgaris*, *Scenedesmus* sp., *Synechococcus* sp., *Synechococcus elongatus*, *Synechocystis* sp., *Arthrospira* sp., *Arthrospira platensis*, *Arthrospira maxima*, *Spirulina* sp., *Chlamydomonas* sp., *Chlamydomonas reinhardtii*, *Dysmorphococcus* sp., *Geitlerinema* sp., *Lyngbya* sp., *Chroococcidiopsis* sp., *Calothrix* sp., *Cyanothece* sp., *Oscillatoria* sp., *Gloeotheca* sp., *Microcoleus* sp., *Microcystis* sp., *Nostoc* sp., *Nannochloropsis* sp., *Anabaena* sp., *Phaeodactylum* sp., *Phaeodactylum tricornutum*. *Dunaliella salina*, some *Arthrospira platensis*, some *Nannochloropsis* sp. and *Synechococcus marinus* are typical microorganisms in embodiments where the liquid media passing through the channels in the device comprises sea water, salty water or brine. Other possible

photosynthetic microorganisms of this kind include members of groups such as *Bracteococcus*, *Chlorella*, *Parachlorella*, *Prototheca*, *Pseudochlorella*, and *Scenedesmus*. Other possibilities include *Achnanthes orientalis*, *Agmenellum*, *Amphiprora hyalina*, *Amphora coffeiformis*, *Amphora coffeiformis lineae*, *Amphora coffeiformis punctata*, *Amphora coffeiformis taylori*, *Amphora coffeiformis tenuis*,
5 *Amphora delicatissima*, *Amphora delicatissima capitata*, *Amphora sp.*, *Anabaena*, *Ankistrodesmus*, *Ankistrodesmus falcatus*, *Boekelovia hooglandii*, *Borodinella sp.*, *Botryococcus braunii*, *Botryococcus sudeticus*, *Bracteococcus minor*, *Bracteococcus medionucleatus*, *Carteria*, *Chaetoceros gracilis*, *Chaetoceros muelleri*, *Chaetoceros muelleri subsalsum*, *Chaetoceros sp.*, *Chlorella anitrata*, *Chlorella Antarctica*, *Chlorella aureoviridis*, *Chlorella candida*, *Chlorella capsulate*, *Chlorella desiccata*, *Chlorella ellipsoidea*, *Chlorella emersonii*, *Chlorellafusca*, *Chlorellafusca var. vacuolata*, *Chlorella glucotropha*,
10 *Chlorella infusionum*, *Chlorella infusionum var. actophila*, *Chlorella infusionum var. auxenophila*, *Chlorella kessleri*, *Chlorella lobophora (strain SAG 37.88)*, *Chlorella luteoviridis*, *Chlorella luteoviridis var. aureoviridis*, *Chlorella luteoviridis var. lutescens*, *Chlorella miniata*, *Chlorella minutissima*, *Chlorella mutabilis*, *Chlorella nocturna*, *Chlorella ovalis*, *Chlorella parva*, *Chlorella photophila*, *Chlorella pringsheimii*, *Chlorella protothecoides* (including any of UTEX strains 1806, 411, 264, 256, 255, 250, 249, 31, 29, 25), *Chlorella protothecoides var. acidicola*, *Chlorella regularis*, *Chlorella regularis var. minima*, *Chlorella regularis var. umbricata*, *Chlorella reisiigii*, *Chlorella saccharophila*, *Chlorella saccharophila var. ellipsoidea*, *Chlorella salina*, *Chlorella simplex*, *Chlorella sorokiniana*, *Chlorella sp.*, *Chlorella sphaerica*, *Chlorella stigmatophora*, *Chlorella vanniellii*, *Chlorella vulgaris*, *Chlorella vulgarisf*
20 *tertia*, *Chlorella vulgaris var. autotrophica*, *Chlorella vulgaris var. viridis*, *Chlorella vulgaris var. vulgaris*, *Chlorella vulgaris var. vulgarisf tertia*, *Chlorella vulgaris var. vulgarisf viridis*, *Chlorella xanthella*, *Chlorella zofingiensis*, *Chlorella trebouxioidea*, *Chlorella vulgaris*, *Chlorococcum infusionum*, *Chlorococcum sp.*, *Chlorogonium*, *Chroomonas sp.*, *Chrysosphaera sp.*, *Cricosphaera sp.*, *Cryptocodium cohnii*, *Cryptomonas sp.*, *Cyclotella cryptica*, *Cyclotella meneghiniana*, *Cyclotella sp.*,
25 *Dunaliella sp.*, *Dunaliella bardawil*, *Dunaliella bioculata*, *Dunaliella granulate*, *Dunaliella maritime*, *Dunaliella minuta*, *Dunaliella parva*, *Dunaliella peircei*, *Dunaliella primolecta*, *Dunaliella salina*, *Dunaliella terricola*, *Dunaliella tertiolecta*, *Dunaliella viridis*, *Eremosphaera viridis*, *Eremosphaera sp.*, *Ellipsoidon sp.*, *Euglena*, *Franceia sp.*, *Fragilaria crotonensis*, *Fragilaria sp.*, *Gleocapsa sp.*, *Gloeothamnion sp.*, *Hymenomonas sp.*, *Haematococcus pluvialis*, *Haematococcus sp.*, *Isochrysis aff galbana*, *Isochrysis galbana*, *Lepocinclis*, *Micractinium*, *Micractinium (UTEX LB 2614)*, *Monoraphidium minutum*, *Monoraphidium sp.*, *Nannochloris sp.*, *Nannochloropsis salina*, *Nannochloropsis sp.*, *Navicula acceptata*, *Navicula biskanterae*, *Navicula pseudotenelloides*, *Navicula pelliculosa*, *Navicula saprophila*, *Navicula sp.*, *Nephrochloris sp.*, *Nephroselmis sp.*, *Nitzschia communis*, *Nitzschia alexandrina*, *Nitzschia communis*, *Nitzschia dissipata*, *Nitzschiafrustulum*, *Nitzschia hantzschiana*,
30 *Nitzschia inconspicua*, *Nitzschia intermedia*, *Nitzschia microcephala*, *Nitzschia pusilla*, *Nitzschia pusilla elliptica*, *Nitzschia pusilla monoensis*, *Nitzschia quadrangular*, *Nitzschia sp.*, *Ochromonas sp.*, *Oocystis parva*, *Oocystis pusilla*, *Oocystis sp.*, *Oscillatoria limnetica*, *Oscillatoria sp.*, *Oscillatoria subbrevis*, *Parachlorella kessleri*, *Pascheria acidophila*, *Pavlova sp.*, *Phagus*, *Phormidium sp.*, *Platymonas sp.*, *Pleurochrysis carterae*, *Pleurochrysis dentate*, *Pleurochrysis sp.*, *Prototheca wickerhamii*, *Prototheca stagnora*, *Prototheca portoricensis*, *Prototheca moriformis*, *Prototheca zopfii*, *Pseudochlorella aquatica*,
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Pyramimonas sp., *Pyrobotrys*, *Rhodococcus opacus*, *Sarcinoid chrysophyte*, *Scenedesmus armatus*,
Schizochytrium, *Spirogyra*, *Spirulina platensis*, *Stichococcus* sp., *Synechococcus* sp., *Tetraedron*,
Tetraselmis sp., *Tetraselmis suecica*, *Thalassiosira weissflogii*, and *Viridiellafridericana*,
Euglenophyceae, *Prasinophyceae*, *Eustigmatophyceae*, *Bacillariophyceae*, *Prymnesiophyceae*,
5 *Pinguiphyceae*, *Dinophyceae*, *Trebouxiophyceae*, *Bicosoecophyceae*, *Katablephariophyceae*,
Chlorophyceae, *Haptophyceae*, *Raphidophyceae*, *Chrysophyceae*, *Coscinodiscophyceae*, *Alveolata*,
Bangiophyceae, *Rhodophyceae*, *Schizotrium* sp., *Crypthecodinium* sp., *Phaeodactylum* sp. and
Odontella sp., *Odontella aurita*, *Botryococcus* genus, *Botryococcus sudeticus*, *Botryococcus braunii*,
Chlamydomonas sp., *Chlamydomonas caudata*, *Chlamydomonas ehrenbergii*, *Chlamydomonas*
10 *elegans*, *Chlamydomonas moewusii*, *Chlamydomonas nivalis*, *Chlamydomonas ovoidae*,
Chlamydomonas reinhardtii, *Chlamydomonas mundane*, *Chlamydomonas dehoryana*,
Chlamydomonas cuiieus, *Chlamydomonas noctigama*, *Chlamydomonas auiato*, *Chlamydomonas*
marviani, *Chlamydomonas proboscigera*. In some embodiments, such organisms may be one or more
of *Haematococcus* sp., *Haematococcus pluvialis*, *Chlorella* sp., *Chlorella autotraphica*, *Chlorella*
15 *vulgaris*, *Scenedesmus* sp., *Synechococcus* sp., *Synechococcus elongatus*, *Synechocystis* sp.,
Arthrospira sp., *Arthrospira platensis*, *Arthrospira maxima*, *Spirulina* sp., *Dysmorphococcus* sp.,
Geitlerinema sp., *Lyngbya* sp., *Chroococcidiopsis* sp., *Calothrix* sp., *Cyanothecae* sp., *Oscillatoria* sp.,
Gloeothecae sp., *Microcoleus* sp., *Microcystis* sp., *Nostoc* sp., *Nannochloropsis* sp., *Anabaena* sp.,
Phaeodactylum sp., *Phaeodactylum tricornutum*, *Dunaliella salina*, some *Arthrospira platensis*, some
20 *Nannochloropsis* sp. and *Synechococcus marinus*. In particular, *Prototheca*, *Chlorella*, *Parachlorella*,
Pseudochlorella, *Scenedesmus*, *Amphora* sp., *Anabaena*, *Chlorella aureoviridis*, *Chlorella vulgaris*,
Dunaliella sp., *Dunaliella bardawil*, *Dunaliella salina*, *Euglena*, *Haematococcus pluvialis*,
Haematococcus sp., *Nannochloropsis salina*, *Nannochloropsis* sp., *Nitzschia communis* *Oscillatoria* sp.,
Scenedesmus armatus, *Schizochytrium*, *Spirogyra*, *Spirulina platensis*, *Stichococcus* sp.,
25 *Synechococcus* sp., *Tetraedron*, *Tetraselmis* sp., *Euglenophyceae*, *Odontella aurita*, *Botryococcus*
genus, *Chlamydomonas* sp., and *Chlamydomonas reinhardtii*, *Porphyridium cruentum*,
Porphyridium sp., are contemplated.

Diatom species can include *N. frigida*, *Nitzschia kerguelensis*, *N. lacuum*, and in particular
30 *Phaeodactylum* sp., *Phaeodactylum Tricornutum*, *Nitzschia* sp., *Cyclotella* sp., and *Cyclotella*
meneghiniana, and diatom classes like *Bacillariophyceae*, *Coscinodiscophyceae*, and *Naviculales*.

Plant species, in particular aquatic plant species including some green algae, may be cultured in
devices and methods according to the invention. Whole plant organisms may be used where
35 appropriate. Suitable species can include members of the duckweed family, *Araceae*, spotless
watermeal, rootless duckweed, *Lemnaceae*, *Lemna thalli*, *Lemna trisulca*, *Spirodela* sp., *Landoltia* sp.,
Lemna gibba, *Lemna minor*, *Lemna aequinoctialis*, *Lemna valdiviana*, *Lemna obscura*, 35 *Spirodela*
polyrhiza, *Wolffia arrhiza*, *Wolffia* sp., and *Spirodela* sp. In particular, *Lemnaceae*, *Wolffia arrhiza* and
Wolffia sp. are contemplated.

Plankton is a general term for ocean microfauna and microflora. Examples for use in the present invention include coccolithophores, dinoflagellates, metazoan plankton, and protozoan plankton, and in particular *Emiliana* sp. such as *Emiliana huxleyi*.

