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Inventor(s)

Sant; Gaurav et al.

CALCIUM HYDROXIDE PRECIPITATION IN AN ELECTROLYTIC REACTOR WITH HYDRODYNAMIC SEPARATION

Abstract

A system and method to precipitate calcium hydroxide at low temperatures ($T < 40^{\circ} \text{C.}$) using an electrolytic reactor with hydrodynamic separation. The calcium can be supplied by any calcium bearing material such as calcium carbonate or basalt rock, or from industrial wastes such as brine or steel slag. The solid feedstock undergoes dissolution, whereas the brine may be utilized as is. Once in solution, the feed stream is directed towards an electrolyzer reactor which comprises a cathode, an anode, and a membrane separator. At the cathode, or in a separate precipitation chamber, an alkaline catholyte solution containing calcium hydroxide (portlandite) and magnesium hydroxide (brucite) precipitates, and hydrogen gas is produced.

Inventors: Sant; Gaurav (Los Angeles, CA), Traynor; Thomas (Los Angeles, CA), Simonetti; Dante (Los Angeles, CA), Leão; Adriano (Los Angeles, CA), Collin; Marie (Los Angeles, CA), Bouissonnié; Arnaud (Los Angeles, CA), Chen; Xin (Los Angeles, CA), Arnold; Ross (Los Angeles, CA), Hovey; Geanna (Los Angeles, CA), Zhu; Shan (Los Angeles, CA)

Applicant: The Regents of the University of California (Oakland, CA)

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application claims the benefit of priority to U.S. Provisional Application No. 63/555,678, filed Feb. 20, 2024, the entire contents of which are hereby incorporated by reference.

BACKGROUND

[0002] Portlandite, or calcium hydroxide ($\text{Ca}(\text{OH})_2$), a byproduct of cement hydration, is commercially produced by mixing lime (calcium monoxide (CaO)) with water through a process known as slaking ($\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca}(\text{OH})_2$). However, to produce CaO , limestone or other calcium carbonate (CaCO_3) containing rocks must undergo thermal decomposition at high temperature (1070-1270° C.) in a lime kiln through a process called calcination ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$), which is estimated to release 0.75 t CO_2 /t of lime produced, 85% quicklime and 15% dolomitic lime. The worldwide demand for cement is anticipated to grow by 12 to 23% by 2050 in response to an increasing global population and urbanization and consequently so will carbon emissions. In view of the foregoing, there is an unmet need for an efficient process for the recovery and separation of calcium hydroxide.

SUMMARY

[0003] In certain aspects, described herein are processes to precipitate calcium hydroxide at low temperatures ($T < 40^\circ \text{C.}$) using an electrolytic reactor with hydrodynamic separation.

[0004] In further aspects, described herein are methods of using the systems disclosed herein.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. 1 is a schematic representation of the $\text{Ca}(\text{OH})_2$ precipitation schema.

[0006] FIG. 2 demonstrates the rate of calcium dissolution as a function of pH for a Basic Oxygen Furnace (BOF) and an Air-Cooled Blast Furnace (ACBF) slag. Lower pH values result in increased dissolution rates.

[0007] FIG. 3 demonstrates the time to reach the simulated target calcium concentration of 100 mM as a function of particle size and solid-to-liquid ratio.

[0008] FIG. 4 demonstrates various mineral solubilities as a function of pH.

[0009] FIG. 5 demonstrates the optimal pH range within which % mass portlandite concentration is maximized.

[0010] FIG. 6 shows the effect of cathode chamber flow channels on cell voltage over time in an exemplary system of the disclosure. Flow channels on the cathode side improve precipitate removal allowing the system to maintain a constant voltage when compared to operating without a flow channel.

[0011] FIG. 7 shows the voltage decrease in an exemplary system with flow channels compared to

without flow channels.

