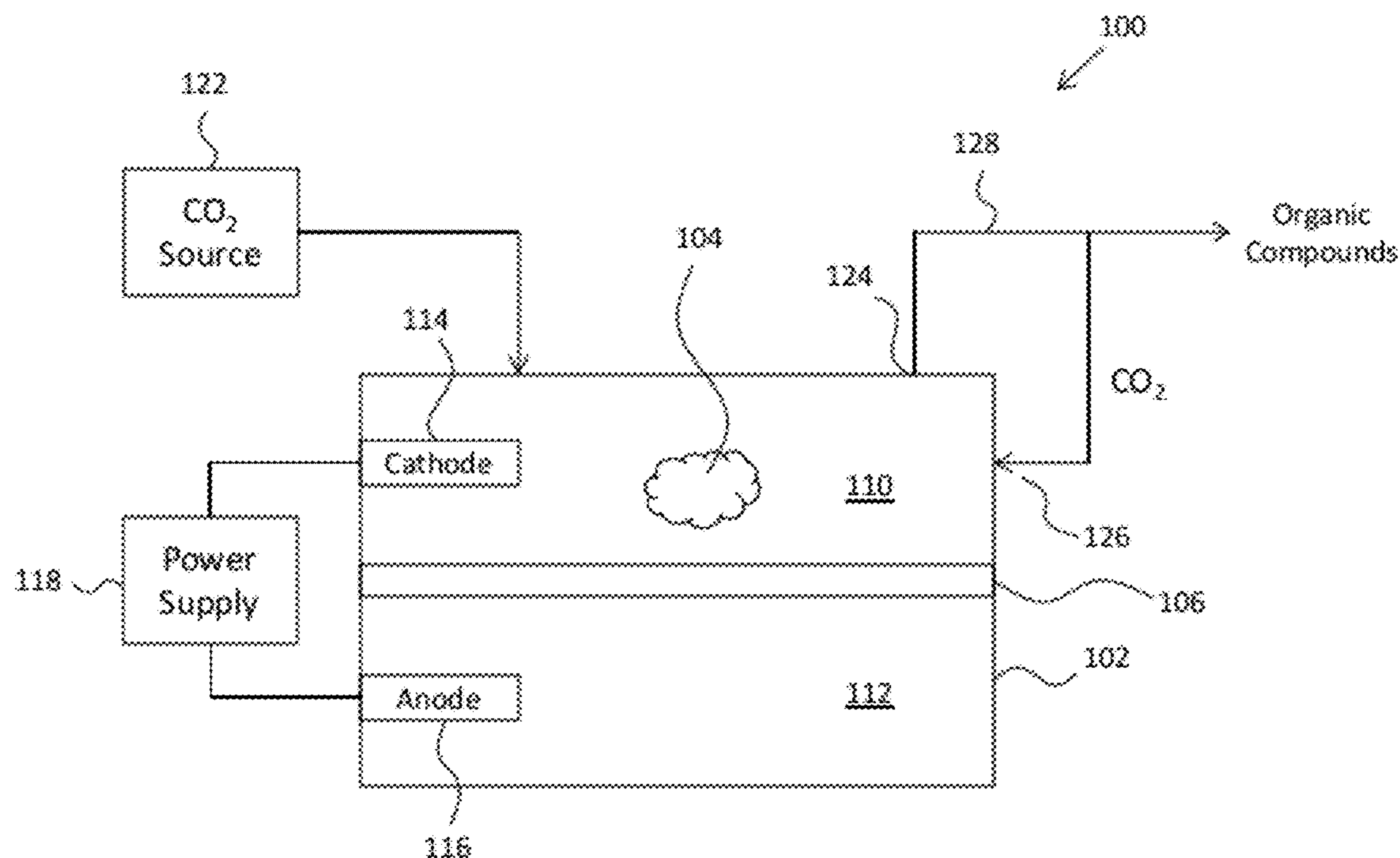


US 20120199492A1

(19) **United States**(12) **Patent Application Publication**
Jin et al.(10) **Pub. No.: US 2012/0199492 A1**(43) **Pub. Date: Aug. 9, 2012**(54) **BIOELECTROCHEMICAL CONVERSION
AND SEQUESTRATION OF CARBON
DIOXIDE INTO ORGANIC COMPOUNDS****Publication Classification**(51) **Int. Cl.**
C25B 3/00 (2006.01)
C25B 9/00 (2006.01)(75) **Inventors:** **Song Jin**, Fort Collins, CO (US);
Paul Harold Fallgren,
Westminster, CO (US); **Zhiyong**
(Jason) Ren, Highlands Ranch, CO
(US); **Robert H. Craig**, Sheridan,
WY (US)(52) **U.S. Cl. 205/413; 204/242**(73) **Assignee:** **NEXT FUEL, INC.**, Sheridan, WY
(US)(21) **Appl. No.: 13/367,471**(22) **Filed: Feb. 7, 2012****Related U.S. Application Data**(60) **Provisional application No. 61/440,672, filed on Feb.**
8, 2011.(57) **ABSTRACT**

A bioelectrochemical system includes a housing defining an internal chamber. A barrier is disposed within the housing and at least partially separates the internal chamber into first and second compartments. The first compartment including at least one of autotrophic or heterotrophic microorganisms disposed therein. A cathode is disposed within the first compartment and is coupled to a power supply, and an anode is disposed within the second compartment and is coupled to the power supply. The carbon dioxide received within the first chamber is transformed into an organic compound.



