METHODS AND SYSTEMS FOR FORMING VATERITE FROM CALCINED LIMESTONE USING ELECTRIC KILN

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims benefit of US Provisional Application No. 63/046,239, filed June 30, 2020, which is incorporated herein by reference in its entirety in the present disclosure.

BACKGROUND

[0002] Carbon dioxide (CO_2) emissions have been identified as a major contributor to the phenomenon of global warming. CO_2 is a by-product of combustion and it creates operational, economic, and environmental problems. It is known that elevated atmospheric concentrations of CO_2 and other greenhouse gases facilitate greater storage of heat within the atmosphere leading to enhanced surface temperatures and rapid climate change. In addition, elevated levels of CO_2 in the atmosphere may also further acidify the world's oceans due to the dissolution of CO_2 and formation of carbonic acid. The impact of climate change and ocean acidification may likely be economically expensive and environmentally hazardous if not timely handled. Reducing potential risks of climate change requires sequestration and avoidance of CO_2 from various anthropogenic processes.

SUMMARY

[0003] Provided herein are processes and systems that relate to using electric kilns to produce clean CO_2 devoid of pollutants that are emitted from the combustion of fuel, such as e.g. fossil fuel; and the sequestration of the clean CO_2 into commercially useful cementitious products or disposal underground.

[0004] In one aspect, there is provided a ~~zero carbon dioxide (CO_2) emission~~ process, comprising: a) calcining limestone ~~in a cement plant~~ in an electric kiln to form a mixture comprising calcium oxide and a ~~first~~ gaseous stream comprising clean carbon dioxide, wherein the clean carbon dioxide or the first gaseous stream comprises no gaseous or non-gaseous component~~s~~ from combustion of fuel; b) treating the mixture comprising calcium oxide with a N-containing salt solution ~~under one or more dissolution conditions~~ to produce a<u>n</u> ~~first~~ aqueous solution comprising calcium salt; and c) contacting the ~~first~~ aqueous solution with the first gaseous stream comprising clean carbon dioxide ~~under one or more precipitation conditions~~ to produce a precipitation material comprising vaterite, aragonite, calcite, <u>precipitated calcium carbonate (PCC)</u> or combination~~s~~ thereof.

[0005] In some embodiments of the foregoing aspect, the calcining limestone in the electric kiln produces less than 20% of at least one component selected from the group consisting of SOx;

thermal NOx; carbon monoxide; metal; volatile organic matter; particulate matter; and combinations thereof. In some embodiments of the foregoing aspect and embodiments, the first

[0023] In one ~~aspect~~embodiment, there is provided a zero carbon dioxide (CO_2) emission process, comprising: a) calcining limestone in a cement plant in an electric kiln to form a mixture comprising calcium oxide and a first gaseous stream comprising clean carbon dioxide, wherein the clean carbon dioxide comprises no gaseous or non-gaseous components from combustion of fuel; b) treating the mixture comprising calcium oxide with a N-containing salt solution under one or more dissolution conditions to produce a first aqueous solution comprising calcium salt and a second gaseous stream comprising ammonia; c) recovering the first gaseous stream comprising clean carbon dioxide and the second gaseous stream comprising ammonia and subjecting the first and the second gaseous streams to a cooling process under one or more cooling conditions to condense a second aqueous solution comprising ammonium bicarbonate, ammonium carbonate, ammonia, or combinations thereof; and d) contacting the first aqueous solution comprising calcium salt with the second aqueous solution comprising ammonium bicarbonate, ammonium carbonate, ammonia, or combinations thereof under one or more precipitation conditions to form a precipitation material comprising vaterite, aragonite, calcite, or combinations thereof.

[0024] In some embodiments of the foregoing aspect, the first and/or the second gaseous streams further comprise water vapor. In some embodiments of the foregoing aspect and embodiments, the first and/or the second gaseous streams further comprise between about 20-50% water vapor.

[0025] In some embodiments of the foregoing aspect and embodiments, the no external water is added to the cooling process.

[0026] In some embodiments of the foregoing aspect and embodiments, the one or more cooling conditions comprise temperature between about 0-100^{o}C; pressure between about 0.5-50 atm; or combination thereof.

