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(71) Applicants: **ARIZONA BOARD OF REGENTS ON BEHALF OF ARIZONA STATE UNIVERSITY** [US/US]; SkySong, 1475 N. Scottsdale Road, Suite 200, Scottsdale, Arizona 85257 (US). **REGENTS OF THE UNIVERSITY OF MICHIGAN** [US/US]; Office of Technology Transfer, 1600 Huron Parkway, 2nd Floor, Ann Arbor, Michigan 48109-2590 (US). **BOARD OF REGENTS, THE UNIVERSITY OF TEXAS SYSTEM** [US/US]; 210 West 7th Street, Austin, Texas 78701 (US).

(72) Inventors: **BOLTZ, Joshua**; 577 E. Baseline Rd., Apt. 2051, Tempe, Arizona 85283 (US). **RITTMANN, Bruce**; 90 West Cottage Ln., Tempe, Arizona 85282 (US). **DAIGER, Glen**; 177 EWRE Building, Ann Arbor, Michigan 48109 (US). **KATZ, Lynn**; University of Texas, Austin, Texas 78712 (US).

(74) Agent: **FULLER, Rodney J.**; Booth Udall Fuller, PLC, 1255 W. Rio Salado Parkway, Suite 215, Tempe, Arizona 85281 (US).

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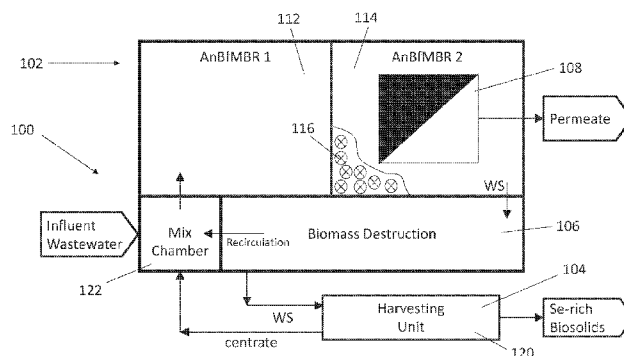


FIG. 2

(57) Abstract: The present invention relates to methods for biological wastewater treatment for Se control in Se-laden wastewater. The Se contaminants in the wastewater include the Se oxyanions selenate (SeO_4^{2-}) and selenite (HSeO_3^-), which are biochemically reduced and transformed to elemental selenium (Se^0) by microorganisms through anaerobic biological reduction. The resulting Se^0 is entrained in the biomass, which is further processed to enable the efficient recovery of concentrated Se^0 .



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SYSTEMS AND METHODS FOR BIOLOGICAL TRANSFORMATION, CONCENTRATION, AND RECOVERY OF SELENIUM FROM WASTEWATER

Related Applications

[0001] This application claims the benefit of and priority to U.S. provisional patent application 63/121,540, filed December 4, 2020, the entirety of the disclosure of which is hereby incorporated by this reference thereto.

Technical field

[0002] The disclosure relates to systems and methods for the treatment of selenium-laden wastewater and the recovery of elemental selenium, which is a by-product of biological wastewater treatment.

Background

[0003] Selenium is a valued resource of limited quantity. Notably, the soils in significant regions of New Zealand, Denmark, Finland, China, and Canada are selenium deficient (Gupta and Gupta 2000). Selenium has been used for manganese electrolysis and in the industrial production of glass, pigments, alloys, lithium-selenium batteries, solar cells, and photoconductors. In glass manufacturing, selenium may be utilized to de-colorize the green tint that is caused by iron impurities and to reduce solar-heat transmission in architectural plate glass. Cadmium sulfoselenide pigments may be used to produce a ruby-red color in ceramics, glass, and plastics. Selenium may additionally be used in blasting caps; in catalysts to enhance selective oxidation; in copper, lead, and steel alloys to improve machinability; in the electrolytic production of manganese to increase yields; in gun bluing for corrosion resistance and improved aesthetics; in plating solutions for improved appearance and durability; in rubber compounding chemicals as a vulcanizing agent; and in thin-film photovoltaic copper-indium-gallium-diselenide (CIGS) solar cells.

[0004] In addition to commercial and industrial applications, trace amounts of selenium are essential for several cellular functions. Selenium is a component of the antioxidant enzymes glutathione peroxidase and thioredoxin reductase which indirectly reduce certain oxidized

molecules in animals and some plants. Selenium also is found in three deiodinase enzymes that convert one thyroid hormone to another. A selenium deficiency in animals can lead to reproductive disorders, birth defects, and has been linked to thyroid disorder. While suitable substitutes exist for many industrial applications, selenium has no replacement for maintaining healthy cellular activity and is an ingredient in many multivitamins, dietary supplements, infant formula, and fertilizers.

[0005] Primary selenium is refined from anode residue that results from the electrolytic refining of copper. Consequently, selenium availability is affected by copper supply, along with the number of facilities that recover selenium. Selenium reserves are based on identified copper deposits and the average selenium content in these copper deposits. Coal typically has a selenium content in the range of 0.5 to 12 parts per million, or approximately 80 to 90 times the average selenium content of copper deposits. However, selenium recovery from coal processing, although technically feasible, is not economical by means of existing technologies (Stillings 2019).

[0006] While selenium is a valued material and essential trace element for all living organisms, toxic quantities of selenium may exist in ecosystems due to human activity. Selenium-laden wastewater can originate from mining and mineral processing, steam electric-power generation, irrigated agriculture in seleniferous soils, and oil and gas industrial activities. Consequently, selenium is a water pollutant that is regulated by the United States EPA.

[0007] Using the authority of the Clean Water Act (CWA), under Title 40 of the Code of Federal Regulations (CFR) Part 423, the US EPA established effluent limit guidelines (ELG) for wastewater discharges emanating from steam electric-power generating facilities. For most existing steam-electric generating units, specified maximum average daily concentrations during any consecutive 30-day period are 29 $\mu\text{g Se/L}$ for the selenium concentration remaining in flue gas desulfurization (FGD) wastewater (EPA 2020). Typical selenium oxyanion concentrations are in the order of 1 to 1,000 $\mu\text{g Se/L}$. Often, the sources of selenium are the oxyanions selenate (SeO_4^{2-}) and/or selenite (HSeO_3^-). Therefore, significant potential exists for coupling the treatment of selenium-laden wastewaters with its concentration and recovery from the wastewater.