[0012] FIG. 8 shows the change in voltage when calcium content is reduced in the anolyte relative to the calcium content of the catholyte in an exemplary system of the disclosure. Testing has shown that an absence of Ca ions in the anolyte results in a lower conductivity of the solution, increasing the resistivity of the system. This results in a higher voltage/EEI. A loss of Ca in the catholyte is also observed when no Ca is in the anolyte.

[0013] FIG. 9 shows comparative data from an exemplary system of the disclosure using a Ni plate cathode or a 316 stainless steel plate cathode. The Ni cathode resulted in a lower required voltage than the 316 stainless steel cathode.

[0014] FIG. 10 shows the effect of anode material on the EEI of exemplary methods of the disclosure.

[0015] FIG. 11 shows the effect of cathode material on the EEI of exemplary methods of the disclosure.

[0016] FIG. 12 shows the effect of electrode spacing on the voltage required in the electrochemical cell. Reducing electrode spacing enhances performance by lowering electrolyte resistance.

[0017] FIG. 13 shows the effect of changing temperatures on exemplary methods of the disclosure. Elevated temperatures enhance performance by increasing conductivity and activity of the system. EEI decreased linearly as temperature was increased, for both seawater and brine solutions.

[0018] FIG. 14 shows the variance in cell temperature over time in exemplary methods of the disclosure.

[0019] FIG. 15 shows the change in EEI as voltage decreases for methods of the disclosure, values calculated for a cell operating at 100% Faradaic efficiency (FE).

[0020] FIG. 16 shows the impact of dosage (influent flowrate) on the Faradaic efficiency (FE) of an exemplary system of the disclosure. Higher influent flowrates resulted in a dramatic increase in FE.

[0021] FIG. 17 shows the effect of calcium ion concentration, [Ca], on the EEI of an exemplary system of the disclosure. Higher [Ca] resulted in a lower EEI, and thus a more efficient system.

DETAILED DESCRIPTION

[0022] To mitigate the emissions released from conventional cement and lime processing, in certain aspects, this disclosure provides systems and methods to precipitate calcium hydroxide at low temperatures ($T < 40^{\circ}\text{C.}$) using an electrolytic reactor or precipitation system with hydrodynamic separation. The calcium can be supplied by any calcium bearing material such as calcium carbonate or basalt rock, or from industrial wastes such as brine or steel slag. To make use of these feedstocks, the calcium ions must be made available in an aqueous solution.

[0023] In certain aspects, described herein are processes for precipitating calcium hydroxide at low temperatures ($T < 40^{\circ}\text{C.}$) using an electrolytic reactor with hydrodynamic separation.

[0024] In certain embodiments, the process comprises at least four major unit operations, shown schematically in FIG. 1: dissolution, impurity removal, nanofiltration and electrolytic precipitation. In certain embodiments, any calcium-bearing material can be used, ranging from calcium carbonate or basalt rocks to industrial wastes such as brine or steel slag. Dissolution rate increases at lower pH (FIG. 2). Increasing the reactive surface area increases the dissolution rate (i.e., calcium release in solution, FIG. 3). Expectedly, slags with higher amorphous content dissolve at greater rates.

[0025] Following dissolution, the feed stream is directed towards the electrolyzer reactor which is composed of a cathode (e.g., a cathode comprising a material selected from iron and its alloys, nickel and its alloys, titanium and its alloys, platinum group metals and alloys thereof, aluminum and its alloys, and carbon-based materials) any of the mentioned substrates coated with platinum or nickel phosphate or molybdenum sulfate, an anode (e.g., platinum group metals or titanium coated with platinum group metals, titanium with mixed metal oxide coatings (such as iridium tin, cobalt manganese, iridium tantalum, iridium ruthenium), carbon-based coatings (e.g., graphite, graphene, carbon nanotube, etc.), and a membrane separator (e.g., PVDF, PTFE, cellulose, a copolymer of