- 5 Some photosynthetic organisms, whether native strains or genetically modified or genetically engineered strains, can have the ability to uptake air-pollutants such as NO₂ (and other NO_x such as NO, N₂O₂, N₂O₃, N₂O₅), SO₂ (and other SO_x such as S₂O₂, SO, SO₃), VOCs, NH₃, or 'greenhouse' gases other than CO₂ such as N₂O. If so, these gases can be conveyed into the chamber to then be transferred into the liquid media by permeating through the first wall composite membrane. These gases
10 can also be derived from and/or be contained within effluent gases.

- The liquid media and/or gas temperature control can be of any type known to the skilled person; typically, it comprises a cooling and/or heating component which is suitably installed around parts of the conduits and/or on the tanks and/or around the bioreactor unit sections and/or before the gas-inlet
15 of the chamber and/or inside the chamber and/or around or inside the reservoir. The cooling and/or heating components can be of any type, and suitably can comprise heat-exchange mechanisms performed by heat exchangers in fluid communication with the liquid-containable compartment, and/or chamber of the bioreactor unit(s), and/or system. The heat exchangers can be of any suitable type, such as heat exchangers between liquid and gas, heat exchangers between two liquids, heat
20 exchangers between two gases, such as shell and tube, flat plate, double tube, tube in tube heat exchangers, air conditioning units (AC). In particular, it is envisioned that heat exchange may be used to maintain optimum liquid media temperature for the photosynthetic microorganisms. Excess heat from the liquid media generated by physiological processes or high environmental temperatures or radiation may be used to heat water for domestic or industrial purposes, or water from sources such as drain
25 water, storm water, sewage water and/or grey water may be used to remove excess heat. Alternatively, cooling fluid can be recycled and the temperature maintained below the temperature of the liquid media using a cooling tower, chiller or other equipment for lowering the temperature of a liquid. Likewise, liquid media and/or gas may be heated when necessary using heat generated from domestic or industrial sources, or other appropriate equipment such as gas boilers, electric boilers, heat pumps, immersion
30 heaters. Heat exchange is suitably carried out in the location of the auxiliary subsystem, before the liquid media and/or gas arrives in the bioreactor unit(s).

- In some embodiments, water or other coolant liquids can be sprayed or applied as a fog, spray, droplets or mist to the external surfaces of the bioreactor units to provide for thermal control of the system by
35 evaporation and/or by any other suitable means. This is of particular benefit in hotter climates where midday temperatures may impact the suitable operating ranges for organisms that are being cultured within the bioreactor system. The coolant spray/fog system may be under the control of the auxiliary subsystem which monitors the temperature of the liquid media inside the liquid-containable compartment. Alternatively, or in addition, the coolant spray/fog system may be subject to an auxiliary
40 subsystem which can monitor the temperature within the chamber. A combination of both set ups is

also feasible. Run off coolant liquid may be collected and recycled. Water vapour comprised within the chamber atmosphere may be collected as condensation and/or via dehumidification apparatus comprised within an auxiliary subsystem and routed to use within the coolant spray/fog system.

- 5 In some other embodiments, the liquid media temperature is controlled by controlling the temperature of the gaseous atmosphere within the chamber by conduction and/or convection and/or by any other suitable means. The temperature of the gaseous atmosphere within the chamber is controlled by an auxiliary subsystem and can be heated and/or cooled by any suitable means. Typically, the atmosphere is cooled by an air conditioning apparatus which is comprised within an auxiliary subsystem that is connected to the chamber through an inlet and an outlet. In some embodiments the heat may be generated by electric heaters that convert an electric current into heat. Infrared light transmission onto transparent or semi-transparent conduits can also be a way to heat liquid media.

- 15 An artificial lighting system can be used that comprises any artificial light source types known to the skilled person, suitably the lighting system comprises LEDs, typically the artificial light source is designed and/or controlled to emit specific wavelengths of electromagnetic radiation (light) corresponding to the photosynthetically active radiation (PAR) needs of any phototrophic microorganisms contained within the device and/or to promote specific biological activity, thereby increasing the production of specific products in the biomass, for example by using LEDs that emit specific wavelengths. For example an LED-based light source can emit wavelengths between approximately 620 nm and 750 nm (red light) to promote the production in some organisms of pigments that absorb mostly red light, such as the pigment phycocyanin. Artificial lighting systems may be comprised within the bioreactor unit(s) and/or bioreactor system(s) that comprises arrays or strips of LEDs or optic fibres. The intensity and quality of the light emitted by the lighting systems could be controlled automatically (following inputs from any kind of sensors like PAR sensors, humidity sensors, temperature sensors, chemical sensors, pH sensors and so on) to promote specific microbial physiological activities and/or to respond to environmental changes and/or to increase or modify the biomass production. Similarly the amount of light transmission (either being natural or artificial light) through a 'switchable' or 'smart glass' material as discussed above can be automatically controlled for similar reasons.

- 35 In some embodiments an artificial lighting system may provide wavelengths of light which can be used to sterilise or disinfect part or all of the bioreactor unit(s) and/or chamber(s) of the invention. This can be as, or in addition to, a cleaning, disinfection or sterilisation process as discussed below. In particular such lighting systems may produce ultraviolet (UV) radiation which can kill or damage bacteria and other unwanted contaminant organisms.

- 40 According to one specific embodiment of the invention, when the biomass concentration in the liquid media comprised within the liquid-containable compartment reaches the desired level, a 3-way valve and/or multiple valves direct the flow into a biomass-separator which separates at least a part of the

biomass from the liquid media, the isolated biomass proceeds into a receptacle for additional processing, while the liquid media is directed back into the bioreactor unit(s). The biomass separator is used to separate biomass from the liquid media of the bioreactor unit(s). It could additionally or alternatively be used to separate metabolites from the liquid media. Suitable separators can be classified into two categories: mechanical and non-mechanical. Mechanical biomass separators use physical forces such as centrifugation, filtration, and sedimentation to separate biomass from the liquid media (liquid phase). Mechanical biomass separators have the advantages of being fast, efficient, and scalable. They can handle large volumes of biomass and separate it into different fractions with high purity and quality. However, mechanical biomass separators also have some disadvantages, when used with delicate organisms or cellular material as mechanical separation may disrupt cells or reduce the biomass value by causing mechanical stress or abrasion. In such instances, it is favoured to utilise non-mechanical biomass separators which rely on gravity, electrical or optical properties of cells to separate biomass from the liquid media (liquid phase). Exemplary non-mechanical biomass separators may include one or more of: gravity separators, membrane filters, adsorption columns, and cell sorting (e.g. FACS). It will be appreciated by the skilled person that the appropriate biomass separation apparatus be selected for the type of organism intended for culture within the bioreactors of the invention.

It may be necessary to regenerate the liquid media filtered by the biomass-separator before returning it to the bioreactor unit(s). In some cases the liquid media will contain metabolites produced by the cultured organisms; these metabolites may need to be destroyed to maintain optimum growth rates, as in many cases the excessive presence of such metabolites causes a reduction in growth. Such metabolites can be removed utilising filtration systems, UV treatment and/or chemical treatments, among any other suitable means. Alternatively the liquid media filtered from the biomass separation process can be discarded. This action of directing the flow into the biomass-separator can be performed continuously and/or periodically and for a predetermined period of time before the valve changes the flow path into the bioreactor unit(s) again. This timing can be optimised with respect to each application, the microorganism used, the surrounding environment and physical location of the device. In another embodiment instead of a binary switch, the valve can change the aperture of the channel thereby controlling the flow rate and amount of liquid media that is delivered to the biomass separation process.

Nutrients can be continuously and/or periodically introduced in the system directly into the reservoir and/or any other suitable parts of the bioreactor system. Water and/or organisms in a liquid media, or cleaning fluid, can be similarly introduced.

All sorts of other system components can be utilised, for example a controllable pressure valve or pressure regulator can be placed in the bioreactor system, in this example the pressure valve can control the volumetric change of the bioreactor unit(s) through the effects of changes in the liquid or gas pressure. Some valves can control the flow rate into the bioreactor unit(s).

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One or more sensors can be embedded entirely or partially in the bioreactor unit(s), in the tanks or conduits auxiliary subsystem, and/or in control or support structures and/or be attached to the inside or outside of external layers or on the surface of internal additional components. Sensors can permit the monitoring of the environment inside the system, particularly within the liquid-containable compartment, in order to enable control of parameters including, but not limited to, liquid media flow rate, liquid media quality, nutrient levels, temperature, biomass extraction rate, gas mixture, and illumination intensity and/or optical shielding to reduce risk of photobleaching. The purpose of this control is to optimise the photosynthetic efficiency of the photosynthetic microorganisms contained within the device, and/or to stimulate specific metabolic/microbial activities and hence to optimise the efficiency of generation of biomass and/or modify its composition.

Embodiments and/or the auxiliary subsystem of the invention can include embedded sensors which can be used, for example, to monitor chemical concentrations such as CO₂ concentrations and/or O₂ concentrations in liquid media and/or chamber atmosphere; and/or to monitor temperature and other environmental and biological parameters, such as toxicity levels and/or to monitor the biomass concentration and/or the total cell density and/or the viable cell density and/or the activity of the organisms in the liquid media.

Similarly, sensors can permit the monitoring of the gaseous atmosphere inside the chamber of the bioreactor unit, in order to enable control of parameters including, but not limited to, gas flow rate, quality, atmospheric composition, temperature, optical clarity and humidity. These sensors can communicate with an auxiliary subsystem. Supplementary air and/or air enriched with CO₂ and/or other gases can optionally be introduced into the inlet to the chamber, if required.

Vents can be installed in supply or exhaust conduits to remove gas that has accidentally entered the hydraulic system (i.e. unwanted gas that is trapped within the liquid-containable compartment), for example during installation of the system, and are typically located in the highest location of the system to facilitate the expulsion of undesirable gas. Such gas may be vented externally (i.e., outside the bioreactor system) or into the chamber.

Sensors comprising transparent/translucent electrically conductive materials and/or any other electrically conductive materials can be provided on any surface of the chamber (inside or outside the chamber) to monitor conditions such as irradiance levels, temperature, humidity or other environmental conditions. These sensors or similar sensors, if located inside the chambers may be used to detect gas concentration levels, humidity and/or temperature in the chamber.

A cleaning procedure can be used to clean and/or sterilise the bioreactor unit(s) and/or any associated liquid-containable compartments and/or the tank(s) and/or all the auxiliary subsystems and/or the chamber(s). A cleaning procedure aims to destroy and remove any and all debris, sedimentation, biofilms and other undesirable material within the bioreactor system. Cleaning can take place when it

is necessary to flush the bioreactor system through, to collect all biomass in the bioreactor system, or for temporary shutdowns. A "cleaning fluid" can be made of any compound known to the skilled person. It may comprise hydrogen peroxide, ethanol, water, saltwater, detergents, bleach, surfactants, alkali, it may be CIP100 or CIP150 from Steris™, it may be Mip SMA from Ecolab™, or any other suitable cleaning composition. The cleaning fluid can enter the system through specific conduits (inlets) in any point of the bioreactor system and can exit at any point of the bioreactor system (outlets) to permit cleaning in specific locations only, if desired, instead of cleaning the entire bioreactor system. Typically, a cleaning liquid like CIP100 is heated to desired temperature, typically over 30°C, and a turbulent flow is maintained for a determined period of time. Flow velocity can be increased for this purpose by changing the flow configuration as illustrated in the embodiment included in Figure 7.

In certain embodiments, the cleaning temperature of the fluid cleaning agent may be no more than about 100°C, about 90°C, about 80°C, about 70°C, about 60°C, about 50°C, about 40°C, typically no more than about 30°C. The cleaning temperature of the fluid cleaning agent may be at least about 1°C, about 10°C, about 20°C, about 30°C, about 40°C, suitably at least about 50°C, about 60°C, optionally at least about 70°C. Typically, this temperature is between about 40°C and about 60°C, suitably between about 30°C and about 70°C, optionally between about 20°C and about 70°C, alternatively between about 20°C and about 80°C.

The cleaning fluid may also be gaseous in nature and can comprise steam, heated air, vapour of any suitable type and/or water vapour, suitably supplied at temperatures above 100°C and/or above 120°C.