Summary

[0008] The present disclosure is directed to methods of recovering selenium from wastewater, e.g., recovered as elemental selenium.

[0009] In some embodiments, the method comprises providing an influent wastewater comprising selenium oxyanions to a biological wastewater treatment system; converting the selenium oxyanions into elemental selenium, wherein the biological wastewater treatment system converts the selenium oxyanions into elemental selenium and produces a waste sludge; and recovering elemental selenium from the waste sludge, wherein an elemental selenium-biomass separation unit separates the elemental selenium from the biomass. The waste comprises biomass and elemental selenium.

[0010] In other embodiments, the method comprises the steps of: providing an influent wastewater comprising selenium oxyanions to a biological wastewater treatment system; converting the selenium oxyanions into elemental selenium, wherein the biological wastewater treatment system converts the selenium oxyanions into elemental selenium and produces a waste sludge that comprises biomass and the elemental selenium; and transferring the sludge to a biomass processing unit, wherein the biomass processing unit reduces the total mass of the waste sludge to produce a processed waste sludge. Compared to the waste sludge, the mass of the elemental selenium is unchanged in the processed waste sludge. The method further comprises returning the processed waste sludge from the biomass processing unit to the biological wastewater treatment system, wherein elemental selenium is further agglomerated in the waste sludge to produce a sludge with concentrated elemental selenium, and then recovering elemental selenium from the sludge comprising concentrated elemental selenium with an elemental selenium-biomass separation unit. The elemental selenium-biomass separation unit substantially separates elemental selenium from the biomass.

[0011] In one aspect, biomass is returned to the biological wastewater treatment system from the biomass processing unit. Then, selenium-rich sludge is periodically removed, or wasted, from the biological wastewater treatment system.

[0012] In one embodiment, the biological wastewater treatment system comprises an anaerobic biofilm membrane bioreactor (AnBfMBR).

[0013] In one embodiment, the biomass in the biomass processing unit is subjected to one or more treatments selected from a group that may include, but is not limited to: a hydrolysis reaction, an oxidation reaction, a reduction reaction, or combinations thereof. In another embodiment, the biomass in the biomass processing unit is subjected to one or more treatments selected from a group that may include, but is not limited to: ozonation, thermal hydrolysis, ultrasound, electrical

fields, mechanical shearing, aerobic digestion, anaerobic digestion, or combinations thereof. In an embodiment, a biomass processing unit reduces the biomass while the mass of elemental selenium is unaffected.

[0014] In some implementations, the influent wastewater contains sufficient macro-nutrients and organic electron donor(s). In one embodiment, macro-nutrients are added to the influent wastewater, wherein the macro-nutrients are selected from a group that may include, but is not limited to: C, N, P, and S. In another embodiment, an organic electron donor is added to the influent wastewater.

Brief Description of the Drawings

[0015] **FIG. 1** depicts, in accordance with certain embodiments, a process for the biological transformation of selenium oxyanions into elemental selenium, concentration of elemental selenium in biomass, and separation of elemental selenium from biomass.

[0016] **FIG. 2** depicts, in accordance with certain embodiments, a schematic of a biological wastewater treatment system for the biological transformation of selenium oxyanions into elemental selenium, concentration of elemental selenium in biomass, separation of elemental selenium from biomass, and recirculation of biomass and centrate back into the beginning of the process.

[0017] **FIG. 3** depicts, in accordance with certain embodiments, a schematic of a biofilm membrane bioreactor system with biofilm carriers suspended in the bioreactor.

[0018] **FIG. 4** depicts, in accordance with certain embodiments, membrane filters with a membrane gap between each of the membrane filters.

Detailed Description

[0019] Detailed aspects and applications of the invention are described below in the drawing and detailed description of the invention. Unless specifically noted, it is intended that the words and phrases in the specification and the claims be given their plain, ordinary, and accustomed meaning to those of ordinary skill in the applicable arts.

[0020] In the following description, and for the purposes of explanation, numerous specific details are set forth to provide a thorough understanding of the various aspects of the invention. It will be understood, however, by those skilled in the relevant arts, that the present invention may be

practiced without these specific details. It should be noted that there are many different and alternative configurations, devices and technologies to which the disclosed inventions may be applied. The full scope of the inventions is not limited to the examples that are described below.

[0021] The singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a step” includes reference to one or more of such steps.

[0022] As used herein, the term “influent wastewater” refers to any water containing, but is not limited to, the oxyanions selenate and/or selenite that are to be substantially transformed into elemental selenium for any variety of reasons. Influent wastewater may be agricultural wastewater, municipal wastewater, steam-power generation wastewater, mining wastewater, refinery wastewater, and other types of wastewater.

[0023] As used herein, the term “biological wastewater treatment system” refers to a bioreactor and liquid-solid separation that transforms selenate and/or selenite present in influent wastewater to elemental selenium, which is predominantly retained in the biomass. The biological wastewater treatment system utilizes bacteria, including suspended growth and/or biofilms, to biochemically transform contaminants in influent wastewater. This may be done in both an anaerobic and an aerobic environment. The biological wastewater treatment system can use a variety of reactors, for example, an anaerobic biofilm membrane bioreactor (AnBfMBR), anaerobic granular sludge reactor, biologically active filter, fluidized bed reactor, or moving bed biofilm reactor.

[0024] As used herein, the term “liquid-solid separation” refers to any device employed to substantially separate undissolved, or suspended, solids from a liquid such as water. Such devices include, but are not limited to, membranes (ceramic or polymeric), granular media, gravity, and sedimentation.

[0025] As used herein, the term “suspended growth” refers to a biological floc or granule, that is, a flocculent or granular mass of microorganisms (as bacteria) suspended in water. A floc is a relatively open structure when compared with a granule. Their suspension in a liquid, such as water, is mixing dependent.

