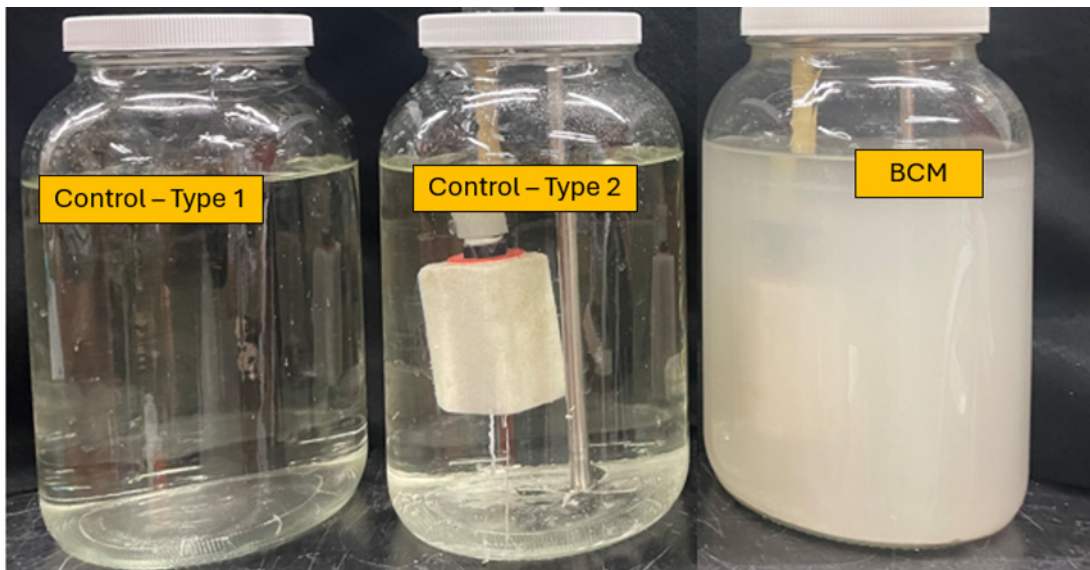




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Biological and Ion Exchange Mining of Reverse Osmosis Concentrate: Enhancing Water and Mineral Extraction from a Salinity Impaired Surface Water



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Cover Image – Three batch tests were run, two controls, one stagnant and one with aeration and mixing. The remaining test had aeration and mixing with added biology and carbon source, which produced precipitation of gypsum (Grace Scarim/Bureau of Reclamation).

Biological and Ion Exchange Mining of Reverse Osmosis Concentrate: Enhancing Water and Mineral Extraction from a Salinity Impaired Surface Water

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Acronyms and Abbreviations

Ag	agricultural
ARW	Arkansas River Water
BCM	biological concentrate management
BV	bed volume
C ₃ H ₈ O ₃	glycerin
Ca	calcium
CaCO ₃	calcite
CaSO ₄	calcium sulfate
CaSO ₄ *2H ₂ O	gypsum
COD	chemical oxygen demand
COSINC	Colorado Shared Instrumentation in Nanofabrication and Characterization
DFC WTL	Denver Federal Center Water Treatment Laboratory
DI	deionized
DO	dissolved oxygen
DOI	U.S. Department of the Interior
EPA	U.S. Environmental Protection Agency
EPS	extracellular polymeric substances
GAL	Green Analytical Laboratories
HRT	hydraulic residence time
IX	ion exchange
K	potassium
kg	kilogram
Li	lithium
Mg	magnesium
MICP	microbially induced calcium precipitation
ML	million liters
MLD	million liters per day
MLVSS	mixed liquor volatile suspended solids
N/A	not available; not applicable
Na	sodium
NAWQA	National Water-Quality Assessment
NF	nanofiltration
P	phosphorus
PFAS	per and polyfluoroalkyl substances
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
PVC	polyvinylchloride
S&T	Science and Technology