For liquid cleaning agents, turbulence aids the removal of debris, sedimentation, biofilms and other undesirable material. In certain embodiments, the Reynolds number of the cleaning fluid inside the liquid-containable compartment and/or the chamber during cleaning may be no more than about 2,000,000, about 1,000,000, about 500,000, about 250,000, about 100,000, about 75,000, about 50,000, about 20,000, about 10,000, or no more than about 5000. The Reynolds number may be at least about 1000, about 2000, about 4000, about 5000, about 10,000, about 20,000, suitably at least about 50,000, about 75,000, about 100,000, optionally at least about 250,000.

The turbulence of the cleaning fluid is related to flow velocity. In some embodiments, for liquid cleaning agents, the flow velocity of the cleaning fluid inside the liquid-containable compartment during cleaning may be no more than about 10 m·s⁻¹, about 5 m·s⁻¹, about 4 m·s⁻¹, about 3 m·s⁻¹, about 2.5 m·s⁻¹, about 2 m·s⁻¹, about 1.5 m·s⁻¹, typically no more than about 1 m·s⁻¹. The flow velocity may be at least about 0.05 m·s⁻¹, about 0.1 m·s⁻¹, about 0.2 m·s⁻¹, about 0.5 m·s⁻¹, about 1 m·s⁻¹, about 1.5 m·s⁻¹, suitably at least about 2 m·s⁻¹, about 2.5 m·s⁻¹, optionally at least about 3 m·s⁻¹. Typically, this flow velocity is between about 0.5 m·s⁻¹ and about 1.5 m·s⁻¹, optionally between about 0.5 m·s⁻¹ and about 2 m·s⁻¹, alternatively between about 0.5 m·s⁻¹ and about 3 m·s⁻¹.

A sterilisation procedure aims to destroy and remove any and all organisms within the system, for permanent shutdown, non-permanent shutdown or decontamination. This approach may include pumping a "sterilising fluid" into the system, for example steam, or a low-temperature dry vapour of hydrogen peroxide, or a sterilising liquid, among other suitable sterilising fluids. A "sterilising fluid" can be made of any compound known to the skilled person. It may comprise sodium hypochlorite, acids, or any other suitable sterilising composition.

Sterilisation may also comprise the use of electromagnetic radiation, typically UV radiation, to disinfect any of the components of the invention, as discussed above. An advantage of a hydrogen peroxide dry vapour is that it does not require high pressure for effective sterilisation. Where it is necessary to pressurise a sterilisation fluid such as steam for effective sterilisation, it may be advisable to first pressurise the chamber atmosphere and subsequently the inside of the liquid-containable compartment, in order to avoid damage or bursting of the bioreactors.

Typically for cleaning and sterilisation, if carried out using a liquid, the entire volume of the liquid-containable compartment(s) would need to be filled with the required fluid and this fluid circulated for an amount of time. Therefore enough cleaning or sterilisation fluid for the entire volume of the system to be cleaned or sterilised needs to be prepared. To reduce this volume, the liquid-containable compartments of the bioreactor system might be cleaned and sterilised in sections, one after the other.

An advantage of some embodiments of the invention is that biomass can be generated continuously within the bioreactor system and can be harvested on a continuous and/or semi-continuous and/or intermittent basis. In other embodiments of the invention the biomass can be generated semi-continuously and/or intermittently (for example, in the case of pure photosynthetic organism that don't generate biomass in the absence of visible light) and can be harvested on a continuous and/or semi-continuous and/or intermittent basis.

It will be appreciated by the skilled person that operation of the bioreactor systems of the invention may vary depending upon the preferred configuration to maximise biomass production under geographical, environmental or process performance constraints. As such, routine workshop modifications to the setup and operations are considered to fall within the remit of the present invention.

Biomass collection

An advantage of some embodiments of the invention is that biomass can be generated continuously within the bioreactor system and can be harvested on a continuous and/or semi-continuous and/or intermittent basis. In other embodiments of the invention the biomass can be generated semi-continuously and/or intermittently (for example, in the case of pure photosynthetic organism that don't generate biomass in the absence of visible light) and can be harvested on a continuous and/or semi-continuous and/or intermittent basis.

The biomass which can be collected from some embodiments of the invention varies depending on the setup and condition of the devices of the invention, the organisms comprised within the bioreactor unit(s), the desires of the users of the invention, and the nature of the separation and treatment of the biomass. The general types of biomass which can be collected from the invention in various
5 embodiments can include, but is not limited to: metabolic products of the cells; secreted proteins and other cellular products; products of photosynthesis, aerobic respiration and/or anaerobic respiration; cell contents including cell organelles, cell membranes, cell walls; macromolecules including polysaccharides such as starches and cellulose, fats, phospholipids, proteins, glycoproteins, glycolipids
10 and/or nucleic acids; carbohydrates such as monosaccharides, disaccharides and/or oligosaccharides; fatty acids and/or glycerol; whole organisms including cells, agglomerations and/or colonies and/or trichomes of unicellular organisms or whole multicellular organisms or parts thereof.

The applications of biomass produced by embodiments of the invention can include, but is not limited
15 to, food feeds for animals, plants or any organisms; feeds suitable for aquatic use such as for aquatic animals or other organisms; pharmaceuticals; cosmetics; fuels; biochemical; oils; oleochemicals, substitutes for mineral oils and mineral oil products; manufactory oils; and vaccines.

Biomass accumulates in the liquid media within the liquid-containable compartment(s). The biomass
20 can be harvested directly from the liquid media. Biomass is mostly formed in the system during travel of the liquid media through the liquid-containable compartment(s) of the bioreactor unit(s), as this is where it spends most time, and, in case of photosynthetic organisms, is supplied with light and CO₂. In order to release biomass, liquid media enters the device via the one or more inlets, passes through the one or more liquid-containable compartments and exits the device, together with biomass that is carried
25 in the flow, via the one or more outlets. The outlet can be connected to a suitable receptacle for receiving the harvested biomass. The accumulated, suspended biomass can be harvested directly from the collected liquid media. In other embodiments of this invention the biomass generated and in suspension in the liquid media is harvested directly from the liquid media. In other embodiments of this invention the biomass generated and in suspension in the liquid media is harvested directly from the liquid media
30 and is not mechanically or manually scraped from any internal surfaces of the liquid-containable compartment(s) other than by the hydraulic forces of the liquid media circulating within the liquid-containable compartment(s).

A particular advantage of the present invention is the ability for biomass to be harvested on a
35 continuous, semicontinuous or batch basis, due to the ability to continually, semi-continuously and/or intermittently circulate the liquid media through the bioreactor system. In certain embodiments, harvests can occur for example when a particular cell concentration and/or density is reached, which can be expressed in grams per litre. The cell concentration at harvest may be no more than about 300 g·L⁻¹, about 200 g·L⁻¹, about 100 g·L⁻¹, about 75 g·L⁻¹, about 50 g·L⁻¹, about 30 g·L⁻¹, about 20 g·L⁻¹, suitably
40 no more than about 10 g·L⁻¹, about 5 g·L⁻¹, typically no more than about 2 g·L⁻¹. The cell concentration

may be at least about 0.1 g·L⁻¹, about 0.5 g·L⁻¹, at least about 1 g·L⁻¹, at least about 2 g·L⁻¹, about 3 g·L⁻¹, about 4 g·L⁻¹, about 5 g·L⁻¹, about 6 g·L⁻¹, about 7 g·L⁻¹, about 8 g·L⁻¹, about 9 g·L⁻¹, about 10 g·L⁻¹, about 20 g·L⁻¹, about 30 g·L⁻¹, about 50 g·L⁻¹, about 75 g·L⁻¹, or at least about 100 g·L⁻¹.

- 5 In certain embodiments, if a percentage of the liquid media passing through the auxiliary subsystem after flowing through the bioreactor unit(s) is constantly harvested, and liquid media is added to the system to replace it at the same rate, a continuous harvest can be attained. Depending on the organism cultured, the volume of the bioreactor system, and the time taken for liquid media to flow through the entire system, any suitable amount can be harvested. In certain embodiments, a percentage of the liquid media passing through the auxiliary subsystem can be continuously, semi-continuously and/or
- 10 intermittently harvested by the auxiliary subsystem. In certain embodiments, the liquid media harvest removal flow rate and media addition flow rate, as a percentage of the liquid media flow rate at the outlet of the bioreactor unit(s), may be no more than about 100%, about 90%, about 70%, about 50%, suitably no more than about 30%, about 20%, about 10%, optionally no more than about 5%. The liquid
- 15 media harvesting removal flow rate and media addition flow rates, as a percentage of the liquid media flow rate at the outlet of the bioreactor unit(s), may be at least about 0.005%, about 0.01%, about 0.1%, about 1%, about 5%, suitably at least about 10%, about 20%, about 30%, about 40% about 50%, optionally at least about 70%, about 80%.
- 20 Figure 10a shows a schematic of an embodiment of the invention with the liquid-containable compartment 1002 connected to a pump 1055. Downstream of the pump are a series of flow sensors. 1050 measures the flow rate of the fluid circulating through the system. 1051 measures the flow rate of liquid media leaving the system from outlet 1053 and 1052 measures the flow rate of liquid media entering the system from inlet 1054. Provided the flow rates measured by 1051 and 1052 are
- 25 substantially equal and less than the fluid circulation flow rate measured by 1050, none of the liquid media added through inlet 1054 will exit directly through outlet 1053 before passing through the bioreactor unit 1005. 1051 and 1052 can be controlled to be the same, therefore substantially maintaining the volume of liquid media in the liquid-containable compartment 1002.
- 30 In certain embodiments, biomass can be harvested intermittently, on a semicontinuous basis. A percentage of the biomass can also be harvested on any suitable temporal basis, for example on an hourly, daily or weekly basis. In certain embodiments, the time between harvests may be no more than about 6 months, about 4 months, about 2 months, about 1 week, about 5 days, about 2 days, suitably no more than about 1 day, about 12 hours, about 6 hours. In certain embodiments, the time between
- 35 harvests may be at least about 0.1 second, about 1 second, about 1 minute, about 1 hour, about 2 hours, about 4 hours, about 6 hours, about 12 hours, suitably at least about 1 day, at least about 5 days, optionally at least about 1 week. The harvested volume can be replaced by the addition of liquid media (with or without additional organisms), and additional nutrients. Harvests can be regular, irregular, manually activated, automatically activated, harvests can be after a set period of time, or can
- 40 be triggered by reaching a certain organism density or biomass concentration or intended product

concentration. As above, the amount taken can vary appropriately, based on the bioreactor system process parameters, the organism and the bioreactor system. In certain embodiments, the volume harvested, as a percentage of the total liquid volume of the bioreactor system, may be no more than about 100%, about 98%, about 95%, about 90%, about 80%, about 70%, about 60%, about 50%, suitably no more than about 30%, about 20%, about 10%. In certain embodiments, the volume harvested over any 24 hours, as a percentage of the total liquid volume of the bioreactor system, may be at least about 0.001%, about 0.01%, about 0.1%, about 0.5%, about 1%, about 5%, suitably at least about 10%, about 20%, about 30%, optionally at least about 50%. In practice, repeated harvesting at close time intervals may be considered as a single harvesting. By way of example, successional harvesting of biomass in periods of less than one second between removal of aliquots is practically the same as continuous harvesting over a longer period.

Figure 10b shows a schematic of an embodiment of the invention with the liquid-containable compartment 1002 connected to a reservoir 1056 that contains an excess volume of liquid media and then to a pump. In this embodiment the removal and addition of liquid media can be carried out in sequence without changing the volume of liquid media in the liquid-containable compartment 1002. Instead, when liquid media is removed from 1053, the excess volume in the reservoir is removed. Subsequently, the replacement liquid media is added via 1054 and the excess volume is restored to the reservoir. Throughout the operations, the volume in the liquid-containable compartment 1002 remained the same. In other embodiments of the invention, the liquid media can be introduced in and/or removed from the reservoir 1056.