[0026] As used herein, the term “biofilm” refers to an accumulation of microorganisms (in a relatively dense layer) on a substratum. The biofilm substratum may be any surface that allows biofilm growth and may include particles such as sand, non-biodegradable bacterial materials, and synthetic surfaces formed from, for example, polystyrene or high-density polyethylene.

[0027] As used herein, the term “biomass” refers to the organic and inorganic particulate matter contained in the biological process and includes particulate matter consisting of bacteria and other microorganisms, microorganism decay products, inorganic particles, other particulates, or any combination thereof.

[0028] As used herein, the term “sludge” refers to compacted organic and inorganic particulate matter suspended in a bioreactor effluent or separated therefrom using liquid-solid separation. The particulate matter may contain suspended growth, detached biofilm fragments, inorganic particles, elemental selenium, other particulates, or any combination thereof. Typically, sludge is compacted by liquid-solid separation processes where the suspended growth, and other particulate matter, is separated from the bioreactor effluent. In some embodiments, a portion of the sludge and water is returned to the bioreactor – via internal recirculation – for even distribution of the suspended growth and/or the return of partially treated water to a zone for further treatment. In order to maintain a desired and stable mass of suspended growth (typically valuated using a stable total suspended-solids concentration), a portion of the sludge is removed, or wasted, from the biological wastewater treatment system of at a rate equivalent to the rate of bacterial growth, or yield. The “waste sludge” may be subjected to further treatment(s) such a thickening, digestion, dewatering, and/or other technologies that are collectively referred to as solids management.

[0029] As used herein, the term “permeate” refers to the water exiting the biological wastewater treatment system with reduced concentrations of selenate and selenite.

[0030] As used herein, the term “biomass processing” refers to any unit that substantially reduces biomass while leaving the mass of elemental selenium unaffected. Biomass processing may include, but is not limited to, ozonation, thermal hydrolysis, ultrasound, electrical fields, mechanical shearing, aerobic digestion, anaerobic digestion, or combinations thereof.

[0031] As used herein, the term “processed waste sludge” refers to biomass processing unit effluent, which is characterized by substantially reduced biomass and a mass of selenium that is unaffected when compared with the biomass processing unit influent, which is waste sludge.

[0032] As used herein, the term “elemental selenium-biomass separation” refers to any unit that substantially separates elemental selenium and biomass, whether it be by physical, chemical, thermal, or mechanical means.

[0033] As used herein, the term “dimension” refers to a measurement of length, width, height, or any other distance measurement relating to the physical size of an object, where the measurement is taken between the two most extreme points of the object along one axis.

[0034] As used herein, the term “solids-residence time” refers to an amount of time that a particular solid spends within the selenium recovery wastewater treatment system.

[0035] Disclosed herein are a selenium recovery wastewater treatment system 100 and a method of recovering elemental selenium from selenium-laden wastewater. The method combines biological and physical processes, and in some aspects, also chemical processes, to transform selenium oxyanions into elemental selenium, concentrate the elemental selenium in biomass, and separate the biomass and elemental selenium. The system 100 for recovering elemental selenium from selenium-laden wastewater comprises a biological wastewater treatment system 102, which may be a bioreactor, and a harvesting unit 104. As a result of the disclosed methods and systems, elemental selenium accumulates in the biological wastewater treatment system 102 in a fashion that results in elemental selenium particles that are more easily separated from the biomass.

[0036] As shown in FIGs. 1 and 2, an influent wastewater enters the biological wastewater treatment system 102. The biological wastewater treatment system 102 transforms selenium oxyanions in the influent wastewater to elemental selenium and produces waste sludge comprising water, biomass, and elemental selenium. The elemental selenium is predominantly entrained in the biomass. In some aspects, the influent wastewater comprises sufficient concentrations of macro-nutrients (for example, C, N, P, and S), micro-nutrients (for example, Se), and/or an organic electron donor (for example, molasses, acetate, methanol, ethanol, or proprietary substrates such as MicroC). In some embodiments, macro-nutrients, micro-nutrients, and an organic electron donor are added to the influent wastewater to enable biological processes.

[0037] Periodically, waste sludge is withdrawn from the biological wastewater treatment system 102 and sent to the harvesting unit 104 where elemental selenium is substantially separated from biomass and water. In some aspects, the biological wastewater treatment system 102 has an effluent from which sludge is sent to the harvesting unit 104 where elemental selenium is substantially separated from biomass and water. The biological wastewater treatment system 102 also has a second effluent stream which is the permeate.

[0038] A wide variety of processes can be used for the biological transformation of selenium oxyanions, and the biological wastewater treatment system 102 can be any system that is capable

of converting selenium oxyanions into elemental selenium. In some embodiments, selenium oxyanions are biochemically transformed into elemental selenium through anaerobic biological reduction reactions. In a non-limiting embodiment, the unit for the biological wastewater treatment system 102 involves a system as disclosed in International PCT Application No. PCT/US21/25666 (the contents of which are incorporated herein by reference in its entirety), which comprises a nonporous hollow-fiber membrane inoculated with hydrogen-autotrophic bacteria in the presence of hydrogen gas. In another embodiment, the biological wastewater treatment system 102 comprises an AnBfMBR as disclosed in International PCT Application No. PCT/US2021/061893 (the contents of which are incorporated herein by reference in its entirety). The AnBfMBR comprises a biofilm carrier on which biofilms grow and a ceramic membrane for liquid-solid separation prior to permeate leaving the biological wastewater treatment system 102.