[0027] In some embodiments of the foregoing aspect and embodiments, the first gaseous stream comprising clean carbon dioxide has faster kinetics in the contacting step to produce the precipitation material compared to a process using regular kiln. In some embodiments of the foregoing aspect and embodiments, the kinetics of the contacting step to produce the precipitation material is more than 5 times faster compared to the process using regular kiln. In some embodiments of the foregoing aspect and embodiments, the faster kinetics of the contacting step results in high yield of the vaterite or more than 80% vaterite. In some embodiments of the foregoing aspect and embodiments, the faster kinetics of the contacting step results in the vaterite with a particle size of between about 0.05-100 microns or between about 0.05-20 microns or between about 0.05-10 microns. In some embodiments of the foregoing aspect and embodiments, the faster kinetics of the contacting step results in the formation of the vaterite with a unimodal distribution of the particles.

[0038] In some embodiments of the foregoing aspect and embodiments, the cementitious product is a formed building material selected from masonry unit, construction panel, conduit, basin, beam, column, slab, acoustic barrier, insulation material, and combinations thereof.

[0039] In one ~~aspect~~embodiment, there are provided product(s) formed by the foregoing process aspect and embodiments.

[0040] In one aspect, there is provided a ~~zero carbon dioxide (CO_2) emission~~ system, comprising:

(i) a calcining system ~~in a cement plant~~ configured for calcining limestone in an electric kiln to form a mixture comprising calcium oxide and a ~~first~~ gaseous stream comprising clean carbon dioxide, wherein the clean carbon dioxide comprises no gaseous or non-gaseous components from combustion of fuel;

(ii) a treatment reactor operably connected to the calcining system configured for receiving the mixture comprising calcium oxide and configured for dissolving the mixture comprising calcium oxide in a N-containing salt solution ~~under one or more dissolution conditions~~ to produce an ~~first~~ aqueous solution comprising calcium salt; and

(iii) a contacting reactor operably connected to the treatment reactor and the calcining system and configured for receiving the ~~first~~ aqueous solution comprising calcium salt and the first gaseous stream comprising clean carbon dioxide, and configured for treating the ~~first~~ aqueous solution comprising calcium salt with the ~~first~~ gaseous stream comprising clean carbon dioxide ~~under one or more precipitation conditions~~ to form a precipitation material comprising vaterite, aragonite, calcite, precipitated calcium carbonate (PCC), or combinations thereof.

[0041] In some embodiments of the foregoing aspect, the treatment reactor further produces a second gaseous stream comprising ammonia and the contacting reactor is further configured for receiving the second gaseous stream comprising ammonia, and configured for treating the first aqueous solution comprising calcium salt with the first gaseous stream comprising clean carbon dioxide and the second gaseous stream comprising ammonia.

[0042] In one aspect, there is provided a zero carbon dioxide (CO_2) emission system, comprising:

(i) a calcining system in a cement plant configured for calcining limestone in an electric kiln to form a mixture comprising calcium oxide and a first gaseous stream comprising clean carbon dioxide, wherein the clean carbon dioxide comprises no gaseous or non-gaseous components from combustion of fuel;

(ii) a treatment reactor operably connected to the calcining system configured for receiving the mixture comprising calcium oxide and configured for dissolving the mixture comprising calcium oxide in a N-containing salt solution under one or more dissolution

WHAT IS CLAIMED IS:

1. A ~~zero carbon dioxide (CO_2) emission~~ process, comprising:

a) calcining limestone ~~in a cement plant~~ in an electric kiln to form a mixture comprising calcium oxide and a ~~first~~ gaseous stream comprising clean carbon dioxide, wherein the clean carbon dioxide comprises no gaseous or non-gaseous component~~s~~ from combustion of fuel;

b) treating the mixture comprising calcium oxide with a N-containing salt solution ~~under one or more dissolution conditions~~ to produce a~~n~~ ~~first~~ aqueous solution comprising calcium salt; and

c) contacting the ~~first~~ aqueous solution with the ~~first~~ gaseous stream comprising clean carbon dioxide ~~under one or more precipitation conditions~~ to produce a precipitation material comprising vaterite, aragonite, calcite, precipitated calcium carbonate (PCC), or combination~~s~~ thereof.

2. The process of claim 1, wherein the fuel is fossil fuel~~calcining limestone in the electric kiln produces less than 20% of at least one component selected from the group consisting of SOx; thermal NOx; carbon monoxide; metal; volatile organic matter; particulate matter; and combinations thereof~~.