Alternatively, the embodiment shown in Figure 10a could be operated in a similar way. However, it does not include a reservoir with an excess volume of liquid media. Therefore, the volume of liquid media in the liquid-containable compartment 1002 will have to be less than its maximum capacity, after the liquid media is removed from the outlet 1053, before the replacement liquid media is added via inlet 1054.

Such continuous or semi-continuous methods have the benefit of a predictable and/or continual production of biomass, do not require new or additional organisms to be introduced into the bioreactor after harvesting, and can allow for reduced variability in product, in contrast to batch processes which are more common with standard fermenters. In a fermenter setup, the risk of contamination means that continuous processes are rarely suitable.

In certain embodiments, a batch process can be used and would involve harvesting substantially the entire volume of liquid media at substantially one time after a set time has elapsed, or a set density of organisms or biomass or product has been reached. This can involve draining substantially the entire system and/or flushing it through with replacement fluid. This approach can be used in conjunction with any continuous or semi-continuous methods, for example when it is required to clean the system or replace the cultured organisms.

Applications

5 The device of this invention can be utilised for many applications, primarily biomass production, but also carbon dioxide removal, the sequestration of nitrogen oxides or other gases, or where the removal of pollutants is needed, or where waste water treatment is needed, or even for aesthetic or decorative applications such as urban furniture or functional artistic installations. The device can thereby be used at locations such as warehouses, breweries, industrial buildings and the like. Similarly, the device can be used in conjunction with transportation vehicles, such as ships, aeroplanes, cars, trucks and other
10 road vehicles. The device can be used indoors and/or outdoors. In some embodiments, the devices of the invention can provide oxygen for devices which aim to supply increased oxygen to support the growth of heterotrophic and/or mixotrophic organisms, for example gas-permeable membrane bioreactors as described in WO2020/225709.

15 Suitable applications for the device of this invention can be any indoor and/or outdoor architectural applications including, but not limited to, being part of a building façade, roofs, sun-canopies, sun shades, windows, and/or indoor ceilings, indoor walls, or indoor floors. Thermal insulation can also be provided to these buildings by the invention.

20 Suitable applications for the device of this invention can be horizontal, vertical or inclined. For these applications the bioreactor unit(s) can be installed in any orientation and/or any position in respect to the ground or in respect to the direction of the Earth's gravitational force. For example, in certain embodiments of the invention, the bioreactor unit(s) can be installed substantially horizontally parallel to the ground or substantially vertically on a building's facade.

25 Suitable applications for the systems described herein can include intensive biomass production applications, including, but not limited to, outdoor intensive biomass production plants using mostly natural light sources, indoor intensive biomass production plants using artificial light sources and/or natural light sources, such as in greenhouses. The biomass can contain food ingredients and/or
30 additives and/or can be used as a protein source for human or animal consumption, or for cell cultures, plant or other fertilising purposes. Further suitable applications for the device of this invention can be together with infrastructures, including, but not limited to, urban infrastructures, motorways, bridges, industrial infrastructures, cooling towers, highways, underground infrastructures, traffic sound barriers, silos, water towers, or hangars.

35 Other suitable applications for the system of this invention can be in combination with waste treatment plants, including, but not limited to, wastewater treatment plants, municipal wastewater treatment plants, sewage anaerobic digestion treatments, manure anaerobic digestion treatments, anaerobic digesters or incinerators.

40

The system of this invention can remove pollutants and/or nutrients (such as nitrates and phosphates) directly from waste water streams which can be diverted inside the liquid-containable compartments. This is favourable in wastewater treatment applications and building/industrial applications where a partial and/or pre- treatment of water is demanded.

5

The system of this invention can be installed on or near to any kind of industrial, agricultural, farming, intensive farming (such as intensive fish farming), manufacture, refinery and/or energy production processes which can supply some or all of the gases for use within the chambers of the bioreactor system.

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The system of this invention can be installed inside any industrial machinery and/or vehicle where the chamber can be substantially composed by their body parts and where the system is used to produce biomass, and/or remove the carbon dioxide from the effluent gases produced by the industrial machinery and/or vehicles.

15

Non-phototrophic Bioreactor Operation

A non-phototrophic bioreactor refers to a type of bioreactor used for the cultivation and growth of organisms that do not rely on photosynthesis for their energy requirements. Unlike phototrophic organisms such as algae or cyanobacteria, which use light as their primary energy source, non-phototrophic organisms obtain energy from other sources such as organic compounds or inorganic chemicals.

Certain embodiments of the invention may comprise a non-phototrophic bioreactor system. These embodiments may comprise a first wall and a second wall. As light may not be required to reach the liquid media in the liquid-containable compartment to enable photosynthesis, the second wall may not necessarily be optically transmissible.

Non-phototrophic bioreactors can be designed to provide optimal conditions for the growth and metabolic activities of non-photosynthetic organisms. These bioreactors typically may comprise a vessel and/or a liquid-containable compartment(s) and/or a bioreactor unit(s) and/or container where the organisms are cultivated and an auxiliary subsystem for controlling various environmental parameters such as temperature, pH, nutrient concentrations, and oxygen supply, and any other other suitable functions.

35

In an alternative embodiment of the present invention the bioreactor may be adapted for production of biomass from (micro)organisms or cell cultures that are not phototrophic taken from Bacteria, Archaea or Eukaryota taxonomy domains, as long as it can be supported in a suitable liquid medium.

The gas atmosphere within the chamber of the bioreactor unit may be modified to suit the needs of the specific requirements of the organism that is being cultured. For example, for aerobic/heterotrophic (micro)organisms an O₂ rich atmosphere may be favoured, with depletion of CO₂ also provided. Corresponding alterations to liquid media composition and the type of biomass harvesting are also organism dependent, however, such alterations are considered to be within the remit of the skilled artisan without requiring extensive departure from the embodiments of the invention as described herein.

More specifically, the cells and/or organisms that can be used in the invention can be part of the taxonomic groups and other defined groups including the following: Cyanobacteria, Protobacteria, Spirochaetes, Gram Positive bacteria, green filamentous bacteria such as Chloroflexia, Planctomycetes, *Bacteroides cytophaga*, *Thermotoga*, *Aquifex*, halophiles, Methanosarcina, Methanobacterium, Methanococcus, *Thermococcus celer*, Thermoproteus, Pyrodictium, Entamoebae, slime moulds such as Mycetozoa, Ciliates, Dinoflagellates, Dinophyceae, Trichomonads, Microsporidia, Diplomonads, Excavata, Amoebozoa, Choanoflagellates, Rhizaria, Foraminifera, Radiolaria, Diatoms, Stramenopiles, brown algae, red algae, green algae, snow algae, Haptophyta, Cryptophyta, Alveolata, Glaucophytes, phytoplankton, plankton, Percolozoa, Rotifera, and cells or whole organisms from animals, fungi or plants.

Suitable bacteria that can be used in the invention can include *Escherichia coli*, *Escherichia coli* BL21(DE3), *Escherichia sp.*, *Acetobacter sp.*, *Acetobacter xylinum*, *Arcina ventriculi*, *Zymomonas mobilis*, *Gluconobacter xylinus*, *Pseudomonas sp. #142*, *Microbacterium laevaniformans*, *Paenibacillus polymyxa*, *Bacillus licheniformis*, *Bacillus subtilis*, *Bacillus macerans*, *Streptococcus salivarius*, *Leuconostoc mesenteroides*, *Aerobacter levanicum*, Gammaproteobacteria and Alphaproteobacteria, *Vibrio sp.*, *Vibrio natriegens*, *Pseudomonas fluorescens*, *Caulobacter crescentus*, *Agrobacterium tumefaciens*, and *Brevundimonas diminuta*. Other suitable bacteria can include *Deinococcus sp.*, *Deinococcus radiodurans*, *Deinococcus geothermalis*, *D. cellulolysiticus*, *D. radiodurans*, *D. proteolyticus*, *D. radiopugnans*, *D. radio philus*, *D. grandis*, *D. indicus*, *D. frigens*, *D. saxicola*, *D. maricopensis*, *D. marmoris*, *D. deserti*, *D. murrayi*, *D. aerius*, *D. aerolatus*, *D. aerophilus*, *D. aetherius*, *D. alpini tundrae*, *D. altitudinis*, *D. apachensis*, *D. aquaticus*, *D. aquatilis*, *D. aquiradiocola*, *D. aquivivus*, *D. caeni*, *D. claudionis*, *D. ficus*, *D. gobiensis*, *D. hohokamensis*, *D. hopiensis*, *D. misasensis*, *D. navajonensis*, *D. papagomensis*, *D. peraridilitoris*, *D. pimensis*, *D. piscis*, *D. radiomollis*, *D. roseus*, *D. Sonorensis*, *D. wulumudiensis*, *D. xibeiensis*, *D. xinjiangensis*, *D. Yyavapaiensis* or *D. yunweiensis bacterium*. In particular, contemplated species include *Escherichia coli*, *Escherichia sp.*, *Acetobacter sp.*, *Zymomonas mobilis*, *Gluconobacter xylinus*, *Pseudomonas sp.*, *Microbacterium laevaniformans*, *Paenibacillus polymyxa*, *Bacillus licheniformis*, *Streptococcus Salivarius*, *Leuconostoc mesenteroides*, *Aerobacter levanicum*, Gammaproteobacteria and alphaproteobacteria, *Vibrio sp.*, *Pseudomonas fluorescens*, *Caulobacter crescentus*, *Agrobacterium tumefaciens*, *Brevundimonas diminuta*, *Deinococcus sp.*, *Meiothermus ruber*, and *Oceanithermus profundus*.