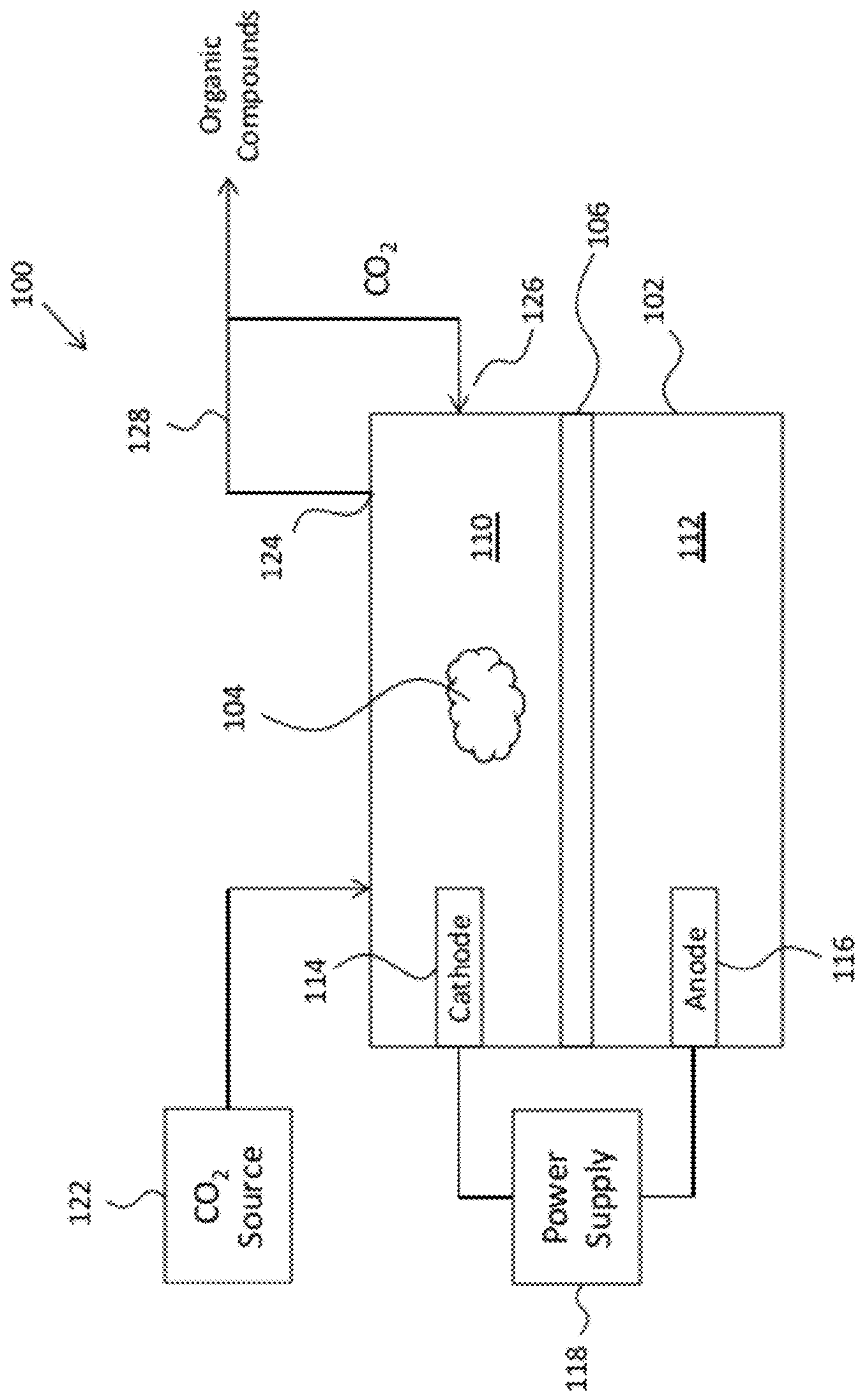


FIG. 1

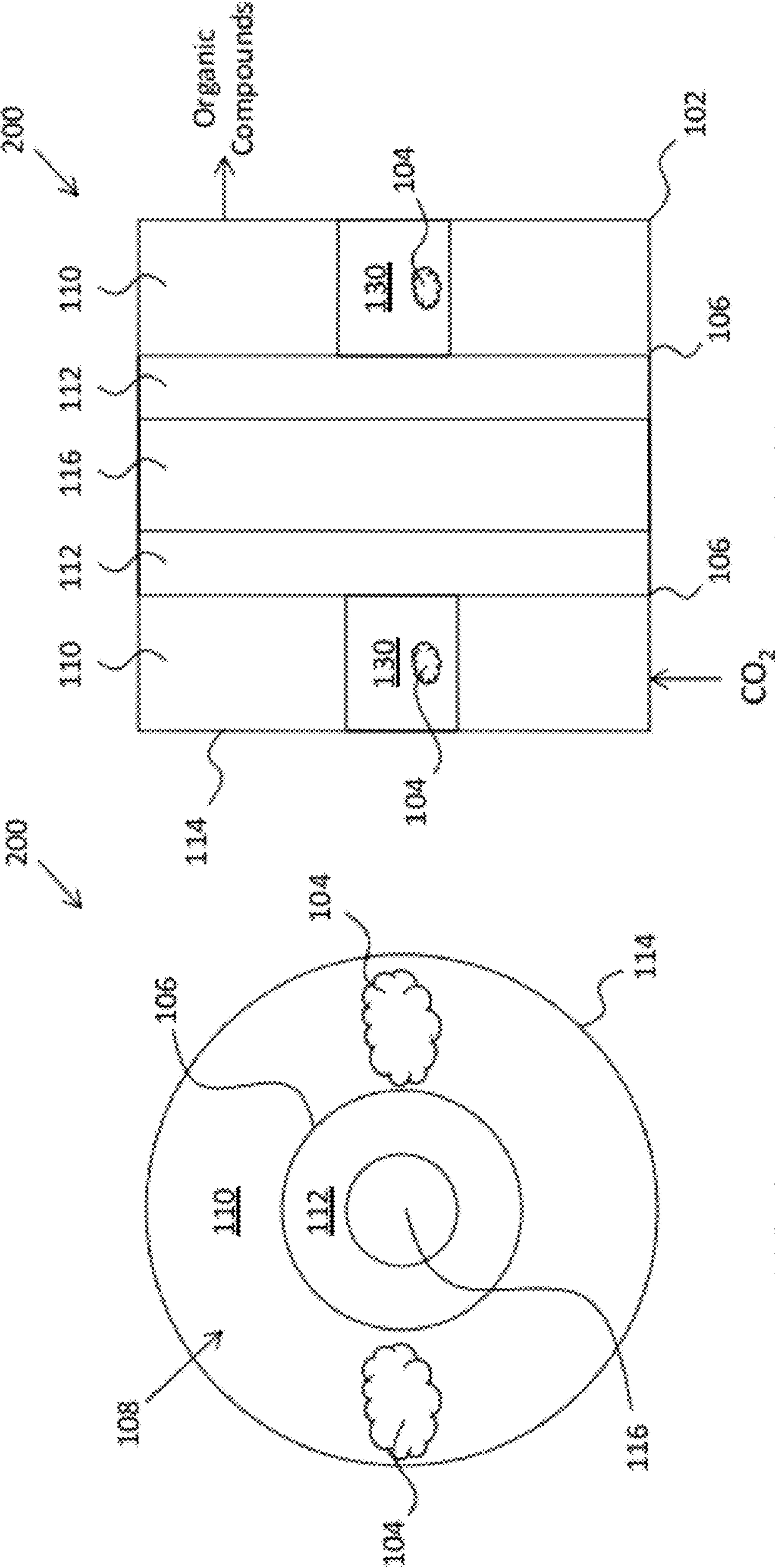


FIG. 2B

FIG. 2A

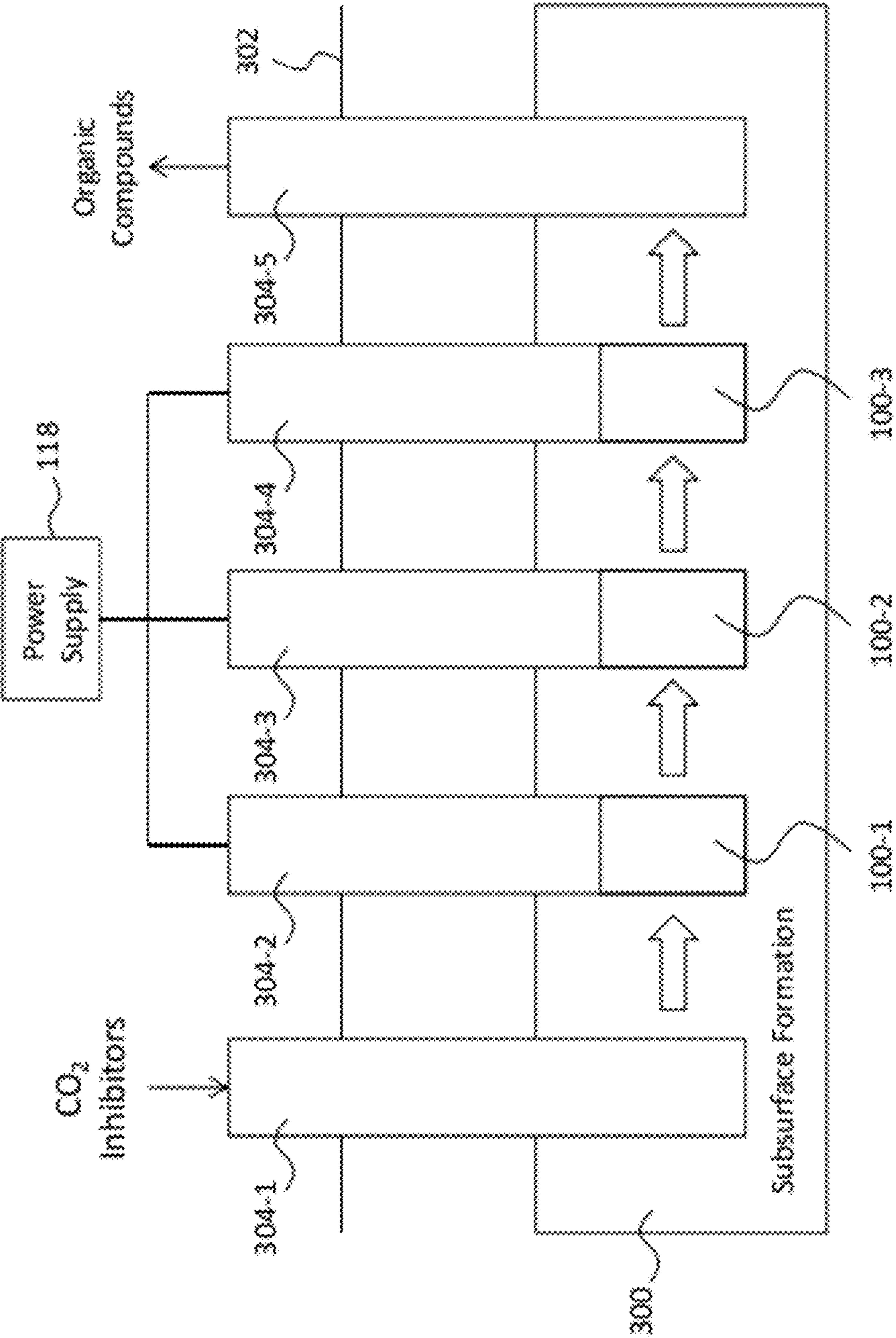


FIG. 3

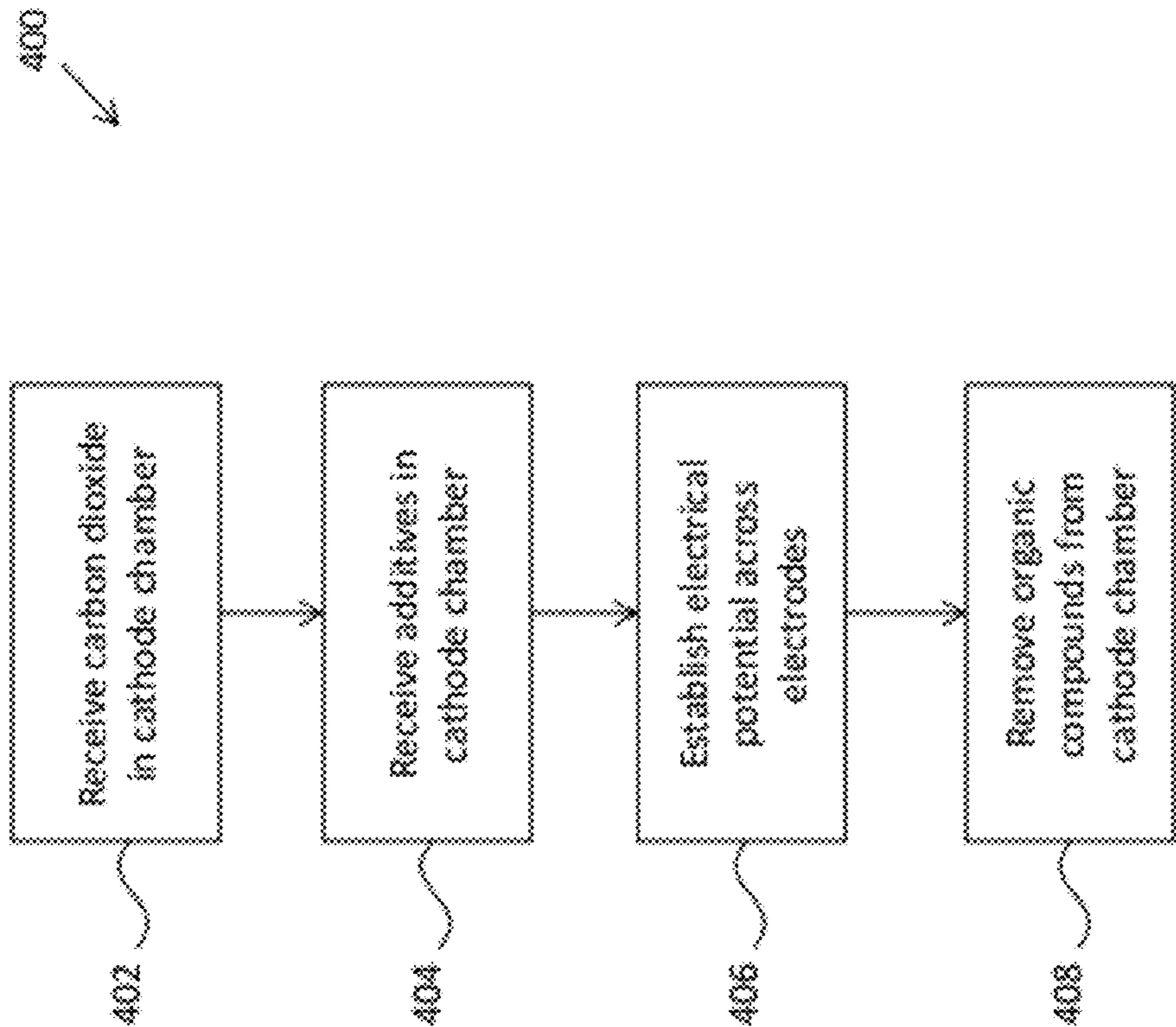