tetrafluoroethylene and sulfonated perfluorovinyl ether, ion exchange membranes). In certain embodiments, at the cathode, an alkaline catholyte solution containing calcium hydroxide (e.g., portlandite) precipitates, and hydrogen gas is produced. To achieve high purity portlandite, the impurities are separated from the aqueous solution comprising dissolved calcium hydroxide through pH control and filtration prior to entering the electrolyzer. In other embodiments, the alkaline catholyte solution containing calcium hydroxide (e.g., portlandite) is provided to a separate precipitation chamber, and precipitation of the calcium hydroxide is conducted in the precipitation chamber. In certain such embodiments, the precipitation chamber is separate from the cathode chamber and in fluid communication with the cathode chamber.

[0026] Following precipitation, the precipitated portlandite is directed towards a settling tank for solid-liquid separation where the solids are collected for use in cement manufacturing. As a consequence of the precipitation reaction, the cathodes may scale over time and may need to be cleaned of the scale material by continuous sonicated pulses, which induce cavitation. This has a notable effect on the mass transport and surface activation of the electrochemical system, where the scaling is removed by dissolving or pitting the inhibiting layer as a consequence of the cavities collapsing near the electrode surface. Moreover, sonication induces a more turbulent flow, further enhancing mass transport. Both of these effects allow for subsequent precipitation reactions to occur more efficiently by ensuring the solid-liquid mass transfer rate between the electrodes and solution remains as elevated as possible. A turbulent flow environment can also be achieved by adjusting the inlet shape and/or the inlet length, or by introducing turbulence promoters (i.e., baffles). As will be appreciated by one of skill in the art, an aspect ratio of the chamber and/or inlet may be varied (e.g., the ratio of the width to the height of an opening of the inlet or the ratio of the length of the chamber to its perpendicular cross section) to enhance or reduce turbulence in the flow of the contents within the chamber and inlet. For example, longer cells (in flow direction) lead to an accelerated flow rate (at a constant volume flow rate and residence time) which leads to more precipitate entrainment and fewer opportunities for Ca(OH)_2 to adhere to the electrode or membrane, thereby reducing scale buildup.

[0027] The hydrogen gas produced may be captured and utilized as a source of energy for the system, further minimizing the carbon intensity of the process. At the anode, an acidic anolyte solution and oxygen gas is produced. The anolyte stream may be recovered and used for pH adjustment as needed.

[0028] A simulated test which had a target calcium ion concentration of 100 mM after the dissolution step to minimize the energy intensity of the electrolyzer was carried out. This test enabled selection of preferred conditions of solid-to-liquid ratio suitable to reach the target of 100 mM in the shortest amount of time. Results indicate that the time to reach the target 100 mM ion concentration can be reduced by using a higher solid-to-liquid ratio, or a smaller particle size (d.sub.50). Generally, ion concentration may be measured by any suitable means, e.g., spectroscopy, spectrometry, chromatography, or electrochemistry.

[0029] To evaluate elimination of slag impurities before portlandite precipitation and to improve purity, bench scale experiments were conducted where slag was dissolved at pH 1 (FIGS. 4-5). The solution was filtered to remove undissolved solids remaining after dissolution and the resulting filtrate solution was alkalized, and then filtered again to remove precipitates, which were analyzed. Results indicate that mineral solubility is a function of pH, thus raising the pH enables removal of impurities resulting in portlandite purity of >70 mass %. A pH of 11.5 should result in further increases in purity while simultaneously decreasing the energy intensity of the electrolysis process.