[0039] The biological wastewater treatment system 102 may be configured to receive and process wastewater comprising selenium oxyanions, including selenate and selenite, as mentioned above. The biological wastewater treatment system 102 may be aerobic or anaerobic. As shown in FIGs. 2 and 3, a membrane filter 108 may be used in conjunction with the biological wastewater treatment system 102 to filter the wastewater and generate permeate. In some embodiments, the membrane filter 108 is at least two membrane filters 108 (see FIG. 4). The membrane filters 108 may be formed of a ceramic material and may be positioned within the biological wastewater treatment system 102. Other materials are also possible. Each membrane filter 108 may be separated from adjacent membrane filters 108 by a membrane gap 110 (see FIG. 4). In some embodiments, the biological wastewater treatment system 102 is partitioned into a first zone 112 and a second zone 114, as shown in FIG. 2. In such an embodiment, the membrane filters 108 may be located within the second zone 114 of the biological wastewater treatment system 102. The biological wastewater treatment system 102 may also have a plurality of biofilm carriers 116 suspended within the biological wastewater treatment system 102 surrounding the membrane filters 108. The plurality of biofilm carriers 116 may be configured to scour the membrane filters 108 to maintain cleaner membrane filters 108 and improve the efficiency of the system 100 in generating permeate. A width of the membrane gap 110 may be at least two times larger than a smallest dimension of a biofilm carrier 116 of the plurality of biofilm carriers 116. The width of the membrane gap 110 may be at least 10 mm. The biological wastewater treatment system 102 may also have a mixer 118 that is configured to agitate the wastewater within the biological

wastewater treatment system 102. The mixer 118 may be positioned within the biological wastewater treatment system 102. The mixer 118 may be a mechanical mixer, a pump or may be accomplished through gas introduction.

[0040] A wide variety of elemental selenium-biomass separation processes may be used to substantially separate elemental selenium from biomass and water. In one non-limiting embodiment, the elemental selenium-biomass separation process includes passing the waste sludge into a centrifuge 120 and spinning the centrifuge 120 to produce a selenium-rich biosolid and a centrate. In another embodiment, the elemental selenium separation process comprises the destruction of biomass through thermal oxidation. The biomass separated from the elemental selenium in the selenium recovery process may be returned to the bioreactor of the biological wastewater treatment system 102 where the macro-nutrients and micro-nutrients can be utilized again for biomass synthesis or discharged from the system. On the other hand, the selenium-rich biosolid that is harvested with the harvesting unit 104 may contain at least 10% elemental selenium. In some embodiments, the selenium-rich biosolid may contain at least 25% elemental selenium or at least 50% elemental selenium. The concentration of selenium within the selenium-rich biosolid may be dependent on the solids-residence time of the biomass within the system 100.

[0041] In some embodiments, the system for recovering elemental selenium from selenium-laden wastewater further comprises a biomass processing unit 106 (see FIG. 1 and 2). The biomass processing unit 106 substantially reduces the total amount of biomass without reducing the amount of elemental selenium entrained in the biomass. In such embodiments, the biological wastewater treatment system 102 comprises an effluent carrying waste sludge into the biomass processing unit 106. Accordingly, the biological wastewater treatment system 102 has an additional influent source, which is the effluent from the biomass processing unit 106.

[0042] Once the waste sludge from the biological wastewater treatment system 102 is sent to a biomass processing unit 106, it is subject to physical, chemical, and/or biological treatments to produce a processed waste sludge. The processed waste sludge comprises elemental selenium and reduced mass when compared to the originating waste sludge. Pulsed electric fields may be applied to the waste sludge to reduce the total mass of the waste sludge without reducing the amount of elemental selenium suspended in the waste sludge. Alternatively, or in addition, conversions occurring in the biomass processing unit 106 include hydrolysis to rupture the biological cells and other particulate matter in the biomass, oxidation of organic matter, reduction of organic matter,

or combinations thereof. In other embodiments, the biomass processing unit 106 treats waste sludge through ozonation, thermal hydrolysis, ultrasound, electrical fields, mechanical shearing, aerobic digestion, anaerobic digestion, or combinations thereof. The products of biomass destruction may include organic components that may be partially or fully biodegradable when returned to the biological wastewater treatment system 102. Macro-nutrients and micro-nutrients in the waste sludge will also be returned to the biological wastewater treatment system 102 where they can be utilized for biomass synthesis.

[0043] Effluent from the biomass processing unit 106, which comprises the processed waste sludge, may be returned, or recirculated, to the biological wastewater treatment system 102, where elemental selenium further agglomerates to produce a sludge with concentrated elemental selenium. Elemental selenium may be recovered from the sludge with concentrated elemental selenium using the harvesting unit 104, where the elemental selenium is separated from the biomass. The biomass separated from the elemental selenium in the selenium recovery process may be returned to the biological wastewater treatment system 102 where the macro-nutrients and micro-nutrients can be utilized again for biomass synthesis or discharged from the system 100. The system 100 may comprise a mixing chamber 122 where the influent wastewater, a portion of the processed waste sludge, and the centrate may be mixed and then passed into the biological wastewater treatment system 102, as shown in FIG. 2.

[0044] As a result of the above-described system 100, selenium may be recovered from wastewater as follows. Influent wastewater is provided to the biological wastewater treatment system 102. A waste sludge comprising biomass and elemental selenium is produced from the influent wastewater. Producing the waste sludge from the influent wastewater may comprise converting the selenium oxyanions into the elemental selenium. The waste sludge may be treated to reduce the total mass of the waste sludge without reducing the elemental selenium, thus producing a processed waste sludge. Before treating the waste sludge, the waste sludge may be passed to the biomass processing unit 106, and after treating the waste sludge, the processed waste sludge may be returned to the biological wastewater treatment system 102. Treating the waste sludge may also comprise at least one of hydrolysis, oxidation of organic matter, reduction of organic matter, ozonation, thermal hydrolysis, ultrasound, electrical fields, mechanical shearing, aerobic digestion, and anaerobic digestion. In some embodiments, a portion of the processed waste sludge is recirculated and mixed with the influent wastewater that is entering the biological

wastewater treatment system 102. The elemental selenium may then be harvested from the processed waste sludge. Harvesting the elemental selenium may comprise passing the waste sludge into the centrifuge 120 and spinning the centrifuge 120 to produce a selenium-rich biosolid and a centrate. In some embodiments, the centrate is then mixed with the influent wastewater that is entering the biological wastewater treatment system 102. Although the above system 100 is described as receiving influent wastewater into the mixing chamber 122 or into the biological wastewater treatment system 102, wastewater may also be introduced to the process at any other point. For example, influent wastewater could also be introduced into the biomass processing unit 106 or into the harvesting unit 104.