SEM/EDS	scanning electron microscopy/energy-dispersive X-ray spectroscopy
Rb	rubidium
Reclamation	Bureau of Reclamation
RO	reverse osmosis
ROC	reverse osmosis concentrate
S	sulfur
SAR	sodium adsorption ratio
SI	saturation index
SM	standard method
S.U.	standard unit
TDS	total dissolved solids
TSC	Technical Service Center
TSS	total suspended solids
UF	ultrafiltration
VSS	volatile suspended solids
WRRF	Water Resource Recovery Facility
ZLD	zero liquid discharge

Symbols

~	approximately equal to
°C	degrees Celsius
=	equal to
g/L	gram per liter
≤	less than or equal to
mg/L	milligram per liter
mS/cm	millisiemens per centimeter
NH ₃ -N	ammonia-nitrogen
µg/L	microgram per liter
%	percent

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Executive Summary

Generation of reverse osmosis concentrate (ROC) is a barrier for reverse osmosis (RO) process application due to challenges managing supersaturated brine. Biological concentrate management (BCM) is a novel utilization of microbes for phosphorus-based antiscalant inactivation contained within ROC, aerobically inducing precipitation. BCM bench-scale reactors treating agricultural drainage impacted ROC inactivated antiscalant by 88 percent (%), precipitating 41% and 10% of ROC calcium and sulfate. Testing indicated ROC precipitated gypsum and calcite, and thermodynamic modeling specified precipitate can be controlled for a pure gypsum recovery at a $\text{pH} \leq 7$, producing approximately (~)125 kilograms of gypsum per million liters of water fed to the RO process. High calcium and sulfate concentrations in agricultural return waters originate as extensively used gypsum soil amendments that can be mined by BCM and resold locally, limiting salt importation and yielding increased crop production. The BCM induced reduction in ROC saturation theoretically increased overall recovery from 85% to 92% when treated with another RO stage. Alternatively, post-BCM mineral mining using cationic ion exchange increased calcium removal and water recovery while providing an opportunity for potassium (K), lithium (Li), magnesium (Mg) and rubidium (Rb) recovery from a volume ~97% smaller than the original flow being treated, yielding 5.0 kg, 0.026 kg, 142 kg, and 0.001 kg of K, Li, Mg, and Rb, per one million liters of RO influent, respectively.

The Manuscript as submitted and accepted to the American Society of Civil Engineers Journal of Environmental Engineering can be found in appendix A.

Appendix A

Biological and Ion Exchange Mining of Reverse Osmosis Concentrate: Enhancing Water and Mineral Extraction from Salinity-Impaired Surface Water, Manuscript Accepted to *ASCE Journal of Environmental Engineering*, 2026, 152(1): 04025092.

Biological and Ion Exchange Mining of Reverse Osmosis Concentrate: Enhancing Water and Mineral Extraction from Salinity-Impaired Surface