Pathogenic organisms can also be cultured in devices according to the invention, for example for use in vaccine production. Further bacteria which may be relevant include *Bacillus subtilis*, *Corynebacterium glutamicum*, *Saccharomyces cerevisiae*, *Zymomonas mobilis*, *Agrobacterium tumefaciens*, *Sinorhizobium meliloti*, *Rhodobacter sphaeroides*, *Paracoccus versutus*, *Pseudomonas fluorescens*,
5 *Pseudomonas putida*, *Salmonella enterica*, *Escherichia fergusonii*, *Yersinia pestis*, *Yersinia pseudotuberculosis*, *Yersinia enterocolitica*, *Shigella flexneri*, *Shigella sonnei*, *Shigella boydii*, *Shigella dysenteriae*, *Pectobacterium atrosepticum*, *Pectobacterium wasabiae*, *Erwinia tasmaniensis*, *Erwinia pyrifoliae*, *Erwinia amylovora*, *Erwinia billingiae*, *Buchnera aphidicola*, *Enterobacter* sp. 638, *Enterobacter cloacae*, *Enterobacter asburiae*, *Enterobacter aerogenes*, *Cronobacter sakazakii*,
10 *Cronobacter turicensis*, *Klebsiella pneumoniae*, *Klebsiella variicola*, *Klebsiella oxytoca*, *Citrobacter koseri*, *Citrobacter rodentium*, *Serratia proteamaculans*, *Serratia* sp. AS12, *Proteus mirabilis*, *Edwardsiella ictaluri*, *Edwardsiella tarda*, *Candidatus Hamiltonella defense*, *Dickeya dadantii*, *Dickeya zeae*, *Pantoea anantis*, *Pantoea* sp. At-9b, *Pantoea vagans*, *Rahnella* sp. Y9602, *Haemophilus parasuis*, *Haemophilus parainfluenzae*, *Pasteurella multocida*, *Aggregatibacter aphrophilus*,
15 *Aggregatibacter actinomycetemcomitans*, *Vibrio cholera*, *Vibrio vulnificus*, *Vibrio parahaemolyticus*, *Vibrio harveyi*, *Vibrio splendidus*, *Photobacterium profundum*, *Vibrio anguillarum*, *Shewanella oneidensis*, *Shewanella denitrificans*, *Shewanella frigidimarina*, *Shewanella amazonensis*, *Shewanella baltica*, *Shewanella loihica*, *Shewanella* sp. ANA-3, *Shewanella* sp. MR-7, *Shewanella putrefaciens*, *Shewanella sediminis*, *Shewanella* sp. MR-4, *Shewanella* sp. W3-18-1, *Shewanella woodyi*,
20 *Psychromonas ingrahamii*, *Ferimonas balearica*, *Aeromonas hydrophila*, *Aeromonas salmonicida*, *Aeromonas veronii*, *Tolumonas auensis*, *Chromobacterium violaceum*, *Burkholderia* sp. CCGE1002, *Azospirillum* sp. B510, *Bacillus anthracis*, *Bacillus cereus*, *Bacillus cytotoxicus*, *Bacillus thuringiensis*, *Bacillus weihenstephanensis*, *Bacillus pseudofirmus*, *Bacillus megaterium*, *Staphylococcus aureus*, *Exiguobacterium sibiricum*, *Exiguobacterium* sp. AT1b, *Macrococcus caseolyticus*, *Paenibacillus polymyxa*,
25 *Streptococcus pyogenes*, *Streptococcus pneumoniae*, *Streptococcus agalactiae*, *Streptococcus mutans*, *Streptococcus thermophilus*, *Streptococcus sanguinis*, *Streptococcus suis*, *Streptococcus gordonii*, *Streptococcus equi*, *Streptococcus uberis*, *Streptococcus dysgalactiae*, *Streptococcus gallolyticus*, *Streptococcus mitis*, *Streptococcus pseudopneumoniae*, *Lactobacillus johnsonii*, *Lactobacillus gasseri*, *Enterococcus faecalis*, *Aerococcus urinae*, *Carnobacterium* sp. 17-4,
30 *Clostridium acetobutylicum*, *Clostridium perfringens*, *Clostridium tetani*, *Clostridium novyi*, *Clostridium botulinum*, *Desulfotomaculum reducens*, *Clostridium lentocellum*, *Erysipelothrix rhusiopathiae*, *Mycoplasma genitalium*, *Mycoplasma pneumoniae*, *Mycoplasma pulmonis*, *Mycoplasma penetrans*, *Mycoplasma gallisepticum*, *Mycoplasma mycoides*, *Mycoplasma synoviae*, *Mycoplasma capricolum*, *Mycoplasma crocodyli*, *Mycoplasma leachii*, *Mesoplasma florum*, *Propionibacterium acnes*,
35 *Nakamurella multipartita*, *Borrelia burgdorferi*, *Borrelia garinii*, *Borrelia afzelii*, *Prochlorococcus marinus*, *Lysinibacillus sphaericus*, *Rhodopirellula baltica*, or combinations thereof. In particular, *Lactobacillus johnsonii*, and *Clostridium acetobutylicum* are contemplated.

Methanotrophic organisms can metabolise methane as a source of carbon and energy. Use of such
40 organisms can be useful in treatment of gas containing methane in devices according to the present

invention, and can therefore have applicability against global warming, as methane is a powerful greenhouse gas. It is noted that the growth of some methanotrophic organisms may also require the provision of methane and/or carbon dioxide in the liquid media, in order to favour specific metabolic pathways and therefore growth. In this case, in some embodiments, the atmosphere maintained within the chamber can be adapted to meet the needs of the cultured organism, for example by providing methane and/or carbon dioxide in the chamber's atmosphere above normal atmospheric levels. Suitable methanotrophic bacteria or archaea that can be used in the invention can include *Methylomonas* 16a ATCC PTA 2402, *Methylobacterium* sp., *Methylobacterium extorquens*, *Methylobacterium radiotolerans*, *Methylobacterium populi*, *Methylobacterium chloromethanicum*, or *Methylobacterium nodulans*, *Methylosinus* sp., *Methylosinus trichosporium* OB3b (NRRL B-11,196), *Methylosinus sporium* (NRRL B-11,197), *Methylocystisparvus* sp., *Methylocystisparvus* (NRRL B-11,198), *Methylomonas* sp., *Methylomonas methanica* (NRRL B-11,199), *Methylomonas albus* (NRRL B-11,200), *Methylococcus* sp., *Methylococcus capsulatus*, *Methylobacter* sp., *Methylobacter capsulatus* Y (NRRL B-11,201), *Methylococcus capsulatus* (NCIMB 11132), *Methylobacterium organophilum*, *Methylobacterium organophilum* (ATCC 27,886), *Methylomonas* sp. AJ-3670 (FERM P-2400), *Methylomicrobium* sp., *Methylomicrobium alcaliphilum*, *Methylocella* sp., *Methylocella silvestris*, *Methylacidiphilum* sp., *Methylacidiphilum inferorum*, *Methylibium* sp., or *Methylibium petroleiphilum*. In particular, *Methylococcus* sp., *Methylobacterium* sp., *Methylomonas* sp., *Methylococcus capsulatus* and *Methylibium petroleiphilum* are contemplated.

So-called probiotic bacteria, archaea and fungi, which are organisms intended to be consumed live to provide health effects, that can be used in the invention include especially *Lactobacillus*, *Bifidobacterium*, *Saccharomyces*, *Enterococcus*, *Streptococcus*, *Pediococcus*, *Leuconostoc*, *Bacillus*, and can include *Escherichia coli*, *Lactococcus*, *Enterococcus*, *Oenococcus*, *Pediococcus*, *Streptococcus* and *Leuconostoc* species, *Lactobacillus* species may include *Lactobacillus plantarum*, *L. johnsonii*, *L. acidophilus*, *L. sakei*, *L. bulgaricus*, *L. salivarius*, *L. acidophilus*, *L. casei*, *L. paracasei*, *L. rhamnosus*, *L. delbrueckii* subsp. *bulgaricus*, *L. brevis*, *L. johnsonii*, *L. plantarum* and *L. fermentum*. Other intended species include *Saccharomyces boulardii*, *Bifidobacterium bifidum*, *Bacillus coagulans*, *Bifidobacterium infantis*, *B. adolescentis*, *B. animalis* subsp. *animalis*, *B. animalis* subsp. *lactis*, *B. bifidum*, *B. longum*, *B. breve*, *Lactococcus lactis*, *Enterococcus faecium*, *Enterococcus durans* and *Streptococcus thermophilus*, *B. subtilis*, and *B. cereus*. In particular, the *Lactobacillus* species, *Bifidobacterium bifidum*, *Bacillus coagulans*, *Bifidobacterium infantis*, *B. adolescentis*, *Bifidobacterium bifidum* and *Bacillus coagulans*, *Bifidobacterium infantis*, *Enterococcus faecium*, and *Streptococcus thermophiles* are contemplated.

Archaea taxonomy groups and species that can be used in the invention include in particular Crenarchaeota, Euryarchaeota, Desulfurococcales, Sulfolobales, Archaeoglobales, Halobacteriales, Methanobacteriales, Methanococcales, Methanopyrales, Thermococcales, Thermoplasmatales, *Aeropyrum pernix*, *Sulfolobus solfataricus*, *Sulfolobus tokodaii*, *Sulfolobus shibatae*, *Archaeoglobus fulgidus*, *Halobacterium* sp., *Metallosphaera sedula*, *Methanobacterium thermoautotrophicum*,

Methanococcus jannaschii, *Methanosarcina acetivorans*, *Methanopyrus kandleri*, *Pyrococcus horikoshii* (shinkaj), *Pyrococcus abyssi*, *Pyrococcus furiosus*, *Thermococcus litoralis*, *Thermococcus barosii*, *Thermoplasma acidophilum*, *Thermoplasma volcanium*, *Halobacterium* sp. NRC-1, *Methanococcus jannaschii* DSM 2661, *Pyrococcus abyssi* GE5, *Thermoplasma acidophilum* DSM 1728, and *Thermoplasma volcanium* GSS 1.

Systems according to the invention can also be used to culture hydrogen oxidising organisms that oxidise hydrogen as a source of energy with oxygen used as a final electron acceptor. They can be divided into aerobes and anaerobes. The former use hydrogen as an electron donor and oxygen as an acceptor while the latter may use sulphate or nitrogen dioxide as electron acceptors. These organisms are able to exploit the special properties of molecular hydrogen (for instance redox potential and diffusion coefficient) thanks to the presence of hydrogenases. The aerobic hydrogen-oxidising bacteria can be facultative autotrophs, but they can also have mixotrophic or completely heterotrophic growth.

Some of these organisms are preferably grown under microaerophilic conditions, that is, in environments containing lower levels of oxygen than present in normal atmosphere. As a result, a chamber oxygen concentration of lower than 21% O₂, typically around 2 to 10% O₂, can be maintained. For example, a mixture of hydrogen, and/or carbon dioxide, and/or oxygen can be supplied. These organisms can include, but are not limited to the genera *Caminibacter*, *Aquifex*, *Ralstonia* and *Paracoccus*, *Hydrogenobacter* sp., *Hydrogenobacter thermophilus*, *Hydrogenovibrio marinus*, *Helicobacter* sp., *Helicobacter pylori*, *Hydrogenophaga* sp., *Hydrogenomonas* sp., *Cupriavidus necator*, *Rhodococcus opacus*, *Alcaligenes* sp., *Alcaligenes eutrophus*, *Alcaligenes latus*, *Alcaligenes paradoxus*, *Alcaligenes ruhlandii*, *Aquaspirillum autotrophicum*, *Bacillus schlegelii*, *Pseudomonas carboxydovorans*, *Pseudomonas facilis*, *Pseudomonas fiava*, *Pseudomonas pseudofiava*, *Pseudomonas hydrogenovora*, *Pseudomonas hydrogenothermophila*, *Pseudomonas palleronii*, *Pseudomonas saccharophila*, *Pseudomonas thermophila*, *Seliberia carboxyhydrogena*, *Flavobacterium autothermophilum*, *Paracoccus denitrificans*, *Xanthobacter autotrophicus*, *X. autotrophicus*, *Arthrobacter* sp. (1IX, RH 12), *Mycobacterium gordonae*, *Nocardia autotrophica*, and *Nocardia opaca*. Some contemplated organisms utilize hydrogen under anaerobic conditions, with sulfate or carbon dioxide as hydrogen acceptors (such as *Desulfovibrio*, *Clostridium aceticum*, *Acetobacterium woodii*, and *Methanobacterium thermo-autotrophicum*).

Yeast species which can be used in the invention include in particular *Saccharomyces cerevisiae*, *Saccharomyces bayanus* and *Saccharomyces boulardii*. Other suitable yeast species include *Saccharomyces* sp, *Saccharomyces pastorianus*, *Saccharomyces carlsbergensis*, *Leucosporidium* sp., *Leucosporidium frigidum*, *Saccharomyces telluris*, *Candida* sp., *Rhodotorula* sp., *Trichosporon* sp, *Schizosaccharomyces pombe*, *Schizosaccharomyces* sp., *Sporidiobolus* sp, *Sporobolomyces* sp., *Candida tropicalis*, group consisting of *Xanthophyllomyces dendrorhous*, *Kluyveromyces lactis*, *Ogataea polymorpha*, *Metschnikowia fructicola*, and any combination thereof. Of these,

Saccharomyces sp., *Leucosporidium sp.*, *Rhodotorula sp.*, *Trichosporon sp.*, *Schizosaccharomyces sp.*, *Sporidiobolus sp.*, *Sporobolomyces sp.*, and *Candida tropicalis* are particularly contemplated.

Fungi which may be used in devices and methods of the invention include filamentous fungi such as
5 *Aspergillus japonicus*, *Aspergillus niger*, *Aspergillus foetidus*, *Aspergillus oryzae*, *Aureobasidium pullulans*, *Sclerotinia sclerotiorum* and *Scopulariopsis brevicaulis*. Mould species include members of groups including *Acremonium sp.*, *Alternaria sp.*, *Aspergillus sp.*, *Cladosporium sp.*, *Fusarium sp.*, *Mucor sp.*, *Penicillium sp.*, *Rhizopus sp.*, *Stachybotrys sp.*, *Trichoderma sp.*, *Trichoderma reesei*, *Trichophyton sp.*, *Aspergillus oryzae*, *Monascus purpureus*, *Penicillium sp.*, *Penicillium nalgiovense*,
10 *Fusarium venenatum*, *Geotrichum candidum*, *Neurospora sitophila*, *Rhizomucor miehei*, *Rhizopus oligosporus*, *Rhizopus oryzae*, *Geotrichum sp.*, *Neurospora sp.*, *Rhizomucor sp.*, *Spinellus fusiger*, and *Spinellus sp.* Of the moulds, the genera *Acremonium sp.*, *Alternaria sp.*, *Aspergillus sp.*, *Cladosporium sp.*, *Fusarium sp.*, *Mucor sp.*, *Penicillium sp.*, *Rhizopus sp.*, *Stachybotrys sp.*, *Trichoderma sp.*, and *Trichophyton sp.* are particularly contemplated.