Claims

1. A selenium-recovery wastewater treatment system, comprising:
a bioreactor configured to receive and process wastewater comprising selenium oxyanions;
a membrane filter configured to filter the wastewater and generate permeate;
a biomass processing unit fluidly coupled to the bioreactor and configured to receive waste sludge comprising biomass and elemental selenium from the bioreactor, treat the waste sludge, and reduce a concentration of the biomass within the waste sludge; and
a harvesting unit fluidly coupled to the biomass processing unit and configured to receive the treated waste sludge from the biomass processing unit and harvest a selenium-rich biosolid from the treated waste sludge.
2. The system of claim 1, wherein the harvesting unit is a centrifuge configured to separate the treated waste sludge into the selenium-rich biosolid and a centrate.
3. The system of claim 2, further comprising a mixing chamber configured to receive the wastewater from an inlet of the wastewater treatment system, a portion of the treated waste sludge from the biomass processing unit, and the centrate from the harvesting unit and mix the wastewater, the treated waste sludge, and the centrate.
4. The system of claim 1, wherein the selenium-rich biosolid contains at least 10% elemental selenium.
5. The system of any one of claims 1-4, wherein the membrane filter comprises at least two membrane filters positioned within the bioreactor and each of the at least two membrane filters is separated from adjacent membrane filters of the at least two membrane filters by a membrane gap.
6. The system of claim 5, further comprising a plurality of biofilm carriers suspended within the bioreactor surrounding the at least two membrane filters, wherein a width of the membrane gap is at least two times larger than a smallest dimension of a biofilm carrier of the plurality of biofilm carriers.

7. The system of claim 6, wherein the width of the membrane gap is at least 10 mm.
8. The system of claim 6, further comprising a mixer configured to agitate the wastewater within the bioreactor.
9. The system of claim 8, wherein the mixer is positioned within the bioreactor.
10. The system of claim 6, wherein the membrane filter is formed of a ceramic material.
11. The system of any one of claims 1-4, wherein the bioreactor is partitioned into a first zone and a second zone.
12. The system of claim 11, wherein the membrane filter is located within the second zone of the bioreactor.
13. A method of recovering selenium from wastewater comprising:
 - providing an influent wastewater comprising selenium oxyanions to a biological wastewater treatment system;
 - producing a waste sludge from the influent wastewater, the waste sludge comprising biomass and elemental selenium;
 - treating the waste sludge to reduce a total mass of the waste sludge without reducing the elemental selenium to produce a processed waste sludge; and
 - harvesting a selenium-rich biosolid from the processed waste sludge.
14. The method of claim 13, wherein producing the waste sludge from the influent wastewater comprises converting the selenium oxyanions into the elemental selenium.
15. The method of claim 13, wherein treating the waste sludge comprises applying pulsed electric fields to the waste sludge.

16. The method of claim 13, further comprising passing the waste sludge to a biomass processing unit before treating the waste sludge and returning the processed waste sludge to the biological wastewater treatment system after treating the waste sludge.

17. The method of claim 13, wherein the selenium-rich biosolid contains at least 10% elemental selenium.

18. The method of any one of claims 13-17, wherein treating the waste sludge comprises at least one of hydrolysis, oxidation of organic matter, reduction of organic matter, ozonation, thermal hydrolysis, ultrasound, electrical fields, mechanical shearing, aerobic digestion, and anaerobic digestion.

19. The method of any one of claims 13-17, wherein harvesting the elemental selenium comprises passing the waste sludge into a centrifuge and spinning the centrifuge to produce the selenium-rich biosolid and a centrate.

20. The method of claim 19, further comprising mixing the centrate with the influent wastewater.

21. The method of any one of claims 13-17, further comprising, after treating the waste sludge, recirculating a portion of the processed waste sludge and mixing the processed waste sludge with the influent wastewater.

22. The method of any one of claims 13-17, wherein the biological wastewater treatment system is anaerobic.

23. The method of any one of claims 13-17, wherein the biological wastewater treatment system is aerobic.

24. The method of any one of claims 13-17, wherein the biological wastewater treatment system comprises:

a bioreactor having at least one inlet and at least one outlet;
at least two membrane filters positioned within the bioreactor and configured to filter the influent wastewater to generate permeate, wherein each of the at least two membrane filters is separated from adjacent membrane filters of the at least two membrane filters by a membrane gap;
and

a plurality of biofilm carriers suspended within the bioreactor surrounding the at least two membrane filters, wherein a width of the membrane gap is at least two times larger than a smallest dimension of a biofilm carrier of the plurality of biofilm carriers.

25. The method of claim 24, further comprising mixing the wastewater and the plurality of biofilm carriers within the bioreactor.

26. The method of claim 24, wherein the bioreactor is partitioned into a first zone and a second zone.

27. The method of claim 26, wherein each of the at least two membrane filters is located within the second zone of the bioreactor.

28. The method of claim 24, further comprising scouring the at least two membrane filters with the plurality of biofilm carriers.

29. The method of any one of claims 13-17, wherein the influent wastewater further comprises at least one macro-nutrient and/or micro-nutrients selected from the group consisting of: C, N, P, S, and Se.

30. The method of claim 29, further comprising adding the at least one macro-nutrient and/or micro-nutrient to the influent wastewater.

31. The method of any one of claim 13-17, wherein the influent wastewater further comprises at least one organic electron donor.

32. The method of claim 31, further comprising adding the at least one organic electron donor to the influent wastewater.