3. The process of claim 1 or 2, wherein the ~~first~~ gaseous stream comprises less than 20% of at least one component selected from the group consisting of SOx; thermal NOx; carbon monoxide; metal; volatile organic matter; particulate matter; and combination~~s~~ thereof, thereby comprising clean carbon dioxide.

~~4. The process of any one of the preceding claims, wherein the first gaseous stream comprises less than 5% of at least one component selected from the group consisting of SOx; thermal NOx; carbon monoxide; metal; volatile organic matter; particulate matter; and combinations thereof, thereby comprising clean carbon dioxide.~~

~~5~~4. The process of any one of the preceding claims, wherein the ~~first~~ gaseous stream comprises between about ~~20~~80-95 vol% clean carbon dioxide.

~~6. The process of any one of the preceding claims, wherein the first gaseous stream comprising clean carbon dioxide does not need scrubbing or needs a smaller scrubbing vent compared to a process using regular kiln.~~

~~7. The process of any one of the preceding claims, wherein the first gaseous stream comprising clean carbon dioxide is more than 80% captive compared to a process using regular kiln.~~

~~8~~5. The process of any one of the preceding claims, wherein the mixture comprising calcium oxide and/or the first aqueous solution comprising calcium salt further comprises between 1-40

wt% of solid~~s~~ selected from the group consisting of silicate, iron oxide, aluminum oxide, other particulate matter~~,~~; and combination~~s~~ thereof.

~~9. The process of any one of the preceding claims, wherein the mixture comprises more than 40 wt% calcium oxide.~~

~~1~~06. The process of any one of the preceding claims, wherein the calcium oxide is an underburnt lime, ~~low reactive~~ dead burnt lime, ~~high reactive~~ soft burnt lime, or combination~~s~~ thereof.

~~11. The process of any one of the preceding claims, wherein the electric kiln is a top-loading electric kiln or a front-loading electric kiln.~~

~~1~~27. The process of any one of the preceding claims, wherein the N-containing salt is N-containing inorganic salt, N-containing organic salt, or combination thereof.

~~13. The process of claim 12, wherein the N-containing salt is N-containing inorganic salt.~~

~~1~~48. The process of claim ~~13~~7, wherein the N-containing inorganic salt is selected from the group consisting of ammonium halide, ammonium acetate, ammonium sulfate, ammonium sulfite, ammonium nitrate, ammonium nitrite, and combination~~s~~ thereof~~;~~.

~~15.~~ ~~The process of claim 14,~~ optionally wherein the ammonium halide is ammonium chloride.

~~16. The process of any one of the preceding claims, wherein the N-containing salt solution is ammonium chloride solution.~~

~~1~~79. The process of claim ~~12~~7, wherein the N-containing salt is N-containing organic salt that has N-containing organic compound selected from the group consisting of aliphatic amine, alicyclic amine, heterocyclic amine, and combination~~s~~ thereof.

~~18~~10. The process of any one of the preceding claims, wherein the treating step further comprises adding anhydrous ammonia or an aqueous solution of ammonia.

~~19. The process of any one of the preceding claims, wherein molar ratio of the N-containing salt: mixture is between about 0.5:1 to 3:1 by weight.~~

~~20. The process of any one of the preceding claims, wherein no external source of carbon dioxide and/or ammonia is used and the process is a closed loop process or a zero emission process.~~

~~21. The process of any one of the preceding claims, wherein the one or more dissolution conditions are selected from the group consisting of temperature between about 20-200°C; pressure between about 0.5-50 atm; N-containing salt wt% in water between about 0.5-50%; or combinations thereof.~~

~~22. The process of any one of the preceding claims, wherein the first aqueous solution further comprises N-containing salt.~~

~~23~~11. The process of any one of the preceding claims, wherein the treating step further produces a second gaseous stream comprising ammonia and the process further comprises removing and optionally recovering the second gaseous stream comprising ammonia~~.~~

~~24. The process of claim 23, wherein the recovering comprises a scrubbing process wherein the scrubbing process comprises scrubbing the second gaseous stream comprising ammonia with hydrochloric acid and water to produce a solution of ammonium chloride.~~

~~25. The process of claim 23 or 24, further comprising contacting the first aqueous solution with the first gaseous stream comprising clean carbon dioxide and the second gaseous stream comprising ammonia.~~

~~26. The process of claim 23 or 24, further comprising recovering;~~ subjecting the ~~first~~ gaseous stream comprising clean carbon dioxide and the second gaseous stream comprising ammonia ~~and subjecting the first and the second gaseous streams~~ to a cooling process ~~under one or more cooling conditions~~ to condense a second aqueous solution comprising ammonium bicarbonate, ammonium carbonate, ammonia, or combination~~s~~ thereof~~.~~

~~27. The process of claim 26, further comprising;~~ and treating the ~~first~~ aqueous solution comprising calcium salt with the second aqueous solution ~~under the one or more precipitation conditions~~ to form the precipitation material.