FIG. 4

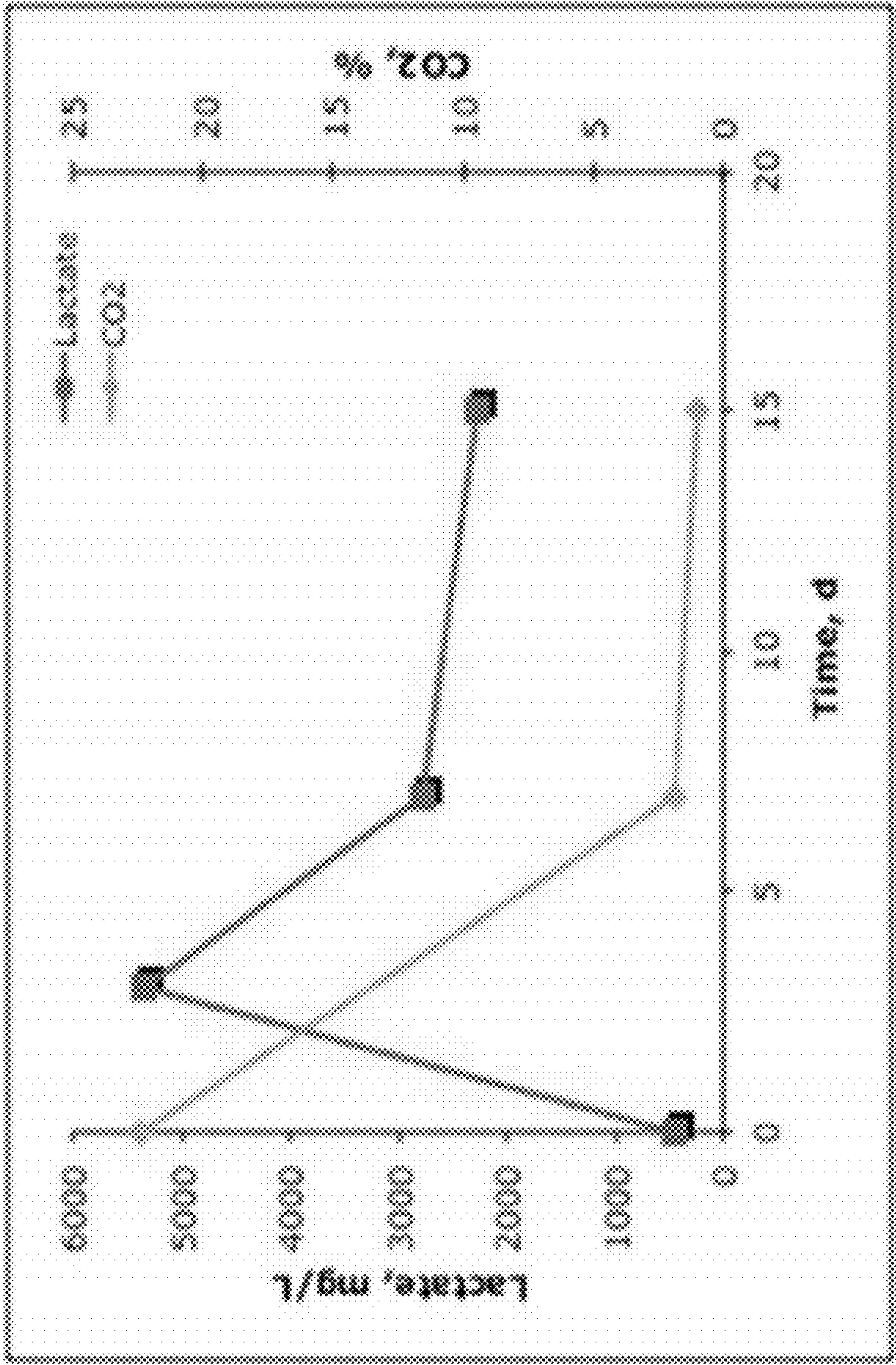


FIG. 5

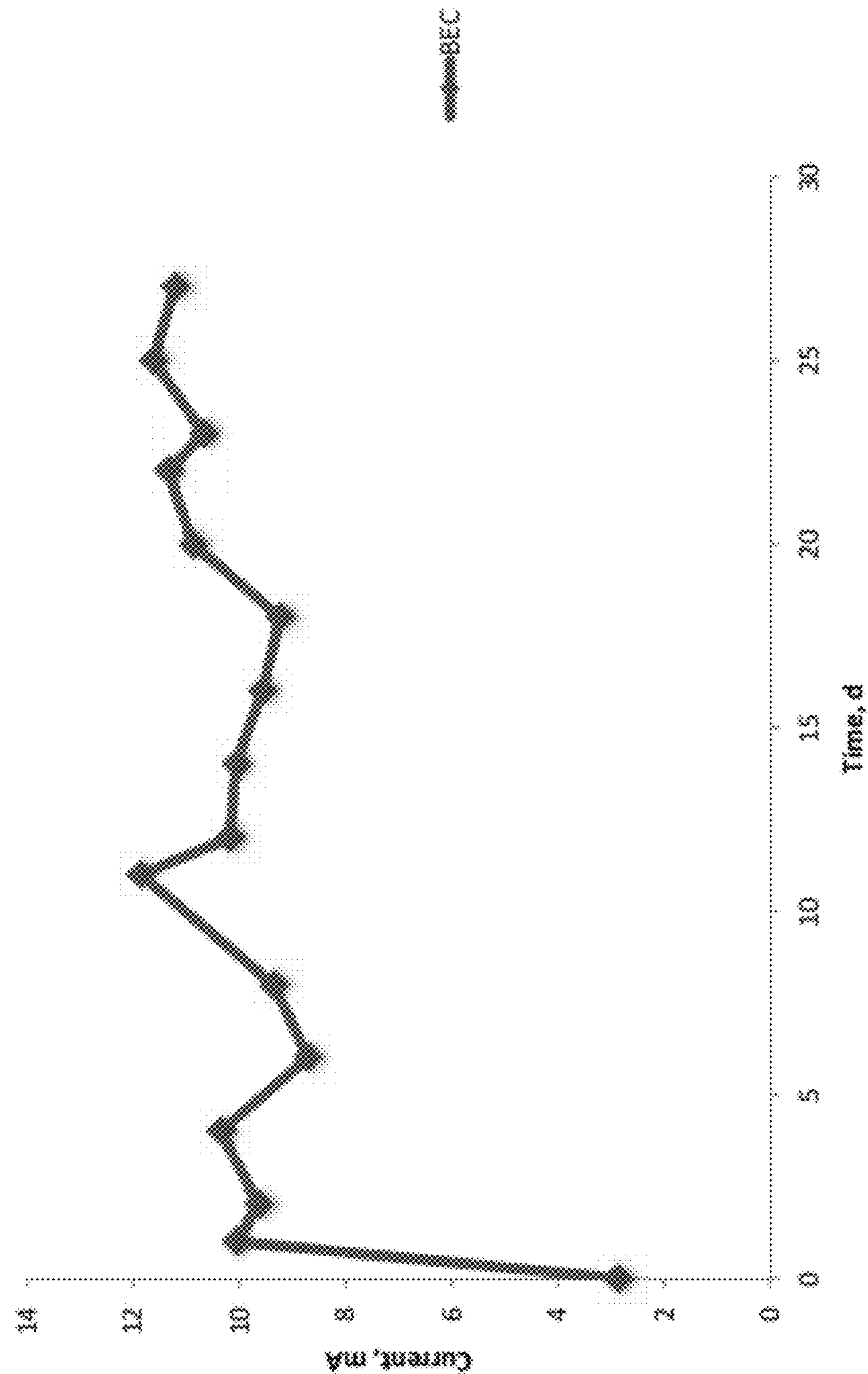


FIG. 6A

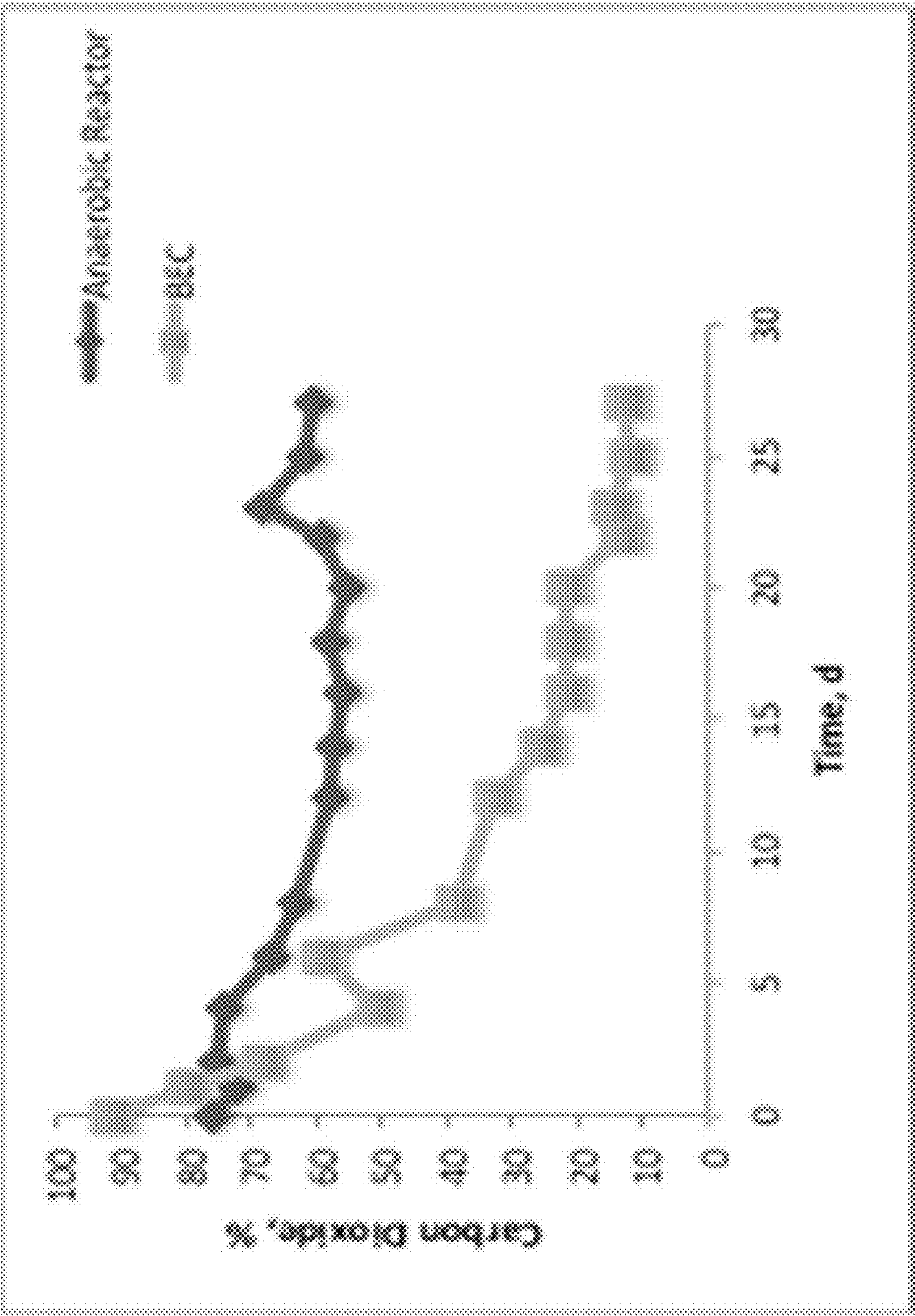


FIG. 6B

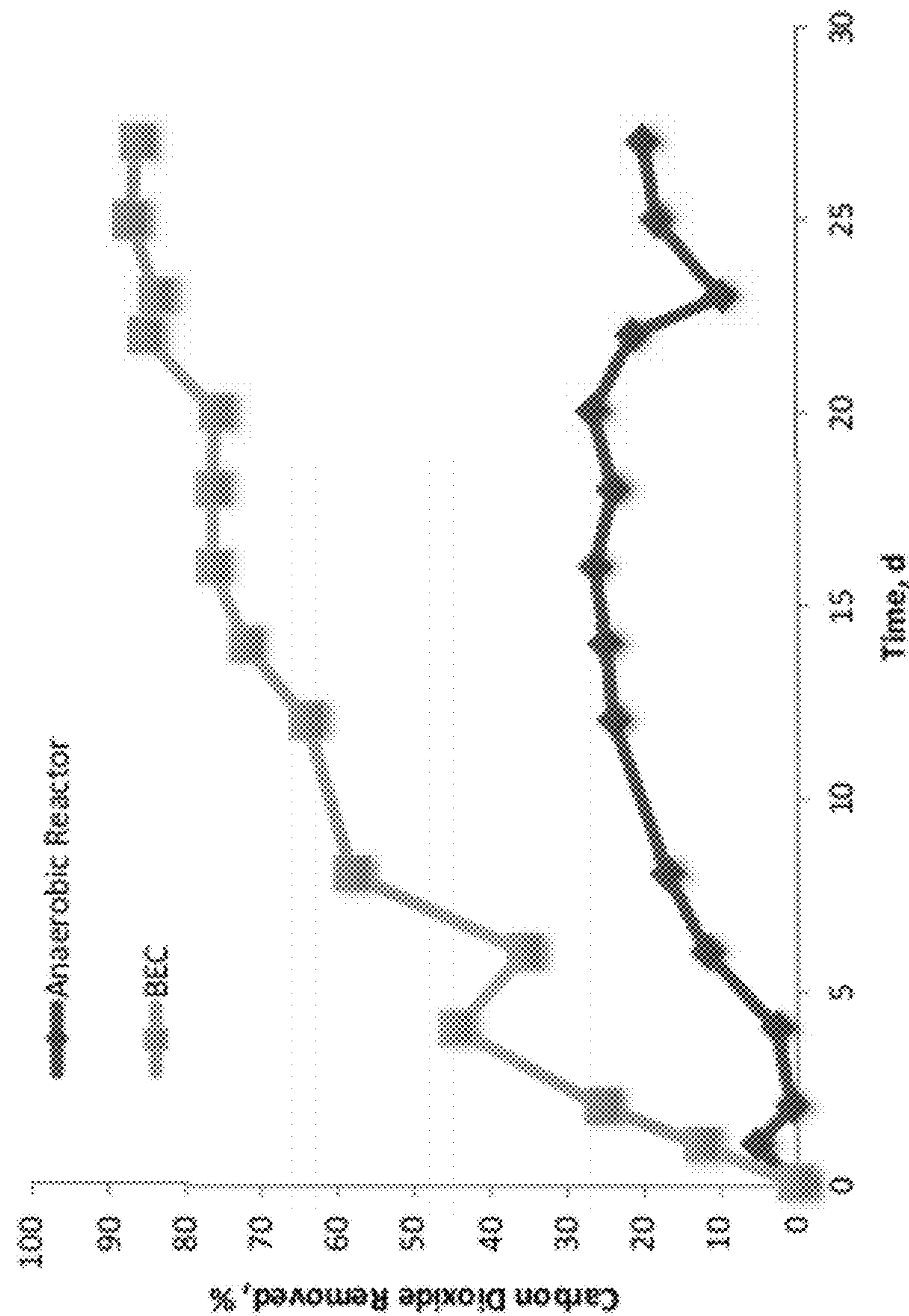


FIG. 6C

Reactor Stream	CO ₂ -C, g	CH ₄ -C, g	TOC, g	CO ₃ -C, g	HCO ₃ -C, g
Gas In	4.38	0.00	0.00	0.00	0.00
Water In	0.00	0.00	0.30	0.00047	1.81
Gas Out	0.30	0.007	0.00	0.00	0.00
Water Out	0.00	0.00	2.20	0.00064	2.48