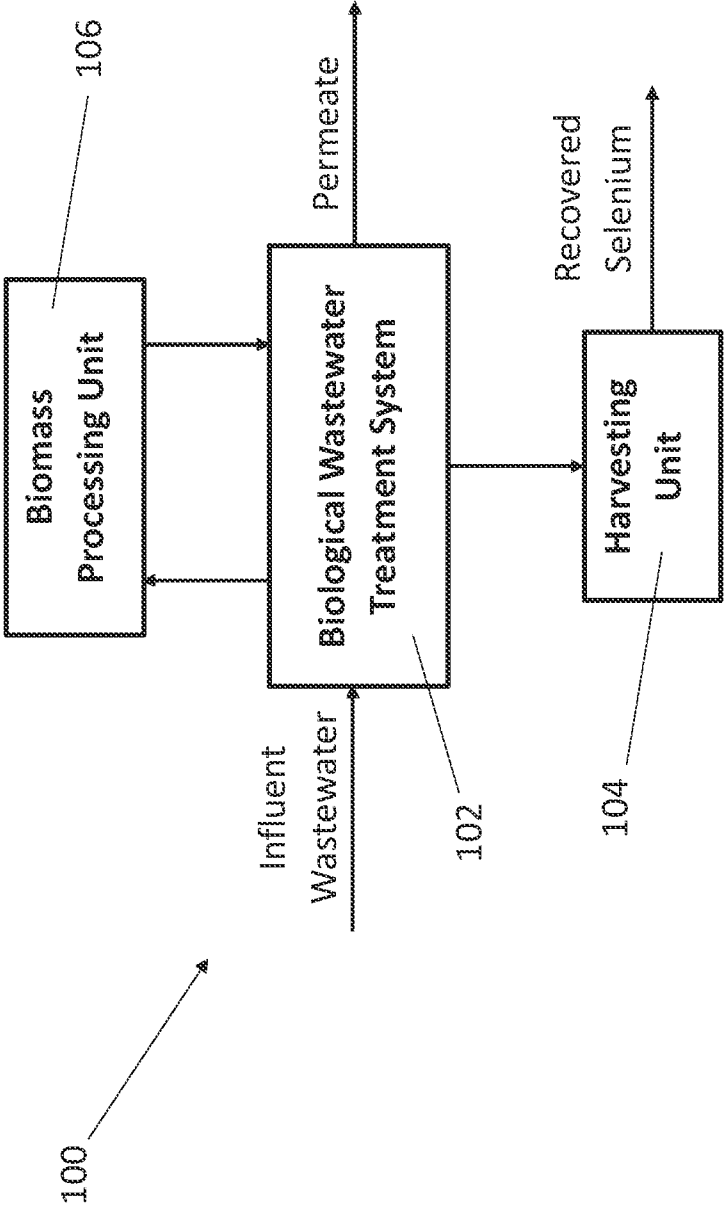


FIG. 1

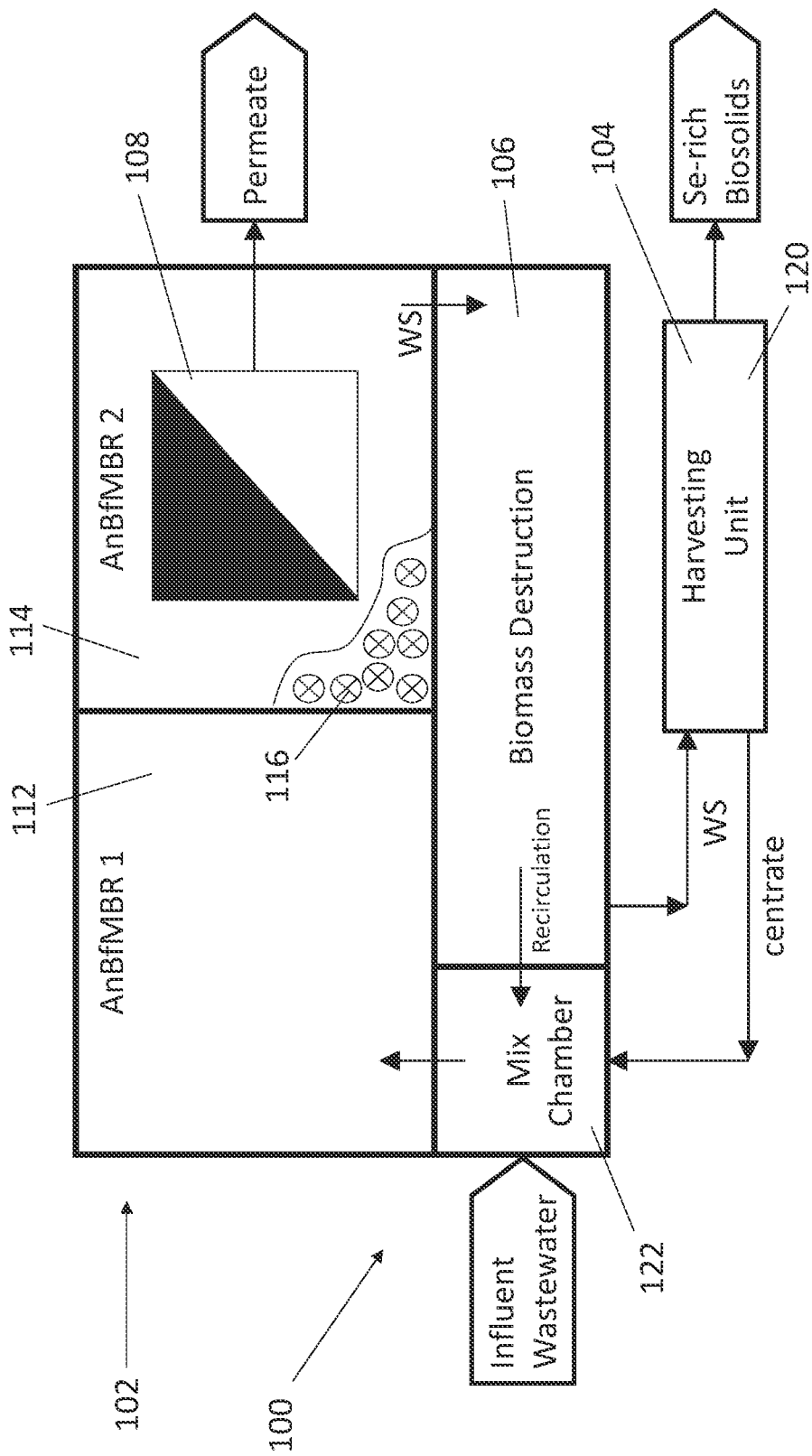


FIG. 2

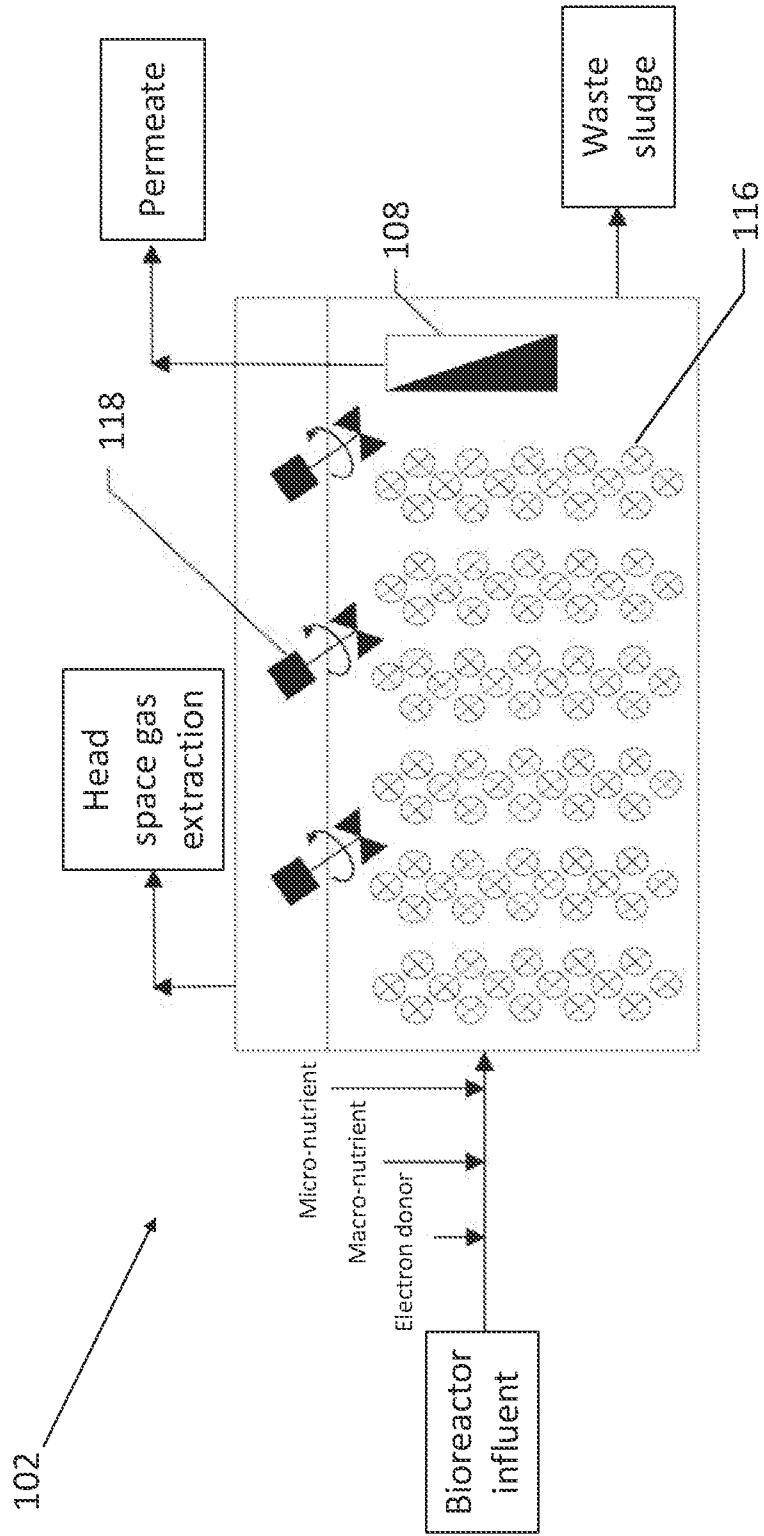


FIG. 3

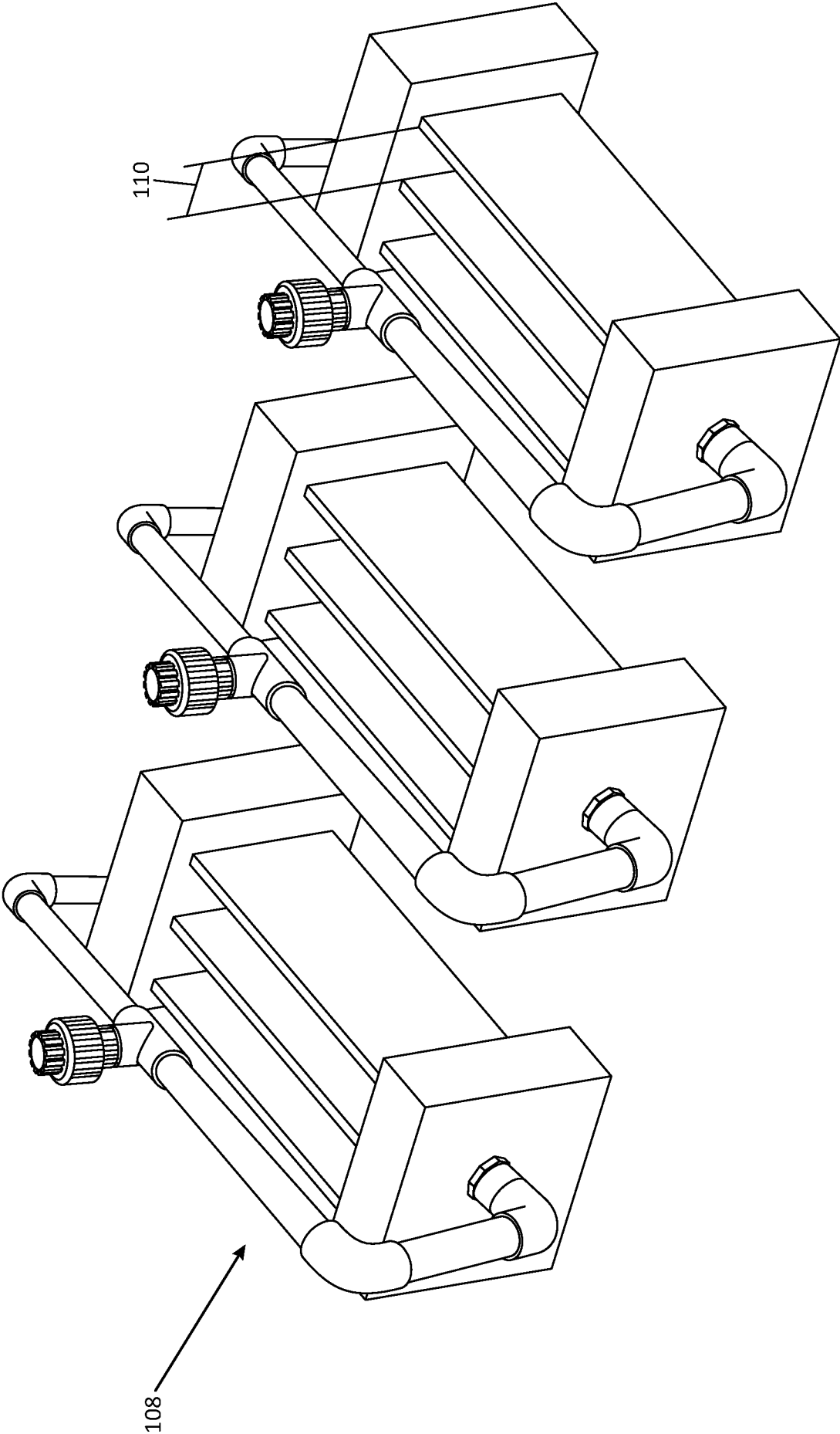


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 21/61900

A. CLASSIFICATION OF SUBJECT MATTER

IPC - C02F 3/00; C02F 11/00 (2022.01)

CPC - C02F 3/00; C02F 3/2806; C02F 3/2853; C02F 11/00; C02F 11/006; C02F 2101/106; Y02W 10/10

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

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

See Search History document

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

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y --- A	US 2013/0260444 A1 (Jin et al.) 03 October 2013 (03.10.2013); entire document, but especially: para [0005], para [0012]- para [0015], para [0017]	13-14, 16-17, 18/(13-14, 16-17), 19/(13-14, 16-17), 20/(19/(13-14, 16-17)), 21/(13-14, 16-17) 1-5, 11-12, 22/(13-14, 16-17), 23/(13-14, 16-17), 29/(13-14, 16-17), 30/(29/(13-14, 16-17)), 31/(13-14, 16-17), 32/(31/(13-14, 16-17)) 6-10, 15, 18/(15), 19/(15), 20/(19/(15)), 21/(15), 22/(15), 23/(15), 24-28, 29/(15), 30/(29/(15)), 31/(15), 32/(31/(15))



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"D" document cited by the applicant in the international application	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"E" earlier application or patent but published on or after the international filing date	"&" document member of the same patent family