Systems of the Disclosure

[0030] In certain aspects, provided herein are systems comprising: [0031] a dissolution chamber disposed at a first end of the system comprising: [0032] a first anolyte inlet disposed at a first end of the dissolution chamber; [0033] a feed inlet disposed at the first end of the dissolution chamber;

and [0034] a first leachate outlet disposed at a second end of the dissolution chamber; and [0035] a first spent mixture outlet disposed at the second end of the dissolution chamber; [0036] a pretreatment chamber coupled to the dissolution chamber comprising: [0037] a first leachate inlet disposed at a first end of the pretreatment chamber and coupled to the first leachate outlet; [0038] a first nanofiltration feed outlet disposed at a second end of the pretreatment chamber; [0039] a first waste stream outlet disposed at the second end of the pretreatment chamber; and [0040] a first filtration membrane disposed between the first leachate inlet and the first nanofiltration feed outlet; [0041] at least one nanofiltration unit coupled to the pretreatment chamber comprising: [0042] a first nanofiltration feed inlet disposed at a first end of the at least one nanofiltration unit and coupled to the first nanofiltration feed outlet; [0043] a first retentate outlet disposed at the first end of the at least one nanofiltration unit; [0044] a first permeate outlet disposed at a second end of the at least one nanofiltration unit; and [0045] a nanofiltration membrane disposed between the first retentate outlet and the first permeate outlet; [0046] an electrolyte chamber coupled to the at least one nanofiltration unit comprising: [0047] a first electrolyte feed inlet coupled to an electrolyte feed source; [0048] a first permeate inlet coupled to the first permeate outlet of the at least one nanofiltration unit; and [0049] a first electrolyte product outlet; [0050] an electrochemical cell coupled to the at least one nanofiltration unit and the electrolyte chamber comprising: [0051] a cathodic chamber coupled to the at least one nanofiltration unit comprising: [0052] a first retentate inlet coupled to the first retentate outlet; [0053] a first conductive element; [0054] a first catholyte solution outlet; [0055] a plurality of flow channels configured to facilitate the passage of fluids through the cathodic chamber; and [0056] a first gas outlet; [0057] an anodic chamber coupled to the cathodic chamber and the electrolyte chamber, comprising: [0058] a first electrolyte product inlet coupled to the first electrolyte product outlet of the electrolyte chamber; [0059] a second conductive element; [0060] a first anolyte solution outlet; and [0061] a second gas outlet; [0062] an electrochemical membrane disposed between the cathodic chamber and the anodic chamber, and [0063] wherein the cathodic chamber and the anodic chamber are in ionic communication; [0064] and the first conductive element and second conductive element are separated by an interelectrode distance of less than about 18 mm; [0065] a settling chamber coupled to the cathodic chamber comprising: [0066] a first catholyte inlet disposed at a top of the settling chamber; [0067] a first mineral outlet disposed at a first bottom of the settling chamber; and [0068] a catholyte supernatant outlet; [0069] an anolyte chamber coupled to the anodic chamber comprising: [0070] a first anolyte solution inlet disposed at a top of the anolyte chamber and coupled to the first anolyte solution outlet of the anodic chamber; and [0071] a second spent mixture outlet.

[0072] In certain embodiments, systems of the disclosure further comprise a precipitation chamber coupled to the cathodic chamber and the settling chamber comprising: [0073] a second catholyte inlet coupled to the first catholyte solution outlet of the cathodic chamber; a precipitate outlet disposed at a bottom of the precipitation chamber; and [0074] a second supernatant outlet disposed at a top of the precipitation chamber and coupled to the first catholyte inlet of the settling chamber. [0075] In certain embodiments, the interelectrode distance is from 0 mm to about 18 mm. In further embodiments, the interelectrode distance is from about 3 mm to about 8 mm. In yet further embodiments, the interelectrode distance is about 3 mm, about 3.5 mm, about 4 mm, about 4.5 mm, about 5 mm, about 5.5 mm, about 6 mm, about 6.5 mm, about 7 mm, about 7.5 mm, or about 8 mm. In certain preferred embodiments, the interelectrode distance is about 3 mm. In certain embodiments, the interelectrode distance is about 3.5 mm. In some embodiments, the interelectrode distance is about 4 mm. In certain embodiments, the interelectrode distance is about 4.5 mm. [0076] In certain embodiments, the pretreatment chamber further comprises an additive inlet configured to allow addition of additives to the pretreatment chamber. For example, the additive inlet may be configured to allow addition of solid additives to the pretreatment chamber. Similarly, the additive inlet may be configured to allow addition of liquid additives to the pretreatment chamber.