FIG. 7

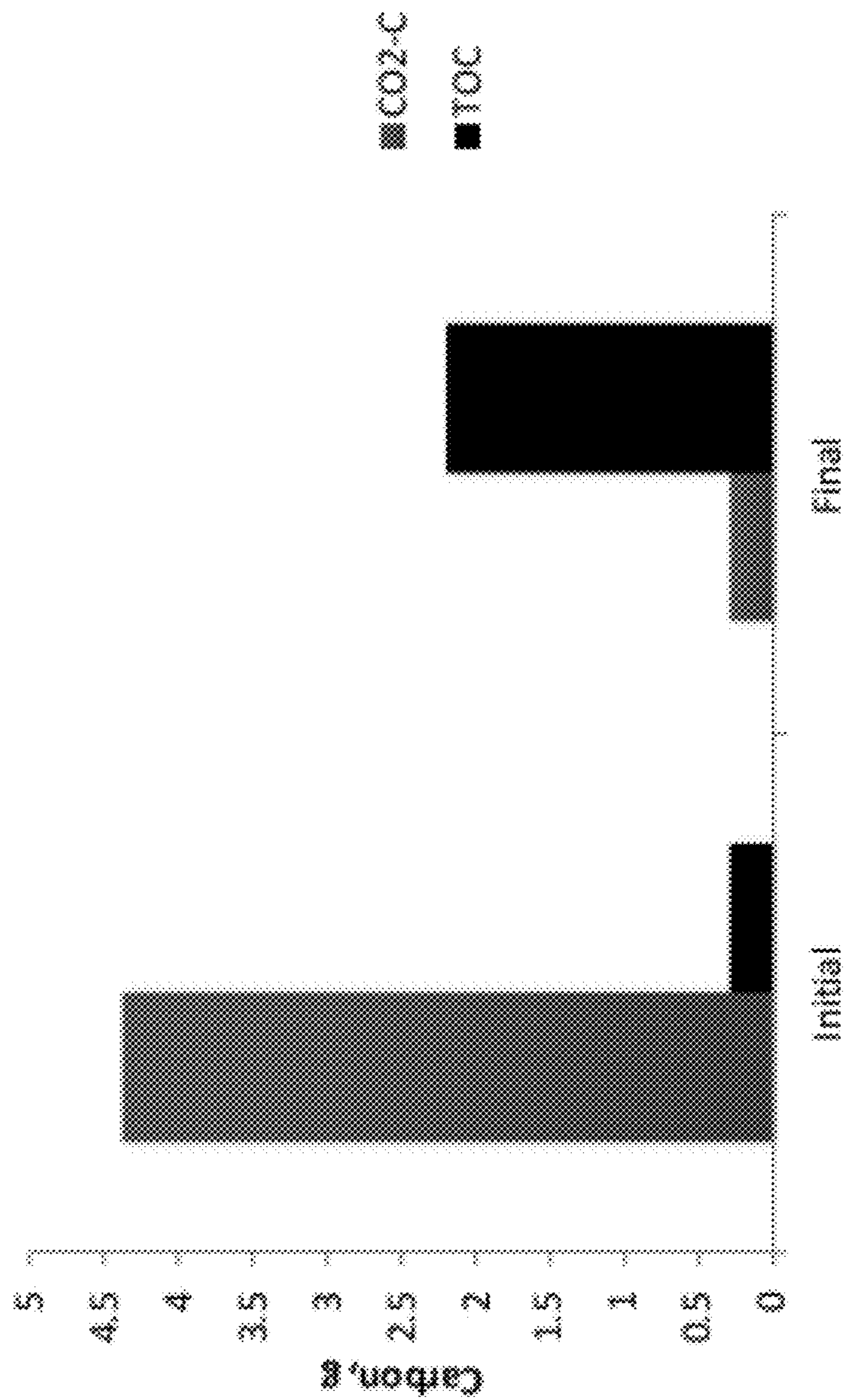


FIG. 8

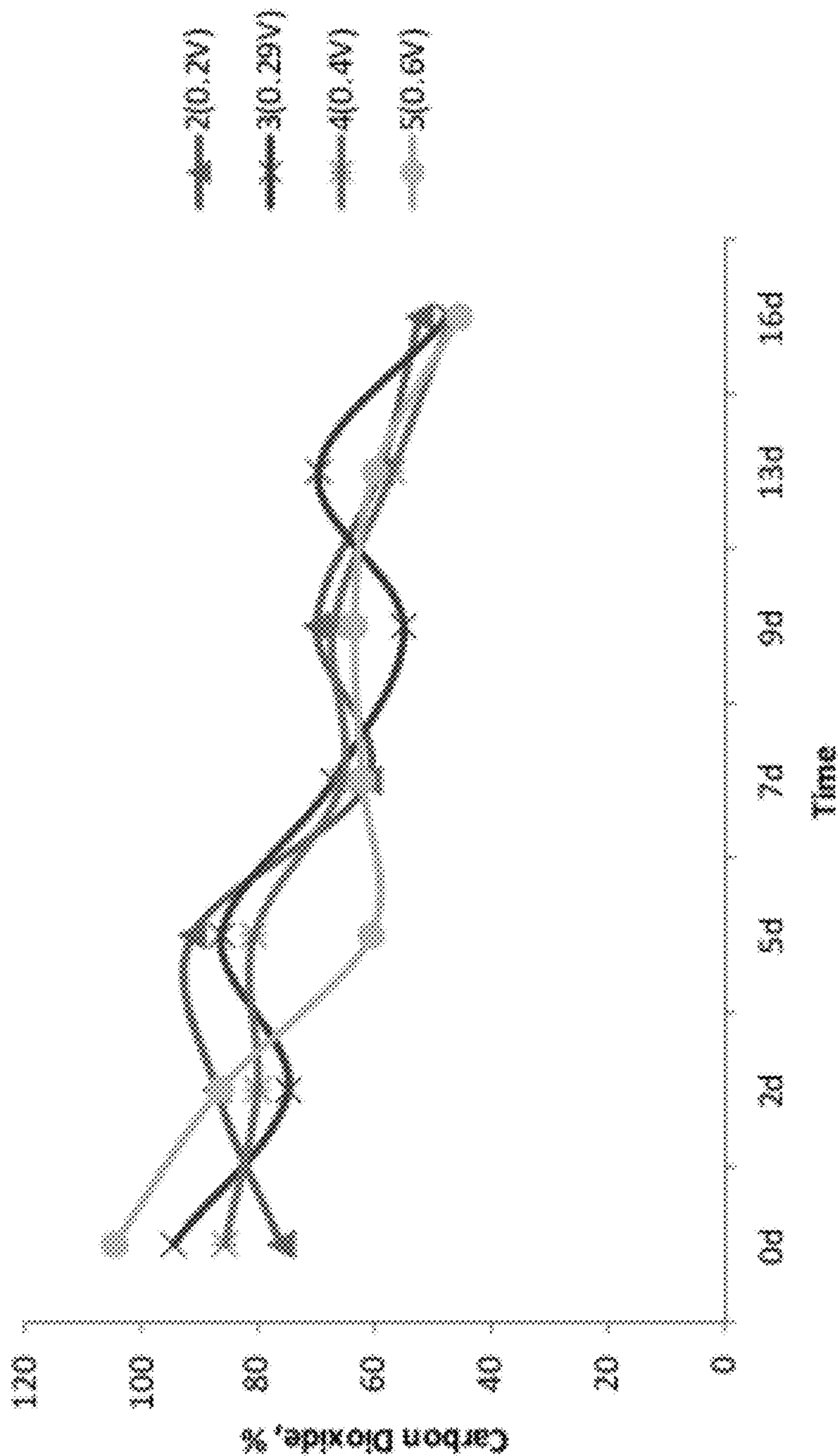


FIG. 9

BIOELECTROCHEMICAL CONVERSION AND SEQUESTRATION OF CARBON DIOXIDE INTO ORGANIC COMPOUNDS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Patent Application No. 61/440,672, which was filed Feb. 8, 2011 and is herein incorporated by reference in its entirety.

FIELD OF DISCLOSURE

[0002] The disclosed systems and methods relate to generating energy and/or chemical compounds. More particularly, the disclosed systems and methods relate to generating energy and/or chemical compounds while consuming carbon dioxide.

BACKGROUND

[0003] Carbon dioxide (CO_2) is used by certain species of microorganisms, which generate byproducts (direct or indirect) that may be used for alternative fuels or other chemicals. Other than cell uptake for energy and cell synthesis (as in photosynthetic and chemoautotrophic microorganisms), some microorganisms reduce CO_2 to organic compounds such as methane (via methanogens), acetate (via acetogens), or potentially other organic compounds (via known and unknown metabolic pathways).

[0004] The application of photosynthetic microbial transformation of CO_2 to organic compounds (e.g., in algal CO_2 conversion to biomass and biofuel) has been attempted for decreasing carbon emission from the industry (e.g., coal-fired power production); however, the process is limited by light availability, and longer retention time and stringency in preventing selective cultures from being contaminated. To be effective, the reaction vessel would require an extremely large area (which would be difficult to control) or other methods to substantially increase microbial CO_2 conversion rates.

[0005] There are some attempts in using pure strain of bacterium to reductively convert CO_2 into methane gas; however, the impossibility of maintaining a single strain condition in a large-scale application of such system prevents its widespread implementation. Additionally, the product of methane is such case is a more potent gas than CO_2 .

SUMMARY

[0006] In some embodiments, a bioelectrochemical system includes a housing defining an internal chamber. A barrier is disposed within the housing and at least partially separates the internal chamber into first and second compartments. The first compartment includes at least one of autotrophic or heterotrophic microorganisms disposed therein. A cathode is disposed within the first compartment and is coupled to a power supply, and an anode is disposed within the second compartment and is coupled to the power supply. Carbon dioxide received within the first chamber is transformed into an organic compound.

[0007] In some embodiments, a method includes receiving carbon dioxide within a first compartment disposed within an internal chamber defined by a housing, receiving an electrical potential across a cathode disposed within the first compartment and an anode disposed within a second compartment within the internal chamber, and extracting organic compounds from the first chamber that are derived from the carbon dioxide. The first and second compartments are at least

partially separated by a barrier. At least one of autotrophic or heterotrophic microorganisms are disposed within the first compartment.