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

01 February 2022

Date of mailing of the international search report

MAR 15 2022

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Kari Rodriguez

Telephone No. PCT Helpdesk: 571-272-4300

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 21/61900

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y --- A	US 2011/0011798 A1 (Borg et al.) 20 January 2011 (20.01.2011); para [0016], para [0017], para [0025], para [0027], para [0056], para [0114], para [0127], para [0128], table 1	1-5, 11-12, 23/(13-14, 16-17) 6-10, 24/(13-14, 16-17), 25/(24/(13-14, 16-17)), 26/(24/(13-14, 16-17)), 27/(26/(24/(13-14, 16-17))), 28/(24/(13-14, 16-17)) 22/(13-14, 16-17), 29/(13-14, 16-17), 30/(29/(13-14, 16-17)), 31/(13-14, 16-17), 32/(31/(13-14, 16-17))
Y --- A	US 2017/0313608 A1 (Frontier Water Systems, LLC) 02 November 2017 (02.11.2017); entire document, but especially: para [0065]- para [0068], para [0070], para [0072], para [0073], para [0086], para [0089], fig. 1	24/(13-14, 16-17), 25/(24/(13-14, 16-17)), 26/(24/(13-14, 16-17)), 27/(26/(24/(13-14, 16-17))), 28/(24/(13-14, 16-17))
Y --- A	US 2013/0105391 A1 (APTwater, Inc.) 02 May 2013 (02.05.2013); para [0002], para [0006], para [0119], fig. 1	5 6-10, 24/(13-14, 16-17), 25/(24/(13-14, 16-17)), 26/(24/(13-14, 16-17)), 27/(26/(24/(13-14, 16-17))), 28/(24/(13-14, 16-17))