15 Slime moulds refer to a number of groups of facultatively multicellular eukaryotes. Suitable examples for use in the present invention include *Physarum polycephalum*, *Fuligo septica*, *Fuligo sp.*, *Stemonitis fusca*, *Stemonitis sp.*, *Diachea leucopodia*, *Diachea sp.*, *Trichia sp.*, *Trichia varia*, *dictyostelids*, *Dictyostelium sp.*, *Dictyostelium purpureum*, *Dictyostelium discoideum*, myxomycetes, dictyostelids,
20 and protosteloids, and in particular Acrasidis, Plasmodiophorids, Labyrinthulomycota, *Fonticula*, *Nuclearia sp.*, *Myxogastria*, *Stemonitis*, and *Physarum sp.*

Rotifers, a group of microscopic and near microscopic animals, may also be used.

25 Capnophiles are also contemplated for use. These microorganisms thrive in the presence of high concentrations of carbon dioxide, and could particularly be used for applications where high carbon dioxide sequestration is desired.

Extremophiles refer to a number of groups of organisms which can tolerate unusual extremes in
30 environment, typically high or low temperatures, extremes of pH, salinity, desiccation and/or radiation levels. Particularly contemplated examples which may be used in devices and methods according to the invention include members of the order Cyanidiales, Galdieriaceae, *Cyanidioschyzon sp.*, *Cyanidiophyceae* class, *Galdieria sp.*, *Cyanidioschyzon merolae* DBV201, *Cyanidium daedaleum*, *Cyanidium maximum*, *Cyanidium partitum*, *Cyanidium rumpens*, *Galdieria daedala*, *Galdieria maxima*,
35 *Galdieria partita*, and especially the species *Galdieria sulphuraria*, *Cyanidium caldarium*, and *Cyanidioschyzon merolae*.

Plankton is a general term for ocean microfauna and microflora. Examples for use in the present invention include coccolithophores, dinoflagellates, metazoan plankton, and protozoan plankton, and in
40 particular *Emiliana sp.* such as *Emiliana huxleyi*.

Amoeboids refer to various groups of cells or unicellular organisms which are able to change their shapes by the extension of pseudopods. Examples of organisms of this kind for use in the present invention include *Chaos carolinense*, *Chaos Diffuens*, *Chaos sp.*, *Naegleria sp.*, *Naegleria fowleri*,
5 *Entamoeba sp.*, *Cercozoan amoeboids*, *Euglypha sp.*, *Euglypha rotunda*, and *Gromia sp.*, *Gromia sphaerica*, *Foraminifera sp.*, *Massisteria voersi*, *Massisteria sp.*, *Pelomyxa palustris*, *Syringammina fragilissima*, and *Syringammina sp.*

In addition, the bioreactor systems of this invention may be used to culture cells from multicellular
10 organisms. In particular, animal cells from animals such as livestock and poultry including chicken, duck, turkey; fish, bovine, or porcine cells, game or aquatic animal species, and insects, Particular cells which can be grown in devices and methods according to the invention include myocyte cells, adipocyte cells, epithelial cells, myoblasts, satellite cells, side population cells, muscle derived stem cells, mesenchymal stem cells, myogenic cells, myogenic pericytes, or mesoangioblasts. Myogenic cells here
15 relate to cells from an embryonic stem cell line, induced pluripotent stem cell line, extraembryonic cell line, or somatic cells, modified to express one or more myogenic transcription factors. In particular, myocytes or similar cells may be grown for use in the production of so-called lab-grown meat, for the nutrition of humans or other animals. Totipotent cells deriving from human embryonic cells and human embryos are excluded.

20

Sulphur oxidizing organisms can also be grown in systems as described. These organisms carry out the oxidation of sulphur to produce energy. Some inorganic forms of reduced sulphur, mainly sulphide ($\text{H}_2\text{S}/\text{HS}^-$) and elemental sulphur (S_8), can be oxidised by chemolithotrophic sulphur-oxidising prokaryotes, usually coupled to the reduction of oxygen (O_2) or nitrate (NO_3^-). Most of these sulphur
25 oxidisers are autotrophs that can use reduced forms of sulphur as electron donors for carbon dioxide (CO_2) fixation. These organisms could be grown using inside the chamber a gas mixture containing CO_2 and another, sulphur-containing gas to deliver the needed forms of sulphur into the liquid media, in particular where the composite membrane is permeable to such a gas. Alternatively the sulphur containing molecule could be added directly in the liquid media via nozzles, in either gaseous or liquid
30 (aqueous) form. Some forms of sulphur which could be used either in the chamber (or by direct addition) include H_2S or using H_2S donor compounds such as NaHS or Na_2S . Relevant organisms include the Beggiatoaceae family, Thiobacillaceae family, Sulfolobales order (Archaea), *Sulfolobus* genera, *Acidianus* genera, *Hydrogenovibrio* crunogenus, and the Desulfobulbaceae family. Relatedly, some Anaerobic sulfur oxidizing organisms can be photosynthetic autotrophs which obtain energy from
35 sunlight but use reduced sulfur compounds instead of water as electron donors for photosynthesis.

In some embodiments, the organisms of the bioreactor are genetically modified to possess a specific trigger that is activated by exposure to a gaseous or vaporised stimulant that can be delivered into the atmosphere comprised within the chamber. When this stimulant is introduced into the chamber it
40 diffuses across the composite membrane of the bioreactor and is delivered into the liquid media. The

stimulant acts as a trigger and induces the organisms to react in a predetermined manner as intended by the genetic intervention. For example, the stimulant may induce the production or cease of production of a particular metabolite and/or may change the production rates of particular metabolites. Hence, Organisms may be modified (or may have a natural ability to) to respond to the presence or
5 absence of certain gases by changing their physiological processes, and the gas mixture supplied to the atmosphere comprised within the chamber, thus, can be controlled to provide or remove such a gas.

As such, the above descriptions regarding the provision of CO₂-enriched and/or O₂ depleted
10 atmosphere within the chamber is applicable to all other suitable gases, the control of which can be used for a variety of purposes. Gases can be introduced into the chamber to control the pH of the liquid media comprised within the bioreactor. According to specific embodiments of the invention the concentration of CO₂ and/or ammonia (NH₃) within the atmosphere may be used to control the pH of the liquid media. The pH may therefore also control the response of organisms such that the modulation
15 of atmospheric gas content or concentration may act as a proxy for pH control and triggering of a desired biological response.

EXAMPLES

20 Example 1

An experimental apparatus was constructed to demonstrate a system according to an embodiment of the invention. A schematic of the apparatus is shown in Figure 11a. It was comprised of 12 liquid-
25 containable compartments 1102 that were 2m long and connected in series with the first wall of each compartment in contact with the internal atmosphere comprised within a single shared chamber 1103. The approximate dimensions of the chamber were 2 x 1 x 0.15m. The outlet of the connected bioreactor units was connected to and in fluid communication with a liquid reservoir 1156. Mounted on the reservoir were a number of sensors that were in contact with the liquid media (1157, 1158, 1159).

30 These sensors included:

1. pH
2. Dissolved Oxygen
3. Conductivity

35 Mounted on the top of the reservoir was a gas sterilising filter 1160 connected to the external environment. This allowed the pressure in the system to be equalised with the environment if the volume in the reservoir was increased or decreased. The outlet of the reservoir was connected to a series of valves that allow liquid media to be removed from and added to the system. The liquid media then entered the pump that circulated it around the system. In this apparatus a positive displacement pump
40 was used. The outlet of the pump passed through a flow sensor and then the internal section of a heat

exchanger. The inlet 1161 and outlet 1162 could be reconfigured automatically to provide either hot water or cold water to the external section of the heat exchanger. This allowed the system to heat and cool the liquid media to the desired setpoint. A temperature sensor was installed just downstream of the exchanger to facilitate this temperature control.

5

On the inlet of the first liquid-containable compartment of the first bioreactor in series, a pressure sensor 1163 was installed to monitor the pressure at that point of the system.

The atmosphere 1003 enclosed by the chamber was in contact with the first wall of all 12 of the bioreactor units. The chamber was rigid and made of stainless steel. It connected to the second wall of the bioreactor units to form a sealed atmosphere. There were three flow connections to the chamber, two inlets and one outlet. All of the connections could be opened and closed automatically with valves. The outlet 1164 was connected to permit venting to the external environment. The first inlet 1165 was connected to a source of compressed CO₂ gas. This could be used to increase the concentration of CO₂ in the chamber. The second inlet 1166 was connected to a compressed air source. This could be used to flush out the contents of the chamber if the outlet 1164 was open. This could be used for a number of reasons including, but not limited to, reducing the build up of humidity in the chamber, reducing the concentration of CO₂, and reducing the concentration of O₂. Connected to the chamber, and in contact with the atmosphere therein, were three further sensors (1167, 1168, 1169).

20

These sensors included:

1. Temperature
2. CO₂ concentration
3. Humidity

25

Above the second walls of the bioreactors was located an LED light source 1130. This provided illumination to the liquid media through the transparent material of the second wall.

Figure 11b illustrates the construction of the bioreactors and the chamber. It shows the composite membrane layer of the liquid-containable compartment 1104, the second wall 1107 and the chamber 1103. The second wall was made from transparent or translucent polymers, the composite membrane from engineering polymer and/or commodity polymers and/or fluoropolymers, and the chamber 1111 from stainless steel. The composite membrane layer was connected to the second wall with adhesive and the second wall was sealed to the chamber with foam interface 1170.

35

The system was inoculated with *Arthrospira platensis* suspended in a nutrient media and exposed to light from the LEDs 1130 that were controlled to be representative of the photoactive radiation recorded in Darwin, Australia in February 2022 [NASA Prediction Of Worldwide Energy Resources (POWER) Data Access Viewer Enhanced (DAVe) v2.3.4].

40

The present invention provided a method for pH control of the liquid media using carbon dioxide. A controlled amount of carbon dioxide was introduced into the bioreactor units through a control system into the gas chamber, which was then absorbed by the microalgae culture through the second wall of the liquid-containable compartment comprising a composite membrane. As shown in Figure 11c, when the pH rose above the desired value, the controller activated the CO₂ control system to introduce a predetermined amount of CO₂ inside the chamber. This increased the CO₂ concentration inside the gas chamber, which was consequently absorbed by the culture medium through the composite membrane and lowered the pH. The pH control system functioned as an automated feedback loop, continuously adjusting CO₂ levels in real-time to maintain an optimal pH environment for the culture.

10

The reactor was run for 17 days and harvested periodically. The concentration of and volume of the liquid media harvested was used to calculate the volumetric productivity of the bioreactor system. The volumetric productivity was then converted to the productivity based on the top flat surface area of the bioreactor and compared to open systems and closed non-permeable systems that incorporate sparging in the art, shown in Table 1. No requirement for direct sparging is a key advantage of the invention over existing technologies known in the art.