[0008] In some embodiments, a system includes a first bioelectrochemical system disposed within a first well formed in a subsurface formation. The first bioelectrochemical system includes a housing defining an internal chamber. A barrier is disposed within the housing and at least partially separates the internal chamber into first and second compartments. The first compartment includes methanogenic microorganisms disposed therein. A cathode is disposed within the first compartment and is coupled to a first power supply, and an anode is disposed within the second compartment and is coupled to the first power supply. Carbon dioxide received within the first compartment of the first bioelectrochemical system is transformed into an organic compound.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1 shows an example of a design of a bioelectrochemical system in which electrical power is used to provide energy/reducing potential for producing organic compounds from CO_2 .

[0010] FIG. 2A is a top-side plan view of another example of an improved bioelectrochemical system in which electrical power is used to provide energy/reducing potential for producing organic compounds from CO_2 .

[0011] FIG. 2B is a cross-sectional side view of the improved bioelectrochemical system illustrated in FIG. 2A.

[0012] FIG. 3 shows an example of a design in which DC power is provided by a variety of sources and biological subsurface matrices including coal seam, depleted oil field, organic-rich shale, and organic-rich underground soil serve as the bioelectrochemical reactor for an in situ bioelectrochemical system to convert CO_2 from flue gas into organic compounds.

[0013] FIG. 4 shows an example of a method of converting carbon dioxide into an organic compound.

[0014] FIG. 5 is a graph of CO_2 reduction and lactate production for an experiment using one example of a bioelectrochemical system.

[0015] FIG. 6A is a graph of current versus time applied to a bioelectrochemical system in accordance with the embodiment illustrated in FIGS. 2A and 2B that was used to generate the curves in FIGS. 6B and 6C.

[0016] FIG. 6B is a graph of CO_2 versus time for a bioelectrochemical system in accordance with the embodiment illustrated in FIGS. 2A and 2B and for an anaerobic reactor.

[0017] FIG. 6C is a graph of CO_2 removed versus time for a bioelectrochemical system in accordance with the embodiment illustrated in FIGS. 2A and 2B and for an anaerobic reactor.

[0018] FIG. 7 is a table of all carbon inputs and outputs in a bioelectrochemical system with an applied electrical potential of 1.5 V.

[0019] FIG. 8 is a chart showing the conversion of carbon from CO_2 to organic carbon in a bioelectrochemical system with an applied electrical potential of 1.5 V.

[0020] FIG. 9 is a graph of CO_2 removed versus time for a bioelectrochemical system at different applied electrical potentials.

DETAILED DESCRIPTION

[0021] This description of the exemplary embodiments is intended to be read in connection with the accompanying drawings, which are to be considered part of the entire written description.

[0022] The disclosed systems and methods include a variety of aspects, which may be selected in different combinations based upon the particular application or needs to be addressed. In some embodiments, bioelectrochemical (BEC) systems are provided to enhance microbial conversion of CO_2 , carbonic acid (H_2CO_3), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) to organic compounds including, but not limited to, carboxylic acids, hydrocarbons, and alcohols. In some embodiments, the use of specific chemical inhibitors of methanogenesis or manipulations of operational conditions, such as pH, redox potential, and retention time are used to enhance microbial conversion of CO_2 , H_2CO_3 , HCO_3^- , and CO_3^{2-} to organic compounds in BEC systems.

[0023] The use of separators comprising a variety of carrier materials that can support physical, chemical, or biological consumption of O_2 produced at anodes in BEC systems. In some embodiments, BEC systems of lower voltage/current are used for CO_2 removal from gas in above ground engineering configurations and in the subsurface such as coal seams, petroleum reservoirs, deep saline aquifers, and the like, where CO_2 -containing gas is injected.

[0024] In some embodiments, a BEC system stimulates microbial activity, such as in biodegradation, nitrate reduction, and hydrogen production. BEC systems include microbial fuel cells, microbial electrolysis cells, and their hybrids and modifications. In BEC systems where low voltage/current is applied, an external direct current (DC) or alternating current (AC) voltage from external power sources or other BEC reactors is connected to at least two electrodes (i.e., an anode and a cathode). The application of the electric field in BEC systems has been demonstrated to enhance the production of organic acids from carbonaceous feedstocks. BEC systems can be applied to enhance microbial conversion of CO_2 to methane. In such systems, separators such as proton exchange membranes (PEMs), cation exchange membranes (CEMs), anion exchange membranes (AEMs), bipolar membranes, and/or glass fibers are used to separate the anode and cathode of a BEC system to prevent exposure to oxygen (O_2) that may evolve from the electrolysis of water.

[0025] Anaerobic consortia involved in low redox pathways include mixed strains of methanogenic microorganisms that produce methane from CO_2 . Other microorganisms in the consortium can produce other organic compounds, which are subsequently consumed for production of methane if not regulated. Inhibition of methanogenesis can shift the microbial metabolic pathways and cause the accumulation of other organic compounds such as acetate. The addition of specific inhibitors of methanogenesis such as 2-bromoethanesulfonic acid (2-BESA) can improve BEC system performance to yield higher volumes of hydrogen.

[0026] The disclosed systems and methods utilize BEC systems to reduce CO_2 and transform it into organic compounds, such as organic acids, and therefore transform CO_2 into value-added products. This is achieved by controlling operational conditions, such as pH retention time, temperature, or using inhibitor(s) to block methanogenesis and accumulate pre-methanogenic compounds. The BEC systems utilize separators made from carbon mesh, fiber glass, plastic etc., which function as a biofilm carrier, to consume O_2 produced at the anode. The BEC systems can be used in an aboveground or a subsurface process, in both in situ and ex situ layouts. The disclosed BEC systems operate with low electrical potential and current (e.g., less than or equal to 30 V/m and/or less than or equal to 500 mA, and more preferably less than or equal to 20 V/m and less than or equal to 200 mA), and electrical stability and consistency are not required. Therefore, advantageously, renewable energy technologies

such as wind or solar power can be readily utilized to provide electricity to BEC systems without adding any carbon footprints, and achieve a sustainable CO_2 reduction and conversion. In some embodiments, a BEC system includes one or more of microbial fuel cells, microbial electrolysis cells, and electrolysis cells, and combinations thereof

[0027] FIG. 1 illustrates one example of an improved BEC system **100**, which is implemented as a closed or single-chamber reactor system. As shown in FIG. 1, BEC system **100** includes a container or housing **102** in which microbes **104** are disposed. A barrier **106** may at least partially divide the interior **108** of housing **102** into a first compartment **110** in which anaerobic microbes **104** are disposed and a second compartment **112**. In some embodiments, barrier **106** may be omitted such that interior **108** of housing **102** is a single compartment. In embodiments in which barrier **106** at least partially separates interior **108** into first and second compartments, cathode **114** is disposed within the first section **110** and an anode **116** is disposed within the second compartment **112**. Cathode **114** and anode **116** are coupled to a power supply **118**.

[0028] First compartment **110** of container **102** includes a first inlet **120** for receiving CO_2 from a CO_2 source **122**. First compartment **110** also includes an outlet **124** configured to expel organic compounds from first section **110**. A second inlet **126** may be coupled to the conduit **128** coupled to outlet **124** to provide a return path for CO_2 that is expelled through outlet **124**. In some embodiments, CO_2 produced in anode compartment **112** is received within cathode compartment **110**.

[0029] Housing or container **102** may be any device having an internal chamber configured to hold a gas or liquid. In some embodiments, water and aqueous solutions are disposed within the interior **108** of container **102** on either side of barrier **106**. One of ordinary skill in the art will understand that other liquids or fluids may be used. Container **102** may be fabricated from stainless steel or other suitable material.

[0030] The anaerobic microbial consortia, i.e., microbes **104**, may include mixed or single strains and be sourced from multiple environments that may include, but are not limited to, anaerobic digesters from municipal or industrial wastewater treatment plants, wetland or marine sediments, landfills, surface waters, groundwater, coal seam and other subsurface formation waters, and custom cultures. The anaerobic microbial consortia **104** may already exist (i.e., indigenous to) in the location of the BEC system in situ. In some embodiments, microbes **104** disposed on the cathode side **110** of container **102** are methanogenic microorganisms that consume CO_2 and break it down into other chemicals.

[0031] Inhibitors may be added to the cathode side **110** of housing **102** to enhance the conversion of CO_2 , H_2CO_3 , HCO_3^- , and CO_3^{2-} to organic compounds. These methogenic inhibitors may be categorized as structural analogs of coenzyme M, hydroxymethylglutaryl-SCoA (HMG-CoA) reductase inhibitors, nitrocompounds, inorganic salts, and halogenated compounds. In some embodiments, the inhibitors may include, but are not limited to, 2-bromoethane sulfonic acid (2-BESA), lumazine, 2-chloroethanesulfonate, 2 mercaptoethanesulfonate, other coenzyme M structural analogs, propynoic acid, ethyl 2 butynoate, other HMG-CoA reductase inhibitors, methyl chloride, chloroform, methyl fluoride, fluoroacetate, ethylene, acetylene, nitrate, nitrite, nitroethane, 2-nitropropanol, phosphate, medium and long chain fatty acids, mevastatin, fluvastatin, and lovastatin. The inhibitors may be added at different amounts and combinations based on the specific application, requirements, and desired

products of the BEC system. In some embodiments, the concentration of inhibitors is between 100 µg/L to 500 mg/L.