~~28. A zero carbon dioxide (CO_2) emission process, comprising:~~

~~a) calcining limestone in a cement plant in an electric kiln to form a mixture comprising calcium oxide and a first gaseous stream comprising clean carbon dioxide, wherein the clean carbon dioxide comprises no gaseous or non-gaseous components from combustion of fuel;~~

~~b) treating the mixture comprising calcium oxide with a N-containing salt solution under one or more dissolution conditions to produce a first aqueous solution comprising calcium salt and a second gaseous stream comprising ammonia;~~

~~c) recovering the first gaseous stream comprising clean carbon dioxide and the second gaseous stream comprising ammonia and subjecting the first and the second gaseous streams to a cooling process under one or more cooling conditions to condense a second aqueous solution comprising ammonium bicarbonate, ammonium carbonate, ammonia, or combinations thereof; and~~

~~d) contacting the first aqueous solution comprising calcium salt with the second aqueous solution comprising ammonium bicarbonate, ammonium carbonate, ammonia, or combinations thereof under one or more precipitation conditions to form a precipitation material comprising vaterite, aragonite, calcite, or combinations thereof.~~

~~29. The process of any one of the claims 23-28, wherein the first and/or the second gaseous streams further comprise water vapor.~~

~~30. The process of any one of the claims 23-29, wherein the first and/or the second gaseous streams further comprise between about 20-50% water vapor.~~

~~31. The process of any one of the claims 26-30, wherein no external water is added to the cooling process.~~

~~32. The process of any one of the claims 26-31, wherein the one or more cooling conditions comprise temperature between about 0-100°C; pressure between about 0.5-50 atm; or combination thereof.~~

~~33~~12. The process of any one of the preceding claims, wherein the ~~first~~ gaseous stream comprising clean carbon dioxide has ~~faster~~ kinetics in the contacting step of more than 5 times faster to produce the precipitation material compared to a process using regular kiln~~.~~

~~34. The process of claim 33, wherein the kinetics of the contacting step to produce the precipitation material is more than 5 times faster compared to the process using regular kiln.~~

~~35. The process of claim 33 or 34,~~; optionally wherein the faster kinetics of the contacting step results in high yield of more than 80% vaterite~~.~~

~~36. The process of claim 33, 34, or 35,~~; optionally wherein the faster kinetics of the contacting step results in the vaterite with a particle size of between 0.05-20 micron~~s~~.

~~37. The process of any one of the preceding claims, wherein the one or more precipitation conditions are selected from the group consisting of pH of the first aqueous solution of between 7-8.5, temperature of the solution between 20-80°C, residence time of between 2-60 minutes, or combinations thereof.~~

~~38. The process of any one of the preceding claims, wherein the limestone is obtained from a cement plant which is a wet process plant or a dry process plant and/or is obtained from a rock quarry.~~

~~39. The process of any one of the preceding claims, wherein the first aqueous solution further comprises solids.~~

~~40. The process of claim 39, further comprising separating the solids from the first aqueous solution after the treatment step by filtration and/or centrifugation.~~

~~41. The process of claim 40, wherein the separated solids are added to the precipitation material as a filler.~~

~~42. The process of claim 40 or 41, wherein the separated solids further comprise residual ammonium halide when the N-containing inorganic salt is the ammonium halide.~~

~~43. The process of claim 42, further comprising recovering the residual ammonium halide from the solids using a recovery process selected from the group consisting of rinsing, thermal decomposition, pH adjustment, and combinations thereof.~~

~~44. The process of claim 39, wherein the solids are not separated from the first aqueous solution and the first aqueous solution is subjected to the contacting step to produce the precipitation material further comprising the solids.~~

~~45. The process of any one of the claims 39-44, wherein the solids comprise silicate, iron oxide, aluminum oxide, or combinations thereof.~~

~~46. The process of any one of the claims 39-45, wherein the solids are between 1-40 wt% in the aqueous solution, in the precipitation material, or combinations thereof.~~

~~47~~13. The process of any one of the preceding claims, further comprising dewatering the precipitation material to separate the precipitation material from supernatant solution~~.~~

~~48. The process of any one of the preceding claims~~, wherein the precipitation material and/or the supernatant solution comprise residual N-containing inorganic salt.