15

Table 1					
Photobioreactor	Volume (m ³)	Algal species	Px, ground (g·m ⁻² ·day ⁻¹)	Sparging	Reference
Invention Embodiment Example 1	0.11	<i>Arthrospira platensis</i>	29.6	No	
Open Pond	-	<i>Arthrospira platensis</i>	5.29 - 9.09	-	Lu et al. (2011) (https://doi.org/10.1007/s10811-010-9552-4)
Fibonacci-type Photobioreactor	0.25	<i>Arthrospira platensis</i> M2	9.15*	Yes	Díaz et al. (2019) (https://doi.org/10.1016/j.procbio.2019.08.008)
Bench-scale Helical Tubular Photobioreactor	0.004	<i>Arthrospira platensis</i> UTEX LB 1926	5.12 - 14.4*	Yes	Casazza et al. (2022) (https://doi.org/10.3390/app12031311)
Coiled Tubular Reactor	0.111	<i>Arthrospira platensis</i> M2	18*	Yes	Tredici and Zitelli (1997) (<a href="https://doi.org/10.1002/(sici)1097-0290(19980120)57:2<187::aid-bit7>3.0.co;2-j">https://doi.org/10.1002/(sici)1097-0290(19980120)57:2<187::aid-bit7>3.0.co;2-j)
Tubular Undulating Row Photobioreactor (TURP)	0.011	<i>Arthrospira platensis</i> M2	22.8	Yes	P. Carlozzi (https://doi.org/10.1007/s002530000355)
Two-Plane Tubular Photobioreactor	0.145	<i>Arthrospira platensis</i> M2	27.8	Yes	Torzillo et al. (1993) (https://doi.org/10.1002/bit.260420714)

*Calculated using the data provided in the paper

20

The ability for the liquid media to be kept under optimal conditions through the homogeneous provision of carbon through the composite membrane from CO₂ added to the chamber, controlling the pH and

facilitating photosynthesis, contributed to this example embodiment achieving higher productivity than any other non-permeable or open bioreactor compared in Table 1.

Furthermore, the effective removal of oxygen through the composite membrane contributed to lower levels of dissolved oxygen, which can be toxic for *Arthrospira platensis* in high concentrations, in the liquid media, further improving productivity.

Although particular embodiments of the invention have been disclosed herein in detail, this has been done by way of example and for the purposes of illustration only. The aforementioned embodiments are not intended to be limiting with respect to the scope of the appended claims, which follow. It is contemplated by the inventors that various substitutions, alterations, and modifications may be made to the invention without departing from the spirit and scope of the invention as defined by the claims.

Example 2

An experimental apparatus was constructed to demonstrate the difference in gas flux and permeability between two types of membranes: a polymer membrane comprised of a homogeneous material and a composite membrane featured in particular embodiments of the invention which comprised of an ultra-thin barrier layer made up of the same material as the homogeneous polymer membrane. A schematic of the setup is represented in Figure 12. The experiment set-up was based on evaluation of the membranes by subjecting them to a pure gas, respectively using a traditional constant pressure method.

The apparatus comprised a test gas cylinder 1201 and regulator 1202 connected using compression-type tubing to the feed side 1207 (bottom side) of the stainless steel permeation test cell with a pressure control valve 1203 and pressure sensor 1204 in between. The permeation cell was placed in a temperature controlled chamber 1206 with a temperature control unit 1205. The permeate gas streams to the top of the test cell 1208 which was connected to another pressure sensor to determine the pressure difference across the membrane and a flow sensor 1209 to measure the permeate gas flow rate through the membranes being tested. Both the feed and permeate sides were comprised of individual vent valves 1210 to expedite the attainment of a steady state in the experiment. Before starting the experiment, all streams were flushed with the test gas to remove any traces of contaminants that could affect the results. Additionally, a leak test was conducted to ensure the integrity of the experimental setup. This method was used for the measurement of the membrane's permeate gas flux (in $\text{k}\cdot\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$), permeability (in GPU) and selectivity (dimensionless) under various operating pressures and temperature conditions.

The sensors included were:

1. Pressure
2. Temperature
3. Gas flow

Each membrane was carefully prepared by cutting it into a circular shape to ensure consistency in testing. The prepared membrane disc 1212 was then sealed in-between the feed side and permeate side of the test cell using a cylindrical gasket 1211 as shown in Figure 12b. Once the membrane was
5 securely positioned, the top and bottom parts of the test cell were uniformly tightened using wing-nuts to ensure that the cell was sealed properly, preventing any gas leaks during the experiment.

To control the flow of gases during the experiment, a needle valve was used to pressurise either CO₂ or N₂ gas, respectively on the feed side of the membrane. Precise adjustment of the gas pressure and
10 temperature were made and the permeate flow rates were measured across a range of operating conditions using a bubble flow metre installed in the permeate line. Once a steady state was attained, indicating that the system has stabilised, permeation data was collected multiple times to ensure accuracy. To gather reliable data, multiple samples of each membrane type were evaluated. Typically,
15 at least five samples were tested, and the results are averaged to obtain a representative value for the membrane's gas permeability.

During the test, one side of the membrane is exposed to the test gas at a controlled pressure, while the other side is connected to a flowmeter whose outlet is left open to the atmosphere. The test gas permeates through the membrane from the high-concentration side to the low-concentration side.
20 Sensors or detectors in the low-concentration compartment measure the amount of substance that has passed through the membrane over a specified period. The data collected was used for the calculation of the respective membrane's permeance in GPU. The significant difference of the permeance between the composite membrane with a 2 micron thick barrier layer and a homogeneous polymer membrane of thickness 100 microns tested at room temperature of $23 \pm 2^{\circ}\text{C}$ and a pressure difference of 1 ± 0.1
25 atm, are shown in Table 2 (below).

Table 2					
Type of Membrane	Thickness of the Membrane	Thickness of the Barrier Layer	Permeance measured at RTP		
			Nitrogen (N ₂)	Oxygen (O ₂)	Carbon dioxide (CO ₂)
<i>Unit</i>	<i>Micrometre</i>	<i>Micrometre</i>	<i>GPU</i>	<i>GPU</i>	<i>GPU</i>
Homogeneous Polymer Membrane	105	105	2.9	6.1	14.0
Ultrathin Barrier Layer Composite Membrane	140	2	148.0	250.2	654.6

With the help of the experimental setup, we found that the composite membrane, with a 2-micron thick barrier layer, exhibited a significantly higher permeance compared to a homogeneous membrane with a thickness of 100 microns. The results, summarised in Table 2, demonstrated that the composite membrane's optimised structure allowed for enhanced gas permeability for all the test gases used in this case. The nitrogen, oxygen, and carbon dioxide gas permeance values for the composite membrane were respectively 51 times, 41 times, and 47 times higher than those of a homogeneous polymer membrane. Therefore, making it significantly more effective and suitable than a homogeneous polymer membrane for applications requiring high gas flux. This higher performance of a composite membrane underscores its potential advantages over traditional homogeneous polymer membranes in the present invention.

Example 3

An experimental apparatus was set up to demonstrate the difference in mechanical strength between two types of membranes: a solid polymer membrane (homogeneous) and a composite membrane. The solid polymer membrane test samples were prepared using the ISO 37 type-1 standard and the composite membrane test samples were prepared using the ISO 527 type-1 standard. A universal testing machine (UTM) was used to test the respective membrane samples by subjecting them to an uniaxial tensile load. For statistical significance, multiple samples (at least 5) of each membrane type were tested, and the average tensile strength values were evaluated. The tensile strength (in MPa) and the strain at break (in %) for the corresponding membrane samples are shown in Table 3.

Table 3			
Membrane	Method	Tensile Strength (MPa)	Strain at Break (%)
Homogeneous Polymer Membrane	ISO 37 type 1	6	450
Ultrathin Barrier Layer Composite Membrane	ISO 527 type 1	54	69

In summary, the results presented in Table 3, demonstrated that the composite membrane exhibited significantly higher mechanical strength compared to the homogeneous membrane. The composite membrane's superior tensile strength compared to a homogeneous polymer membrane can be attributed to its composite structure, where each layer is optimised for specific functionalities. The tensile strength of the composite membrane was around 800% more than that of the homogeneous polymer membrane, which strongly emphasises its potential advantages in the present invention. Further, the strain at break measured for the composite membrane was around 85% less than that of the homogeneous polymer membrane, indicating that the composite membrane is less prone to deformation under load. Thereby, also emphasising its potential advantages in robustness and durability of the present invention. Therefore, it can be concluded that for bioreactors utilising gas permeable membranes, composite membranes offer a more reliable option for applications requiring operational hydraulic pressures. Their enhanced structural integrity and tailored functionalities make them far better suited to withstand the demands of such systems compared to homogeneous polymer membranes.

CLAIMS

1. A bioreactor system for the production of biomass, the system comprising:
at least one bioreactor unit which comprises at least one liquid-containable compartment, wherein the liquid-containable compartment comprises,
 - (i) a first wall, wherein the first wall comprises a composite membrane that is permissible to transfer of gases therethrough, wherein the composite membrane comprises at least one barrier layer and at least one reinforcement layer; and
 - (ii) a second wall, wherein the second wall comprises material that is optically transmissible to visible light and that is substantially less gas permeable than the first wall, wherein the first and second walls cooperate to define the liquid-containable compartment within the bioreactor unit.
2. The system of claim 1, wherein liquid-containable compartment comprises an inlet and an outlet so as to permit circulation of liquid through the liquid-containable compartment.
3. The system of any one of claims 1 or 2, wherein the liquid-containable compartment is configured to withstand a hydraulic pressure of greater than 50 millibars, typically greater than 100 millibars, suitably greater than 500 millibars, or optionally greater than 1 bar.
4. The system of any one of claims 1 to 3, wherein the barrier layer is comprised of a gas permeable polymer material,
5. The system of any one of claims 1 to 4, wherein the barrier layer is substantially non-porous.
6. The system of claim 4 or 5, wherein the gas permeable polymer barrier layer is comprised of a material selected from: silicones, polysiloxanes, polydimethylsiloxanes (PDMS), fluorosilicone, organosilicones, VMQ (Vinyl Methyl Siloxane), PVMQ (Phenyl vinyl methyl siloxane), silicon-oxide polymers, sulfonated polyetheretherketone (SPEEK), amino-organosilanes such as gamma-aminopropyltriethoxysilane (γ -APS), poly(ethylene oxide), poly(butylene terephthalate), poly(ethylene oxide), poly(butylene terephthalate) block copolymers (PEO-PBT), cellulose (including plant cellulose and bacterial cellulose), cellulose acetate (celluloid), nitrocellulose, or cellulose esters.
7. The system of any one of claims 1 to 6, wherein the composite membrane further comprises at least one intermediate layer.
8. The system of any one of claims 1 to 7, wherein the first and second walls cooperate to define an inwardly facing surface of the liquid-containable compartment within the bioreactor unit, and wherein the inwardly facing surface of the first and/or second walls is substantially hydrophobic.

9. The system of claim 8, wherein the inwardly facing surface has a contact angle with water of greater than 90 degrees.
10. The system of claim 8, wherein the inwardly facing surface of the first wall has a contact angle with water of greater than 90 degrees.
11. The system of any one of claims 1 to 7, wherein the first and second walls cooperate to define an inwardly facing surface of the liquid-containable compartment within the bioreactor unit, and wherein the inwardly facing surface of the first and/or second walls is substantially hydrophilic.
12. The system of any one of claims 1 to 11, wherein the first wall and/or the second wall are comprised of material having a Yield strength of not less than 0.5 MPa, 1 MPa, 1.5 MPa, 2 Mpa, 5 Mpa, 10 Mpa, or 20 Mpa.
13. The system of any one of claims 1 to 12, wherein second wall is comprised of a structurally rigid material.
14. The system of any one of claims 1 to 13, wherein the second wall is comprised of a material selected from: high density polyethylene (HDPE), acrylic, PVC, ETFE, PTFE, silicone rubber, polycarbonate, epoxy resin, or glass (including laminated glass).
15. The system of any one of claims 1 to 14, wherein the liquid-containable compartment has an elongate configuration.
16. The system of any one of claims 1 to 15, wherein the at least one bioreactor unit further comprises a housing that accommodates a portion of the at least one liquid-containable compartment, wherein the housing cooperates with the portion of the at least one liquid-containable compartment to define a chamber having an atmosphere within, and wherein the at least one liquid-containable compartment is orientated such that the first wall is exposed to the atmosphere within the chamber.
17. The system of any one of claims 1 to 16, wherein the at least one bioreactor unit comprises a plurality of liquid containing compartments.
18. The system of claim 17, wherein the plurality of liquid containing compartments are in fluid communication with each other and are connected to each other in series.
19. The system of claim 18, wherein the plurality of liquid containing compartments are arranged in parallel.