[0032] Additionally, pH buffers may also be added to the cathode compartment **110**. The pH buffers may be added in sufficient amounts to maintain the pH in the cathode compartment **110** between 5.0 and 9.0. Examples of the pH buffers include, but are not limited to, acids and bases such as HCl, NaOH, KOH, MgOH, H₂SO₃, acetic acid, phosphoric acid, monobasic phosphate salts, dibasic phosphate salts, carbonate salts, bicarbonates salts, Tris buffer, HEPES, MESs, and MOPS. Concentrations of the pH buffers may be added such that the pH of the system is within the range of 5.0-9.0.

[0033] Barrier **106** disposed between the anode **116** and cathode **114** may be fabricated from carbon mesh, carbon cloth, carbon fiber, glass fiber, polyester, nylon fiber, cellulose, PTFE, plastics, and ion exchange membranes. The material itself may consume or block O₂ produced at anode **116** from electrolysis of water, or it may support biofilms composed of microorganisms that consume O₂. Barrier **106** may be shaped and configured in different combinations to fit the specific needs of the BEC system that has been designed for a specific application. In some embodiments, barrier **106** completely divides interior **108** into separate compartments **110**, **112**, and in other embodiments barrier **106** partially divides interior **108** into separate compartments **110**, **112**.

[0034] The electrodes, i.e., cathode **114** and anode **116**, may be fabricated from carbon, carbon fiber, stainless steel, galvanized steel, copper, and other conductive materials or nonconductive materials with conductive coatings. The electrodes **114**, **116** may be shaped and configured in different combinations to fit the specific needs of the BEC system that has been designed for a specific application. The wires connecting the electrodes to the electrical power source **118** may include stainless steel, copper, aluminum, or titanium, to name a few possible materials. Wire may be connected to the electrodes at single or multiple points through physical joints and configurations that are sealed and insulated to avoid water intrusion. Segments inside water or at close proximity to water may be insulated.

[0035] Electrical power source **118** may provide DC and/or AC power to electrodes **114**, **116**. A battery may be used to provide DC voltage to the BEC system either by direct application or indirectly through recharging batteries. Other electrical sources **118** may include, but are not limited to, fuel driven generators (gasoline, diesel fuel, natural gas, biofuels, hydrogen, etc.), solar power systems, wind power systems, microbial fuel cells, and other renewable energy sources. If a load is used, the resistance of the load may range from 0.001-10,000 ohms. The electrical potentials, currents, and resistances can be increased or decreased depending on the specific needs of the BEC system as will be understood by one of ordinary skill in the art.

[0036] Carbon dioxide source **122** may be a flue gas of an industrial power plant, such as a coal-fired plant. One of ordinary skill in the art will understand that CO₂ source **122** may be any other source of CO₂. For example, stack emission from cement plants, steel plants, landfill incinerators, oil refineries, natural gas power plants, chemical plants, plastic production plants, pulp and paper mills, wastewater treatment plants, and other plants combusting fossil fuels and giving off CO₂. In some embodiments, the CO₂ is produced by microbial reactions at anode **116**.

[0037] The organic compounds produced by BEC system **100** from CO₂, H₂CO₃, HCO₃⁻, and CO₃²⁻ may be produced with or without the addition of chemical inhibitors of methanogenesis. Examples of the organic compounds include, but are not limited to, organic acids, organic salts, hydrocarbons,

alcohols, amines, esters, ethers, amides, lactams, and other categories of organic compounds.

[0038] FIGS. **2A** and **2B** illustrates another example of an improved BEC system **200** in which anode **116** is disposed at the center of container **102**, which has its outer wall used as cathode **114**. Granulated sludge **130**, in which microbes **104** are disposed, is located within cathode chamber **110**. Cathode chamber **110** is separated from anode chamber **112** by separator **106**. The embodiment illustrated in FIGS. **2A** and **2B** advantageously maximizes the volume on the cathode side of the BEC system **200**.

[0039] These BEC systems **100**, **200** described above can be operated as static or continuous flow systems with varying hydraulic retention times and gas injection flows. The organic compounds that are produced can be separated and recovered from the effluent (product) stream and may be utilized based on the typical uses for the type organic compounds that were produced.

[0040] BEC systems **100**, **200** may be implemented in subsurface formations to enhance the conversion of CO₂, H₂CO₃, HCO₃⁻, and CO₃²⁻ to organic compounds. For example, FIG. **3** illustrates a plurality of BEC systems **100-1**, **100-2**, **100-3** disposed in a subsurface formation **300** located below ground surface **302**. Subsurface formations may include, but are not limited to, bituminous, subbituminous, lignite, coal seams, petroleum reservoirs, shale, saline aquifers, and groundwater aquifers, to name a few possibilities.

[0041] A plurality of wells **304-1**, **304-2**, **304-3**, **304-4**, and **304-5** extend from surface **302** into subsurface formation **300**. Carbon dioxide and inhibitors may be injected into the subsurface formation **300** via well **300-1**. As described above, the CO₂ source **122** (not shown in FIG. **3**) may be a flue of a coal-burning plant or other industrial plants. BEC systems **100-1**, **100-2**, and **100-3** are respectively disposed at the bottom of wells **304-2**, **304-3**, and **304-4**, and well **304-5** is used to extract organic compounds from subsurface formation **300**. Carbon dioxide, inhibitors, and organic compounds may flow through subsurface formation **300** from one well **304** to another well **304**.

[0042] Power supply **118** may be disposed above surface **302** and connected to BEC systems **100-1**, **100-2**, and **100-3** via wires as will be understood by one of ordinary skill in the art. As described above, power supply **118** may be from a power grid or from a renewable energy system such as, for example, a solar power system, a hydrogen generator, fuel cell, and/or a wind power system.

[0043] Organic compounds may or may not be recovered down gradient from the BEC systems **100**, **200** from a recovery or producing well **304**. Methane may be a byproduct of the process and can be utilized for energy to power the BEC systems **100**, **200** or be transferred to a natural gas pipeline. The organic compounds may be separated and utilized based on the typical uses for the type organic compounds that were produced. The organic compounds may also remain in subsurface formations **300** (coal has been found to be a good subsurface formation for long-term storage) to sequester carbon in a non-hazardous form. The BEC systems **100**, **200** may be installed in single or multiple wells **304** as illustrated in FIG. **3**, or anodes **116** and cathodes **114** may be installed in separate wells **304**. The configurations of the electrodes **114**, **116** or BEC systems **100**, **200** may be varied based on subsurface characteristics, extent of the amount of CO₂, H₂CO₃, HCO₃⁻, and CO₃²⁻ to be injected, and desired yields of organic compounds.

[0044] FIG. **4** is a flow diagram of one example of a method **400** of converting CO₂ into organic compounds in accordance with a BEC system **100**, **200**. At block **402**, CO₂ is received

within a cathode chamber **110**. The CO₂ may be received in cathode chamber **110** from a CO₂ source **122** such as a flue of a coal-burning power plant or other sources as described above.

[0045] At block **404**, additives, e.g., inhibitors and/or pH buffers, are received within cathode chamber **110**. Examples of methogenic inhibitors include, but are not limited to, 2-BESA, lumazine, 2-chloroethanesulfonate, 2 mercaptoethanesulfonate, other coenzyme M structural analogs, propynoic acid, ethyl 2 butyrate, other HMG-CoA reductase inhibitors, methyl chloride, chloroform, methyl fluoride, fluoroacetate, ethylene, acetylene, nitrate, nitrite, nitroethane, 2-nitropropanol, phosphate, medium and long chain fatty acids, mevastatin, fluvastatin, and lovastatin. The inhibitors may be added at different amounts and combinations as will be understood by an ordinarily skilled person in the art.

[0046] The pH buffers may be from organic or inorganic sources. Examples of such organic or inorganic source of pH buffers include, but are not limited to, phosphates, carbon, Tris buffer, HEPES, MESs, and MOPS, to name a few possibilities.

[0047] At block **406**, an electrical potential is established across electrodes **114**, **116**. The electrical potential may be a DC or AC potential generated by power supply **118**. Power supply may be a battery, a fuel driven generators (gasoline, diesel fuel, natural gas, biofuels, hydrogen, etc.), solar power systems, wind power systems, microbial fuel cells, and other renewable energy sources. If a load is used, the resistance of the load may range from 0.001-10,000 ohms. The electrical potentials, currents, and resistances can be increased or decreased depending on the specific needs of the BEC system with as will be understood by those of ordinary skill in the art.

[0048] At block **408**, organic compounds are removed from BEC system **100**, **200**. In some embodiments, the organic compounds may be emitted from BEC systems **100**, **200**, but remain in subsurface formations **300** to sequester carbon in a non-hazardous form. Examples of the organic compounds include, but are not limited to, organic acids, organic salts, hydrocarbons, alcohols, amines, esters, ethers, amides, and other categories of organic compounds. In addition to organic compounds, methane may be a byproduct of the process and can be utilized for energy to power the BEC systems **100**, **200** or be transferred to a natural gas pipeline.