[0077] In some embodiments, the pretreatment chamber comprises at least one waste stream outlet disposed at the second end of the pretreatment chamber. For example, the pretreatment chamber may comprise a first waste stream outlet disposed at the second end of the pretreatment chamber. Additionally, the pretreatment chamber may further comprise a second waste stream outlet disposed at the second end of the pretreatment chamber.

[0078] In certain embodiments, the precipitation chamber further comprises a recycle loop outlet disposed at a bottom of the precipitation chamber, and the cathodic chamber further comprises a recycle loop inlet, wherein the recycle loop outlet is coupled to the recycle loop inlet. In further embodiments, the recycle loop inlet is configured to pass a solid from the precipitation chamber to the cathodic chamber. As will be appreciated by one of skill in the art, solids from the precipitation chamber (e.g. precipitated $\text{Ca}(\text{OH})_2$) may be provided to the cathodic chamber via the recycle loop outlet and recycle loop inlet, thereby introducing solid particulate “seeds,” or crystal nucleation sites, to the contents of the cathodic chamber, allowing solids to precipitate in a catholyte mixture instead of on the first conductive element, thereby reducing scaling of the first conductive element.

Methods of the Disclosure

[0079] In certain aspects, provided herein are methods comprising: [0080] combining a solid comprising target ions and a neutral fluid or an acidic fluid in a dissolution chamber, thereby forming a first suspension; [0081] passing the first suspension into a pretreatment chamber configured to remove impurities from and filter the first suspension to form a nanofiltration feed solution comprising the target ions; [0082] passing the nanofiltration feed solution into at least one nanofiltration unit configured to separate the nanofiltration feed solution to form a permeate and a retentate comprising the target ions; [0083] passing the retentate via a first retentate outlet to an electrochemical cell; [0084] performing an electrochemical process comprising: [0085] applying a voltage to a cathode and an anode in the electrochemical cell; [0086] contacting the cathode disposed inside the electrochemical cell with the retentate thereby forming hydrogen gas and a catholyte solution; [0087] contacting the anode disposed inside the electrochemical cell with an anolyte solution thereby producing oxygen gas; [0088] wherein an electrochemical membrane is disposed between the anode and the cathode, and the cathode and anode are in ionic communication; [0089] passing the catholyte solution via a catholyte solution outlet into a settling chamber and precipitating mineral precipitates from the catholyte solution, thereby forming mineral precipitates and a catholyte supernatant; [0090] passing the mineral precipitates from the settling chamber via a mineral outlet.

[0091] In certain preferred embodiments, the target ions comprise Ca^{2+} . In some preferred embodiments, the solid is a rock or mineral comprising calcium (e.g., limestone).

[0092] In certain embodiments, the target ions comprise Ca^{2+} and the method has a gross EEI of less than about 4 MWh/t $\text{Ca}(\text{OH})_2$, and preferably less than about 3 MWh/t $\text{Ca}(\text{OH})_2$. In further embodiments, the method has an EEI from about 2 MWh/t $\text{Ca}(\text{OH})_2$ to about 4 MWh/t $\text{Ca}(\text{OH})_2$. In yet further embodiments, the method has an EEI of about 2 MWh/t $\text{Ca}(\text{OH})_2$, about 2.5 MWh/t $\text{Ca}(\text{OH})_2$, about 3 MWh/t $\text{Ca}(\text{OH})_2$, about 3.5 MWh/t $\text{Ca}(\text{OH})_2$, or about 4 MWh/t $\text{Ca}(\text{OH})_2$.

Definitions

[0093] Unless otherwise defined herein, scientific and technical terms used in this application shall have the meanings that are commonly understood by those of ordinary skill in the art. Generally, nomenclature used in connection with, and techniques of, chemistry, chemical engineering, electrical engineering and civil engineering described herein, are those well-known and commonly used in the art.