~~49. The process of claim 48, wherein the residual N-containing inorganic salt comprises ammonium halide, ammonium acetate, ammonium sulfate, ammonium sulfite, ammonium hydrosulfide, ammonium thiosulfate, ammonium nitrate, ammonium nitrite, or combinations thereof.~~

~~50~~14. The process of claim ~~48 or 49~~13, further comprising ~~removing and optionally recovering ammonia and/or N-containing inorganic salt from the residual N-containing inorganic salt comprising~~ removing and optionally recovering the residual N-containing inorganic salt from the supernatant aqueous solution and/or removing and optionally recovering the residual N-containing inorganic salt from the precipitation material~~.~~

~~51. The process of claim 50, further comprising;~~ optionally wherein recovering the residual N-containing inorganic salt from the supernatant aqueous solution ~~using~~ comprises recovery process selected from the group consisting of thermal decomposition, pH adjustment, reverse osmosis, multi-stage flash, multi-effect distillation, vapor recompression, distillation, and combination~~s~~ thereof.

~~52. The process of claim 50,~~; optionally wherein the step of removing and optionally recovering the residual N-containing inorganic salt from the precipitation material comprises heating the precipitation material between about 100-360ºC to evaporate the N-containing inorganic salt from the precipitation material with optional recovery by condensation of the N-containing inorganic salt.

~~53~~15. The process of any one of the preceding claim~~s 52~~, wherein the N-containing ~~inorganic~~ salt is ammonium chloride which evaporates from the precipitation material in a form comprising ammonia gas, hydrogen chloride gas, chlorine gas, or combination~~s~~ thereof~~.~~

~~54. The process of any one of the claims 50-53,;~~ optionally further comprising recycling the recovered residual ammonia and/or N-containing inorganic salt back to the treating and/or contacting step of the process.

~~55. The process of any one of the preceding claims, wherein the one or more precipitation conditions are selected from temperature, pH, pressure, ion ratio, precipitation rate, presence of additive, presence of ionic species, concentration of additive and ionic species, stirring, residence time, mixing rate, forms of agitation, presence of seed crystal, catalyst, membrane, or substrate, dewatering, drying, ball milling, and combinations thereof.~~

~~56~~16. The process of any one of the preceding claims, wherein the vaterite is stable vaterite or reactive vaterite.

~~57~~17. The process of claim ~~56~~16, further comprising adding water to the precipitation material comprising reactive vaterite and transforming the reactive vaterite to aragonite and/or calcite wherein the aragonite and/or the calcite sets and hardens to form cement or cementitious product.

~~58~~18. The process of claim ~~57~~17, wherein the cementitious product is a building material, formed building material, and/or artificial marine structure~~selected from masonry unit, construction panel, conduit, basin, beam, column, slab, acoustic barrier, insulation material, and combinations thereof~~.

19. The process of claim 16, further comprising forming a non-cementitious product from the precipitation material comprising vaterite wherein the non-cementitious product is selected from the group consisting of paper, polymer product, lubricant, adhesive, rubber product, chalk, asphalt product, paint, abrasive for paint removal, personal care product, cosmetic, cleaning product, personal hygiene product, ingestible product, agricultural product, soil amendment product, pesticide, environmental remediation product, and combination thereof.

20. The process of any one of the preceding claims, further comprising adding an additive to the aqueous solution or to the precipitation material, wherein the additive is selected from the group consisting of fatty acid ester, sodium decyl sulfate, lauric acid, sodium salt of lauric acid, urea, citric acid, sodium salt of citric acid, phthalic acid, sodium salt of phthalic acid, taurine, creatine, dextrose, poly(n-vinyl-1-pyrrolidone), aspartic acid, sodium salt of aspartic acid, magnesium chloride, acetic acid, sodium salt of acetic acid, glutamic acid, sodium salt of glutamic acid, strontium chloride, gypsum, lithium chloride, sodium chloride, glycine, sodium citrate dehydrate, sodium bicarbonate, magnesium sulfate, magnesium acetate, sodium polystyrene, sodium dodecylsulfonate, poly-vinyl alcohol, and combination thereof.