EXAMPLES

[0049] A laboratory bench-scale BEC system was tested for transforming CO₂ to an organic compound. Two carbon electrodes were installed in a 3.8-L batch reactor and carbon mesh was inserted in between the electrodes. The reactor was filled with 3 L of common mineral medium composed of constituents such as ammonium, phosphates, potassium, magnesium, calcium, sulfate, cobalt, nickel, and other trace metals. The reactor (headspace and the medium) was purged with compressed pure CO₂. The reactor was sealed by inserting a connection to a modified manometer and a methanogenic inhibitor, 2-BESA, was added to the solution in the reactor. The BEC reactor was then inoculated with 300 mL of granulated sludge from an anaerobic digester. The electrodes were connected to an AC-DC converter, which was set to 1.5 V. The headspace gas composition and organic compounds in the reactor solution were determined and quantified during operation.

[0050] The results shown in FIG. 5 indicate that CO₂ composition in the BEC reactor headspace decreased from 22.4 to 1.84% (92% decrease) within 7 d. The CO₂ concentration was less than 1% after 15 d. Within 4 d, lactate (or similar compound detected on LC-MS) was detected in the solution at a

concentration 5332 mg/L, which eventually decreased to 2258 mg/L after 15 d, possibly due to cell uptake, which can be eliminated by rapid product removal or a flow through design below. Zero to trace amounts of methane was detected in the headspace gas. The results of this test demonstrate the feasibility of applying inhibitors to a methanogenic consortium and applying our BEC technique to enhance transformation of CO₂ to an organic compound.

[0051] A BEC system **200** in accordance with the embodiment illustrated in FIG. 2 was constructed and tested. Cathode **114** was a stainless steel mesh, and anode **116** was a stainless steel rod. The barrier/separator **106** was a polyester fabric. The cathode compartment **110** of the BEC system **200** and a disconnected control anaerobic reactor were filled with granulated sludge **130** from a wastewater treatment plant anaerobic digester. The reactors were filled to 16 L of amendments solution leaving 4 L headspace. Gas collection bag of 5.57-L capacities were connected to the reactor headspace. A gas cylinder was used as the carbon dioxide source **122** to add carbon dioxide to the reactors. The electrodes **114**, **114** were connected to a DC source set at 1.5 V. The current supplied to electrodes **114**, **116** is shown in the graph in FIG. 6A. Approximately 86% of carbon dioxide was removed within 27 d in the BEC system **200**, while the control reactor yielded a 20% decrease in CO₂ as illustrated in FIGS. 6B and 6C.

[0052] The disclosed systems and methods advantageously utilize BEC systems to transform CO₂ into organic compounds. The BEC systems may be implemented in combination with CO₂ producing systems, such as coal-burning or other industrial plants, to reduce the amount of CO₂ released into the atmosphere. Not only do the BEC systems reduce the amount of CO₂ released into the atmosphere, but the improved BEC systems advantageously transform CO₂ into value-added products such as organic compounds and methane.

[0053] The table illustrated in FIG. 7 shows the amount of carbon input into the BEC system and the amount of carbon output. Based on a carbon balance, a 77% recovery is observed, where carbon on the electrodes and precipitated inorganic carbon is not accounted for. The increase in total organic carbon with the decrease of CO₂ is shown in FIG. 8, which confirms microbial utilization of CO₂.

[0054] A separate test was conducted with different applied electrical potentials of 0.2, 0.29, 0.4, and 0.6 V. As shown in FIG. 9, the amount of CO₂ decreased by 31-56%, where the lowest reduction occurring at 0.2 V and the highest reduction occurring at 0.6 V.

[0055] Although the invention has been described in terms of exemplary embodiments, it is not limited thereto. Rather, the appended claims should be construed broadly, to include other variants and embodiments of the invention, which may be made by those skilled in the art without departing from the scope and range of equivalents of the invention.

What is claimed is:

1. A bioelectrochemical system, comprising:
 - a housing defining an internal chamber;
 - a barrier disposed within the housing and at least partially separating the internal chamber into first and second compartments, the first compartment including at least one of an autotrophic or a heterotrophic microorganisms disposed therein;
 - a cathode disposed within the first compartment and coupled to a power supply; and
 - an anode disposed within the second compartment and coupled to the power supply,
 wherein carbon dioxide received within the first compartment is transformed into an organic compound.

2. The bioelectrochemical system, wherein the carbon dioxide is received within the first compartment from a carbon dioxide source.

3. The bioelectrochemical system of claim 1, wherein a biofilm that consumes oxygen is disposed on the barrier.

4. The bioelectrochemical system of claim 1, wherein an inhibitor is disposed within the first compartment.

5. The bioelectrochemical system of claim 4, wherein the inhibitor includes at least one of 2-bromoethane sulfonic acid (2-BESA), lumazine, 2-chloroethanesulfonate, 2 mercaptoethanesulfonate, other coenzyme M structural analogs, propynoic acid, ethyl 2 butynoate, other HMG-CoA reductase inhibitors, methyl chloride, chloroform, methyl fluoride, fluoroacetate, ethylene, acetylene, nitrate, nitrite, nitroethane, 2-nitropropanol, phosphate, medium and long chain fatty acids, mevastatin, fluvastatin, and lovastatin.

6. The bioelectrochemical system of claim 1, wherein the power supply includes a battery.

7. The bioelectrochemical system of claim 1, wherein the power supply includes a renewable energy power source.

8. The bioelectrochemical system of claim 1, wherein the housing is disposed within a subsurface formation.

9. The bioelectrochemical system of claim 1, wherein a pH buffer is disposed within the first compartment to maintain a pH within the first compartment between 5.0 and 9.0.

10. The bioelectrochemical system of claim 1, wherein the at least one of autotrophic or heterotrophic microorganisms includes multiple strains of methanogenic microorganisms.

11. A method, comprising:

receiving carbon dioxide within a first compartment disposed within an internal chamber defined by a housing; receiving an electrical potential across a cathode disposed within the first compartment and an anode disposed within a second compartment within the internal chamber, the first and second compartments at least partially separated by a barrier, the first compartment including at least one of autotrophic or heterotrophic microorganisms disposed therein; and

extracting organic compounds from the first chamber that are derived from the carbon dioxide.

12. The method of claim 11, further comprising receiving inhibitors in the first compartment.

13. The method of claim 12, wherein the inhibitor includes at least one of 2-bromoethane sulfonic acid (2-BESA), lumazine, 2-chloroethanesulfonate, 2 mercaptoethanesulfonate, other coenzyme M structural analogs, propynoic acid, ethyl 2 butynoate, other HMG-CoA reductase inhibitors, methyl chloride, chloroform, methyl fluoride, fluoroacetate, ethylene, acetylene, nitrate, nitrite, nitroethane, 2-nitropropanol, phosphate, medium and long chain fatty acids, mevastatin, fluvastatin, and lovastatin.

14. The method of claim 11, wherein the carbon dioxide is received within the first compartment from a carbon dioxide source.

15. The method of claim 11, wherein a biofilm that consumes oxygen is disposed on the barrier.

16. The method of claim 11, wherein the electrical potential across the cathode and anode is created by a power supply.

17. The method of claim 11, further comprising receiving a pH buffer in the first compartment to maintain a pH of the first compartment between 5.0 and 9.0.

18. The method of claim 11, wherein the at least one of autotrophic or heterotrophic microorganisms include multiple strains of methanogenic microorganisms.

19. A system, comprising:

a first bioelectrochemical system disposed within a first well formed in a subsurface formation, the first bioelectrochemical system including:

a housing defining an internal chamber;

a barrier disposed within the housing and at least partially separating the internal chamber into first and second compartments, the first compartment including multiple strains of methanogenic microorganisms disposed therein;

a cathode disposed within the first compartment and coupled to a first power supply; and

an anode disposed within the second compartment and coupled to the first power supply,

wherein carbon dioxide received within the first compartment of the first bioelectrochemical system is transformed into an organic compound.

20. The system of claim 19, wherein the first power supply includes a renewable energy power source.

21. The system of claim 19, further comprising:

a second bioelectrochemical system disposed within a second well formed in the subsurface formation, the second bioelectrochemical system including:

a housing defining an internal chamber;

a barrier disposed within the housing and at least partially separating the internal chamber into first and second compartments, the first compartment of the second bioelectrochemical system including anaerobic microorganisms disposed therein;

a cathode disposed within the first compartment and coupled to one the first power supply or a second power supply; and

an anode disposed within the second compartment and coupled to one of the first or second power supplies,

wherein carbon dioxide received within the first compartment of the second bioelectrochemical system is transformed into an organic compound.

22. The system of claim 21, wherein the second power supply includes a renewable energy power source.

23. The system of claim 19, wherein a biofilm that consumes oxygen is disposed on the barrier.

24. The system of claim 19, wherein an inhibitor is disposed within the first compartment of the first bioelectrochemical system, the inhibitor including at least one of 2-bromoethane sulfonic acid (2-BESA), lumazine, 2-chloroethanesulfonate, 2 mercaptoethanesulfonate, other coenzyme M structural analogs, propynoic acid, ethyl 2 butynoate, other HMG-CoA reductase inhibitors, methyl chloride, chloroform, methyl fluoride, fluoroacetate, ethylene, acetylene, nitrate, nitrite, nitroethane, 2-nitropropanol, phosphate, medium and long chain fatty acids, mevastatin, fluvastatin, and lovastatin.

25. The system of claim 19, wherein a pH buffer is disposed within the first compartment to maintain a pH within the first compartment between 5.0 and 9.0.

* * * * *