[0094] The methods and techniques of the present disclosure are generally performed, unless otherwise indicated, according to conventional methods well known in the art and as described in various general and more specific references that are cited and discussed throughout this

specification.

[0095] Chemistry terms used herein, unless otherwise defined herein, are used according to conventional usage in the art, as exemplified by “The McGraw-Hill Dictionary of Chemical Terms”, Parker S., Ed., McGraw-Hill, San Francisco, C.A. (1985).

[0096] All publications, patents and published patent applications referred to in this application are specifically incorporated by reference herein. In case of conflict, the present specification, including its specific definitions, will control.

[0097] As used herein, the term “particle size” refers to the mean particle size (d.sub.50) as determined through, e.g., dynamic light scattering.

[0098] As used herein, the term “production capacity” refers to the upper boundary of the dry mass of pure product equivalents that may be produced per unit of time.

[0099] As used herein, the term “spent solution” refers to residual solution utilized in a prior step of a process (e.g., nanofiltration or electrolysis) which may optionally be re-used or discarded depending on the user's needs and the configuration of the system.

[0100] As used herein the term EEI refers to Electrical Energy Intensity, which is a measure of the total electrical energy required by a process to produce a given amount of a product (e.g., a ton of Ca(OH).sub.2). EEI values referred to in the present disclosure are calculated according to the formula: $EEI = [(current\ applied) \cdot (voltage)] / (mass\ of\ Ca(OH).sub.2\ produced)$. In methods of the present disclosure, the value of the electric potential (voltage) applied to the cathode and anode in the electrochemical positively correlates with the EEI of the process. For example, a process having an EEI of about 3 MWh/tCa(OH).sub.2 would be considered more energy efficient than a process having an EEI of 5 MWh/tCa(OH).sub.2 by one of ordinary skill in the art.

[0101] As used herein, the term “hydrodynamic separation” refers to the physical separation of two fluid feed streams or processes that are usually or may be combined. For example, the term may refer to, e.g., separation of an anolyte from a catholyte stream in an electrochemical process. The term “hydrodynamic separation” may also be used herein to refer to the separation of an electrolysis chamber (e.g., where H.sup.+ and OH.sup.- ions are produced from aqueous solutions) and a precipitation chamber (e.g., where an aqueous ionic species comprising the OH.sup.- ions is precipitated from solution) such that the precipitation of the hydroxide species occurs in the precipitation chamber instead of in the electrolysis chamber.

[0102] As used herein, the term “interelectrode distance” refers to the magnitude of the minimum distance between an outer face of a first conductive element and an outer face of a second conductive element.

INCORPORATION BY REFERENCE

[0103] All publications and patents mentioned herein are hereby incorporated by reference in their entirety as if each individual publication or patent was specifically and individually indicated to be incorporated by reference. In case of conflict, the present application, including any definitions herein, will control.

EQUIVALENTS

[0104] While specific embodiments of the subject invention have been discussed, the above specification is illustrative and not restrictive. Many variations of the invention will become apparent to those skilled in the art upon review of this specification and the claims below. The full scope of the invention should be determined by reference to the claims, along with their full scope of equivalents, and the specification, along with such variations.

Claims

1-84. (canceled)

85. A system comprising: a dissolution chamber disposed at a first end of the system comprising: a first anolyte inlet disposed at a first end of the dissolution chamber; a feed inlet disposed at the first