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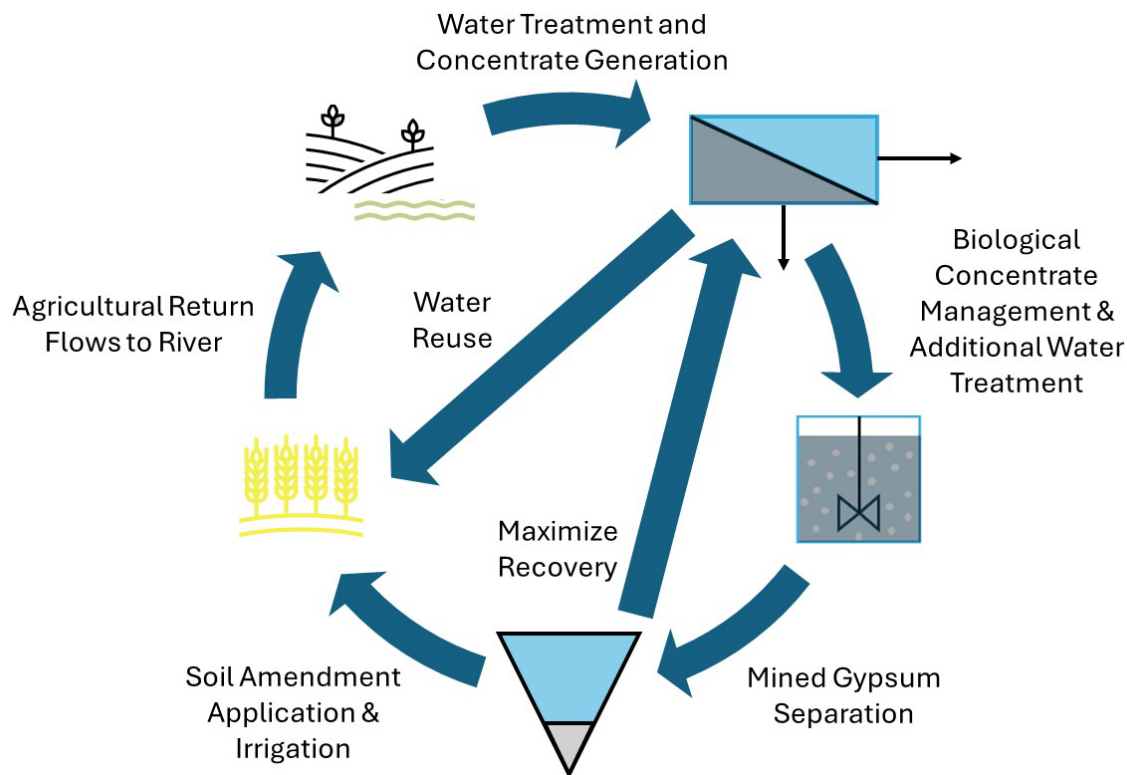
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Graphical Abstract



Abstract

Generation of reverse osmosis concentrate (ROC) is a barrier for reverse osmosis (RO) process application due to challenges managing supersaturated brine. Biological concentrate management (BCM) is a novel utilization of microbes for phosphorus-based antiscalant inactivation contained within ROC, aerobically inducing precipitation. BCM bench-scale reactors treating agricultural drainage impacted ROC inactivated antiscalant by 88 percent (%), precipitating 41% and 10% of ROC calcium and sulfate. Testing indicated ROC precipitated gypsum and calcite, and thermodynamic modeling specified precipitate can be controlled for a pure gypsum recovery at a $\text{pH} \leq 7$, producing approximately (~)125 kilograms of gypsum per million liters of water fed to the RO process. High calcium and sulfate concentrations in agricultural return waters originate as extensively used gypsum soil amendments that can be mined by BCM and resold locally, limiting salt importation and yielding increased crop production. The BCM induced reduction in ROC saturation theoretically increased overall recovery from 85% to 92% when treated with another RO stage. Alternatively, post-BCM mineral mining using cationic ion exchange increased calcium removal and water recovery while providing an opportunity for potassium (K), lithium (Li), magnesium (Mg) and rubidium (Rb) recovery from a volume ~97% smaller than the original flow being treated, yielding 5.0 kilograms (kg), 0.026 kg, 142 kg, and 0.001 kg of K, Li, Mg, and Rb, per 1 million liters of RO influent, respectively.

Practical Applications

Salinity mobilized through agriculture returns and soil releases impact downstream users by compromising water quality in receiving rivers, lakes and groundwaters. Salinity increases for receiving waters limits potable and agricultural usage capability. The Arkansas River seasonally enters Kansas almost 7 times saltier than standards for potable water. Part of this salinity originates from agricultural amendments added to upstream farmland soils for increased crop yields, which eventually return to the river. While reverse osmosis treatment is capable of recovering 85% of Arkansas River water for potable or agricultural uses, the remaining 15%, termed reverse osmosis concentrate, is now 47 times more saline than potable water standards. This publication presents a novel process to manage this super saturated salinity through low energy biological mitigation, termed biological concentrate management (BCM). Applying this process can selectively remove gypsum from reverse osmosis concentrate, a soil amendment that can be locally valorized, as well as potassium, lithium, magnesium and rubidium when processed further. Overall beneficial water recovery exceeds 90% and the remaining reverse osmosis concentrate is simpler to manage through other means such as evaporation. This process can be widely applied across salinity-impacted locations, such as California's Central Valley, Central Kentucky's Headwaters, Chesapeake Bay Watershed, Great Lakes region, Upper Arkansas River Corridor and agricultural hubs that apply gypsum soil amendments.