21. The process of any one of the preceding claims, wherein the vaterite is unimodal, bimodal, or multimodal distribution of a particulate composition with an average particle size of between 0.1-100 micron.

22. The process of any one of the preceding claims, further comprising blending the precipitation material with Portland Cement, aggregate, or combination thereof.

23. The process of any one of the preceding claims, further comprising mixing the precipitation material with one or more admixture selected from the group consisting of set accelerator, set retarder, air-entraining agent, foaming agent, defoamer, alkali-reactivity reducer, bonding admixture, dispersant, coloring admixture, corrosion inhibitor, damp-proofing admixture, gas former, permeability reducer, pumping aid, shrinkage compensation admixture, fungicidal admixture, germicidal admixture, insecticidal admixture, rheology modifying agent, finely divided mineral admixture, pozzolan, aggregate, wetting agent, strength enhancing agent, water repellent, reinforced material, and combination thereof.

24. The process of claim 23, wherein the reinforced material is a fiber made of zirconia, aluminum, glass, steel, carbon, ceramic, grass, bamboo, wood, fiberglass, synthetic material, or combination thereof.

~~59. A product formed by the process according to any one of the preceding claims.~~

~~60~~25. A ~~zero carbon dioxide (CO_2) emission~~ system, comprising:

(i) a calcining system ~~in a cement plant~~ configured for calcining limestone in an electric kiln to form a mixture comprising calcium oxide and a ~~first~~ gaseous stream comprising clean carbon dioxide, wherein the clean carbon dioxide comprises no gaseous or non-gaseous component~~s~~ from combustion of fuel;

(ii) a treatment reactor operably connected to the calcining system configured for receiving the mixture comprising calcium oxide and configured for dissolving the mixture comprising calcium oxide in a N-containing salt solution ~~under one or more dissolution conditions~~ to produce an ~~first~~ aqueous solution comprising calcium salt; and

(iii) a contacting reactor operably connected to the treatment reactor and the calcining system and configured for receiving the ~~first~~ aqueous solution comprising calcium salt and the ~~first~~ gaseous stream comprising clean carbon dioxide, and configured for treating the ~~first~~ aqueous solution comprising calcium salt with the ~~first~~ gaseous stream comprising clean carbon dioxide ~~under one or more precipitation conditions~~ to form a precipitation material comprising vaterite, aragonite, calcite, precipitated calcium carbonate (PCC), or combination~~s~~ thereof.

~~61~~26. The system of claim ~~60~~25, wherein the treatment reactor further produces a second gaseous stream comprising ammonia and the contacting reactor is further configured for receiving the second gaseous stream comprising ammonia, and configured for treating the ~~first~~ aqueous solution comprising calcium salt with the ~~first~~ gaseous stream comprising clean carbon dioxide and the second gaseous stream comprising ammonia.

~~62. A zero carbon dioxide (CO_2) emission system, comprising:~~

(i) a calcining system in a cement plant configured for calcining limestone in an electric kiln to form a mixture comprising calcium oxide and a first gaseous stream comprising clean carbon dioxide, wherein the clean carbon dioxide comprises no gaseous or non-gaseous components from combustion of fuel;

(ii) a treatment reactor operably connected to the calcining system configured for receiving the mixture comprising calcium oxide and configured for dissolving the mixture comprising calcium oxide in a N-containing salt solution under one or more dissolution conditions to produce a first aqueous solution comprising calcium salt, and a second gaseous stream comprising ammonia;

(iii) a cooling reactor operably connected to the calcining system and the treatment reactor and configured for receiving the first gaseous stream comprising clean carbon dioxide and the second gaseous stream comprising ammonia, and configured for subjecting the first and the second gaseous streams to a cooling process under one or more cooling conditions to condense a second aqueous solution comprising ammonium bicarbonate, ammonium carbonate, ammonia, or combinations thereof; and

(iv) a contacting reactor operably connected to the treatment reactor and the cooling reactor and configured for receiving the first aqueous solution comprising calcium salt and the second aqueous solution comprising ammonium bicarbonate, ammonium carbonate, ammonia, or combinations thereof, and configured for treating the first aqueous solution with the second aqueous solution under one or more precipitation conditions to form a precipitation material comprising vaterite, aragonite, calcite, or combinations thereof.