end of the dissolution chamber; and a first leachate outlet disposed at a second end of the dissolution chamber; and a first spent mixture outlet disposed at the second end of the dissolution chamber; a pretreatment chamber coupled to the dissolution chamber comprising: a first leachate inlet disposed at a first end of the pretreatment chamber and coupled to the first leachate outlet; a first nanofiltration feed outlet disposed at a second end of the pretreatment chamber; a first waste stream outlet disposed at the second end of the pretreatment chamber; and a first filtration membrane disposed between the first leachate inlet and the first nanofiltration feed outlet; at least one nanofiltration unit coupled to the pretreatment chamber comprising: a first nanofiltration feed inlet disposed at a first end of the at least one nanofiltration unit and coupled to the first nanofiltration feed outlet; a first retentate outlet disposed at the first end of the at least one nanofiltration unit; a first permeate outlet disposed at a second end of the at least one nanofiltration unit; and a nanofiltration membrane disposed between the first retentate outlet and the first permeate outlet; an electrolyte chamber coupled to the at least one nanofiltration unit comprising: a first electrolyte feed inlet coupled to an electrolyte feed source; a first permeate inlet coupled to the first permeate outlet of the at least one nanofiltration unit; and a first electrolyte product outlet; an electrochemical cell coupled to the at least one nanofiltration unit and the electrolyte chamber comprising: a cathodic chamber coupled to the at least one nanofiltration unit comprising: a first retentate inlet coupled to the first retentate outlet; a first conductive element; a first catholyte solution outlet; a plurality of flow channels configured to facilitate the passage of fluids through the cathodic chamber; and a first gas outlet; an anodic chamber coupled to the cathodic chamber and the electrolyte chamber, comprising: a. first electrolyte product inlet coupled to the first electrolyte product outlet of the electrolyte chamber; a second conductive element: a first anolyte solution outlet; and a second gas outlet; an electrochemical membrane disposed between the cathodic chamber and the anodic chamber, and wherein the cathodic chamber and the anodic chamber are in ionic communication; a settling chamber coupled to the cathodic chamber comprising: a first catholyte inlet disposed at a top of the settling chamber; a first mineral outlet disposed at a first bottom of the settling chamber; and a catholyte supernatant outlet; an anolyte chamber coupled to the anodic chamber comprising: a first anolyte solution inlet disposed at a top of the anolyte chamber and coupled to the first anolyte solution outlet of the anodic chamber; and a second spent mixture outlet.

86. The system of claim 85, wherein the first conductive element and second conductive element are separated by an interelectrode distance from 0 mm to about 18 mm.

87. The system of claim 85, wherein the feed inlet is a calcium feed inlet.

88. The system of claim 85, wherein the dissolution chamber further comprises an apparatus, disposed at a position between the first and second ends of the dissolution chamber, selected from a mechanical agitator, a sonicator, or an impeller.

89. The system of claim 85, wherein the first conductive element is in the form of a mesh, plate, or rod and is selected from iron, iron alloy, nickel, nickel alloy, titanium, titanium alloy, aluminum, aluminum alloy, and platinum, or a combination of any of the foregoing.

90. The system of claim 85, wherein the first conductive element is in the form of a mesh, plate, or rod and is selected from transition group metals, platinum group metals, or a combination of any of the foregoing.

91. The system of claim 89, wherein the first conductive element further comprises a coating comprising platinum, nickel phosphate, or molybdenum sulfate.

92. The system of claim 85, wherein the first gas is hydrogen.

93. The system of claim 85, wherein the second conductive element is selected from a group VIII metal, a group IX metal, a group X metal, titanium clad with a group VIII metal, titanium clad with a group LX metal, titanium clad with a group X metal, and titanium clad with mixed metal oxide, or a combination of any of the foregoing.

94. The system of claim 85, wherein the second conductive element is selected from a transition

group metal, platinum group metal, or a combination of any of the foregoing.

95. The system of claim 85, wherein the electrochemical membrane comprises PVDF, PTFE, cellulose, a copolymer of tetrafluoroethylene and sulfonated perfluorovinyl ether, sodium polystyrene sulfonate, poly(2-acrylamido-2-methyl-1-propanesulfonic acid), poly(acrylamido-N-propyltrimethylammonium chloride), poly[(3-(methacryloylamino)-propyl]trimethylammonium chloride), or polyethylenimine.