A	Tan et al. "Comparative performance of anaerobic attached biofilm and granular sludge reactors for the treatment of model mine drainage wastewater containing selenate, sulfate and nickel" Chemical Engineering Journal, Vol 345 (31 March 2018): pages 545-555; abstract, page 546 col 2 para 4, page 546 col 2 para 6, page 547 col 1 para 1, fig. 1a	6-10, 24/(13-14, 16-17), 25/(24/(13-14, 16-17)), 26/(24/(13-14, 16-17)), 27/(26/(24/(13-14, 16-17))), 28/(24/(13-14, 16-17))
X --- A	US 2012/0152761 A1 (Pickett et al.) 21 June 2012 (21.06.2012); entire document, but especially: para [0005], para [0016], para [0018], para [0025]- para [0028], fig. 2	13-14, 18-19 15, 18/(15), 19/(15), 20/(19/(15)), 21/(15), 22/(15), 23/(15), 24/(15), 25/(24/(15)), 26/(24/(15)), 27/(26/(24/(15))), 28/(24/(15)), 29/(15), 30/(29/(15)), 31/(15), 32/(31/(15))
X, P	WO 2021/207039 A1 (Arizona Board of Regents on behalf of Arizona State University) 14 October 2021 (14.10.2021); entire document	1-32
A	US 2019/0092667 A1 (Aquatech International, LLC) 28 March 2019 (28.03.2019); entire document	1-32
A	US 2013/0248443 A1 (Guan et al.) 26 September 2013 (26.09.2013); entire document	1-32
A	Yan et al. "High-rate microbial selenate reduction in an up-flow anaerobic fluidized bed reactor (FBR)" Science of the Total Environment, Vol 749 (14 September 2020): pages 1-11; entire doc	1-32