20. The system of any one of claims 1 to 19, wherein the system further comprises an auxiliary sub-system, wherein the auxiliary sub-system is in fluid communication with the liquid compartment within the at least one bioreactor unit.

21. The system of claim 20, wherein the auxiliary sub-system comprises a pump for maintaining circulation of liquid through the liquid-containable compartment.

22. The system of claims 20 and 21, wherein the auxiliary sub-system comprises a biomass collector.

23. The system of any one of claims 20 to 22, wherein the atmosphere within the chamber may be at a pressure greater than or less than atmospheric pressure.

24. The system of any one of claims 20 to 23, wherein the composition of the atmosphere within the chamber can be controlled by an atmospheric control sub-system, and wherein the atmospheric control sub-system is configured to alter the atmospheric composition of the chamber by:

- (i) increasing or reducing O₂ concentration; and/or
- (ii) increasing or reducing CO₂ concentration; and/or
- (iii) adding or removing water vapour, including steam.

25. The system of any one of claims 1 to 24, wherein the barrier layer has:

(i) an oxygen permeability of at least 100 Barrer, at least 200 Barrer, at least 300 Barrer, at least 400 Barrer, at least 500 Barrer, at least 600 Barrer, at least 700 Barrer, at least 800 Barrer, at least 900 Barrer, at least 1000 Barrer, at least 1250 Barrer, at least 1500 Barrer, and at least 2000 Barrer; and/or

(ii) a carbon dioxide permeability of at least 200 Barrer, at least 400 Barrer, at least 600 Barrer, at least 800 Barrer, at least 1000 Barrer, at least 1500 Barrer, at least 2000 Barrer, at least 2500 Barrer, at least 3000 Barrer, at least 3500 Barrer, at least 4000 Barrer, at least 4500 Barrer, at least 5000 Barrer, and at least 7500 Barrer.

26. The system of any one of claims 1 to 25, wherein the barrier layer has:

(i) a permeability rate for oxygen of at least: $10^{-15} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, suitably at least $10^{-14} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-13} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-12} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-11} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-10} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-9} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; and/or

(ii) a permeability rate for carbon dioxide of at least: $10^{-13} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-12} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-11} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-10} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-9} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at

least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-2} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

27. The system of any one of claims 1 to 26, wherein the barrier layer has a thickness of at least $0.1 \text{ } \mu\text{m}$, at least $1 \text{ } \mu\text{m}$, optionally at least $5 \text{ } \mu\text{m}$, suitably at least $10 \text{ } \mu\text{m}$.

28. The system of any one of claims 1 to 27, wherein the liquid-containable compartment comprises a liquid growth medium.

29. The system of claim 28, wherein the system comprises a microbial or algal organism selected from: a photoautotroph, a chemotroph and a mixotroph.

30. The system of claim 29, wherein the microbial or algal organism is selected from one or more of Cyanobacteria, Protobacteria, Spirochaetes, Gram Positive bacteria, green filamentous bacteria such as Chloroflexia, Planctomycetes, Bacteroides cytophaga, Thermotoga, aquifex, halophiles, Methanosarcina, Methanobacterium, Methanococcus, Thermococcus celer, Thermoproteus, Pyrodictum, Entamoebae, slime moulds such as Mycetozoa, Ciliates, Trichomonads, Microsporidia, Diplomonads, Excavata, Amoebozoa, Choanoflagellates, Rhizaria, Foraminifera, Radiolaria, Diatoms, Stramenopiles, brown algae, red algae, green algae, snow algae, Haptophyta, Cryptophyta, Alveolata, Glaucophytes, phytoplankton, plankton, Percolozoa, Rotifera, and cells or whole organisms from animals, fungi or plants.

31. The system of any one of claims 1 to 30, wherein the liquid-containable compartment(s) encompasses a volume of at least 100 L , typically at least 1000 L , suitably at least 5000 L , optionally at least $10,000 \text{ L}$.

32. The system of any one of claims 1 to 31, wherein the bioreactor is a photobioreactor.

33. A bioreactor unit suitable for incorporation into a bioreactor system, wherein the bioreactor unit comprises at least one liquid-containable compartment, wherein the liquid-containable compartment comprises,

- (i) a first wall, wherein the first wall comprises a composite membrane layer that is permissible to transfer of gases therethrough, wherein the composite membrane comprises at least one barrier layer and at least one reinforcement layer; and
- (ii) a second wall, wherein the second wall comprises material that is optically transmissible to visible light and that is substantially less gas permeable than the first wall, wherein the first and second walls cooperate to define the liquid-containable compartment within the bioreactor unit,

and wherein the liquid-containable compartment comprises an inlet and an outlet so as to permit circulation of liquid through the liquid-containable compartment.

34. The bioreactor unit of claim 33, wherein the barrier layer is comprised of a gas permeable polymer material.

35. The bioreactor unit of any one of claims 33 or 34, wherein the barrier layer is substantially non-porous.

36. The bioreactor unit of claim 34 or 35, wherein the gas permeable polymer barrier layer is comprised of a material selected from: silicones, polysiloxanes, polydimethylsiloxanes (PDMS), fluorosilicone, organosilicones, VMQ (Vinyl Methyl Siloxane), PVMQ (Phenyl vinyl methyl siloxane), silicon-oxide polymers, sulfonated polyetheretherketone (SPEEK), amino-organosilanes such as gamma-aminopropyltriethoxysilane (γ -APS), poly(ethylene oxide), poly(butylene terephthalate), poly(ethylene oxide), poly(butylene terephthalate) block copolymers (PEO-PBT), cellulose (including plant cellulose and bacterial cellulose), cellulose acetate (celluloid), nitrocellulose, or cellulose esters.

37. The bioreactor unit of any one of claims 33 to 36, wherein the first and second walls cooperate to define an inwardly facing surface of the liquid-containable compartment within the bioreactor unit, and wherein the inwardly facing surface is substantially hydrophobic.

38. The bioreactor unit of claim 37, wherein the inwardly facing surface has a contact angle with water of greater than 90 degrees.

39. The bioreactor unit of claim 37, wherein the inwardly facing surface of the first wall has a contact angle with water of greater than 90 degrees.

40. The bioreactor unit of any one of claims 33 to 36, wherein the first and second walls cooperate to define an inwardly facing surface of the liquid-containable compartment within the bioreactor unit, and wherein the inwardly facing surface is substantially hydrophilic.

41. The bioreactor unit of any one of claims 33 to 40, wherein the first wall and/or the second wall are comprised of material having a Yield strength of not less than 0.5 MPa, 1 MPa, 1.5 MPa, 2 Mpa, 5 Mpa, 10 Mpa, or 20 Mpa.

42. The bioreactor unit of any one of claims 33 to 41, wherein second wall is comprised of a structurally rigid material.

43. The bioreactor unit of any one of claims 33 to 42, wherein the second wall is comprised of a material selected from: high density polyethylene (HDPE), acrylic, PVC, ETFE, PTFE, silicone rubber, polycarbonate, epoxy resin, or glass (including laminated glass).

44. The bioreactor unit of any one of claims 33 to 43, wherein the liquid-containable compartment has an elongate configuration.

45. The bioreactor unit of any one of claims 33 to 44, wherein the at least one bioreactor unit further comprises a housing that accommodates a portion of the at least one liquid-containable compartment, wherein the housing cooperates with the portion of the at least one liquid-containable compartment to define a chamber having an atmosphere within, and wherein the at least one liquid-containable compartment is orientated such that the first wall is exposed to the atmosphere within the chamber.

46. The bioreactor unit of any one of claims 33 to 45, wherein the at least one bioreactor unit comprises a plurality of liquid containing compartments.

47. The bioreactor unit of claim 46, wherein the plurality of liquid containing compartments are in fluid communication with each other and are connected to each other in series.

48. The bioreactor unit of claim 46, wherein the plurality of liquid containing compartments are arranged in parallel.

49. The bioreactor unit of any one of claims 33 to 48, wherein the barrier layer has:

(i) an oxygen permeability of at least 100 Barrer, at least 200 Barrer, at least 300 Barrer, at least 400 Barrer, at least 500 Barrer, at least 600 Barrer, at least 700 Barrer, at least 800 Barrer, at least 900 Barrer, at least 1000 Barrer, at least 1250 Barrer, at least 1500 Barrer, and at least 2000 Barrer; and/or

(ii) a carbon dioxide permeability of at least 200 Barrer, at least 400 Barrer, at least 600 Barrer, at least 800 Barrer, at least 1000 Barrer, at least 1500 Barrer, at least 2000 Barrer, at least 2500 Barrer, at least 3000 Barrer, at least 3500 Barrer, at least 4000 Barrer, at least 4500 Barrer, at least 5000 Barrer, and at least 7500 Barrer.

50. The bioreactor unit of any one of claims 33 to 48, wherein the barrier layer has:

(i) a permeability rate for oxygen of at least: $10^{-15} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, suitably at least $10^{-14} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-13} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-12} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-11} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-10} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-9} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; and/or

(ii) a permeability rate for carbon dioxide of at least: $10^{-13} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-12} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-11} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-10} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-9} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-8} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-7} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-6} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-5} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-4} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, at least $10^{-3} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and typically at least $10^{-2} \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

51. The bioreactor unit of any one of claims 33 to 50, wherein the barrier layer has a thickness of at least $0.1 \mu\text{m}$, suitably at least $1 \mu\text{m}$, optionally at least $5 \mu\text{m}$, and optionally at least $10 \mu\text{m}$.

52. The bioreactor unit of any one of claims 33 to 51, wherein the bioreactor unit is a photobioreactor unit.

53. A process for the production of microbial biomass, the process comprising growing a microbial culture within a system as defined in any of claims 1 to 32.

54. The process of claim 53, wherein the system comprises a liquid medium comprised within a liquid-containable compartment and wherein the liquid medium generates a positive hydraulic pressure of greater than 50 millibars, typically greater than 100 millibars, suitably greater than 500 millibars, or optionally greater than 1 bar.

55. The process of any one of claims 53 or 54, wherein the microbial biomass is obtained from a microbial or algal organism selected from: a photoautotroph, a chemotroph and a mixotroph.

56. The process of claim 55, wherein the microbial or algal organism is selected from one or more of Cyanobacteria, Protobacteria, Spirochaetes, Gram Positive bacteria, green filamentous bacteria such as Chloroflexia, Planctomycetes, Bacteroides cytophaga, Thermotoga, aquifex, halophiles, Methanosarcina, Methanobacterium, Methanococcus, Thermococcus celer, Thermoproteus, Pyrodictum, Entamoebae, slime moulds such as Mycetozoa, Ciliates, Trichomonads, Microsporidia, Diplomonads, Excavata, Amoebozoa, Choanoflagellates, Rhizaria, Foraminifera, Radiolaria, Diatoms, Stramenopiles, brown algae, red algae, green algae, snow algae, Haptophyta, Cryptophyta, Alveolata, Glaucophytes, phytoplankton, plankton, Percolozoa, Rotifera, and cells obtained from whole organisms of animals, fungi or plants.

57. A photobioreactor system for the production of microbial biomass, the system comprising:
a plurality of bioreactor units that define a circuit, wherein each bioreactor unit comprises at least one liquid-containable compartment, wherein the liquid-containable compartment comprises,

(i) a first wall, wherein the first wall comprises a composite membrane that is permissible to transfer of gases therethrough, wherein the composite membrane comprises at least one barrier layer and at least one reinforcement layer; and

(ii) a second wall, wherein the second wall comprises material that is optically transmissible to visible light and that is substantially less gas permeable than the first wall,

wherein the first and second walls cooperate to define the liquid-containable compartment within the bioreactor unit; and

(iii) an inlet and an outlet so as to permit circulation of liquid media there-through;

wherein the liquid-containable compartments encompass a volume of at least 100 L; and wherein each liquid-containable compartment is configured to withstand a hydraulic pressure of greater than 100 millibars.