96. The system of claim 85, wherein the first mineral outlet is a Ca(OH)₂ outlet.

97. The system of claim 85, further comprising a precipitation chamber coupled to the cathodic chamber and the settling chamber comprising: a second catholyte inlet coupled to the first catholyte solution outlet of the cathodic chamber; a precipitate outlet disposed at a bottom of the precipitation chamber; and a second supernatant outlet disposed at a top of the precipitation chamber and coupled to the first catholyte inlet of the settling chamber.

98. The system of claim 85, wherein the anolyte chamber further comprises a first recycled anolyte outlet, and wherein the dissolution chamber further comprises a first recycled anolyte inlet coupled to the first recycled anolyte outlet.

99. The system of claim 85, wherein the electrochemical cell has a production capacity of about 1 kg/day, about 2 kg/day, about 3 kg/day, about 4 kg/day, about 5 kg/day, about 6 kg/day, about 7 kg/day, about 8 kg/day, about 9 kg/day, about 10 kg/day, about 15 kg/day, about 20 kg/day, about 25 kg/day, about 30 g/day, about 40 g/day, about 50 g/day, about 60 g/day, about 70 g/day, about 80 g/day, about 90 g/day, about 100 g/day, about 125 g/day, about 150 g/day, about 175 g/day, or about 200 g/day.

100. The system of claim 85, wherein the electrochemical cell has an electrode area of about 6 cm², about 8 cm², about 10 cm², about 12 cm², about 14 cm², about 16 cm², about 18 cm², about 20 cm², about 22 cm², about 24 cm², about 2500 cm², about 3500 cm², about 4500 cm², about 5500 cm², about 6500 cm², about 7500 cm², about 8500 cm², about 9500 cm², or about 10,500 cm².

101. The system of claim 85, wherein the electrochemical cell has a Faradaic efficiency of greater than about 95% at an influent flowrate of about 20 mL/min and a reactor volume of about 40 L, about 45 L, about 50 L, about 55 L, about 60 L, about 65 L, about 70 L, about 75 L, about 80 L, about 85 L, or about 90 L.

102. The system of claim 85, wherein the system is configured to produce a metal salt.

103. The system of claim 85, wherein the electrochemical cell has an applied current density of about 300 A/m², about 500 A/m², about 1000 A/m², about 3000 A/m², about 5000 A/m², about 10000 A/m², about 15000 A/m², about 20000 A/m², about 25000 A/m², or about 30000 A/m².

104. The system of claim 85, wherein the nanofiltration membrane comprises a plurality of pores, and each of the plurality of pores has a pore diameter of from about 0.001 to about 0.01 μm.

105. The system of claim 85, wherein the system comprises one nanofiltration unit coupled to the pretreatment chamber.

106. A method comprising: combining a solid comprising target ions and a neutral fluid or an acidic fluid in a dissolution chamber, thereby forming a first suspension; passing the first suspension into a pretreatment chamber configured to remove impurities from and filter the first suspension to form a nanofiltration feed solution comprising the target ions; passing the nanofiltration feed solution into at least one nanofiltration unit configured to separate the nanofiltration feed solution to form a permeate and a retentate comprising the target ions; passing the retentate via a first retentate outlet to an electrochemical cell; performing an electrochemical process comprising: applying a voltage to a cathode and an anode in the electrochemical cell; contacting the cathode disposed inside the electrochemical cell with the retentate thereby forming hydrogen gas and a catholyte solution; contacting the anode disposed inside the electrochemical cell with an anolyte solution thereby producing oxygen gas; wherein an electrochemical membrane

is disposed between the anode and the cathode, and the cathode and anode are in ionic communication; passing the catholyte solution via a catholyte solution outlet into a settling chamber and precipitating mineral precipitates from the catholyte solution, thereby forming mineral precipitates and a catholyte supernatant; passing the mineral precipitates from the settling chamber via a mineral outlet.