Keywords

Salinity; Reverse Osmosis; Biological Concentrate Management; Reverse Osmosis Concentrate Mining; Gypsum Recovery; Potassium, Lithium, Magnesium and Rubidium Recovery

1.0 Introduction

Approximately 30 percent (%) of the Earth's total available freshwater is stored as groundwater, whereas the largest freshwater percentage (approximately [~] 69%) is stored in unavailable ice caps, glaciers and permanent snow (U.S. Geological Survey [USGS] 2019). As fresh groundwater sources are depleted from overdraw and aridification (Colorado River Research Group 2018; Kansas Geological Survey 2023; USGS 2018), brackish groundwater (Allama et al. 2002; Clayton et al. 2014), water reuse (Hejase et al. 2022; Wetterau et al. 2013), sea water sources (Elimelech and Phillip 2011; Shaffer et al. 2012), and agricultural (Ag) drainage impacted waters (Rahardianto et al. 2007) can be desalinated for beneficial use. To remove salinity, i.e., total dissolved solids (TDS), from these sources, membrane separation using nanofiltration (NF), rejecting principally multivalent ions, and reverse osmosis (RO) treatment processes can be implemented as best available technologies (Crittenden et al. 2012).

Maximizing beneficial water extraction from saline sources typically requires antiscalant and dispersants be dosed into the NF or RO influent to maintain supersaturation of sparingly soluble TDS constituents (Bond and Veerapaneni 2007; Crittenden et al. 2012). As diffusion driven water permeates the NF or RO membrane, rejected charged and larger molecular weight solvated constituents concentrate into a supersaturated saline brine, termed RO concentrate (ROC) herein. Antiscalants, typically constituted with phosphates, phosphonates, or polycarboxylates (Antony and Leslie 2014), maintain ROC salts exceeding saturation indices dissolved by interfering with the formation of crystalline solids for time periods ranging from minutes to days or longer, dependent on factors such as saturation index (SI) (Lyster et al. 2010), pH (Rosenberg et al. 2012), formulation (Qu et al. 2020), induction time (Hasson et al. 2003; Jain et al. 2019), and temperature (Qu et al. 2020). Phosphate and phosphonate-based antiscalants introduce additional phosphorus (P) in the ROC and, depending on concentrate management technique, may require additional treatment to meet the U.S. Environmental Protection Agency's (EPA's) National Pollution Elimination System (NPDES) discharge permits to prevent nutrient loading and eutrophication in receiving waters (EPA 2025b). Current antiscalant degradation methods include seeded precipitation (McCool et al. 2012), advanced oxidation processes (Greenlee et al. 2011, 2014; Lee et al. 2023), and adsorption (Boels et al. 2012); however, such processes require large chemical additions/energy inputs, and/or need to be tested full-scale. ROC is a byproduct that presents disposal challenges, compounded when natural outfalls (e.g., direct ocean discharge, access to permeable saline aquifers) (Bond and Veerapaneni 2007) do not exist. Inland concentrate is typically discharged into receiving waters (Crittenden et al. 2012), evaporation ponds (Ahmed et al. 2000; Arnal et al. 2005), chemically induced/seeded precipitation processes (Bond & Veerapaneni 2007), deep well injected (Cappelle 2018) or further treated by energy intensive evaporative processes (Backer et al. 2022; Giwa et al. 2017). Drawbacks of current inland ROC treatment methods include 1) constant chemical addition, thereby increasing TDS and solids production using chemically-enhanced seeded precipitation (Choi et al. 2021; McCool et al. 2012), 2) energy requirements to thermally achieve zero liquid discharge (ZLD) (Ziolkowska 2015) using crystallization (Dahmardeh et al. 2019; Hamed et al. 2000; Turek et al. 2005), distillation (Deshmukh et al. 2018), and evaporation (Ahmed et al. 2000; Turek et al. 2005), and/or 3) processes that remain untested against actual ROC. ROC discharge can be complicated by fluctuating influent water quality and concentration of toxic

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constituents; additionally, lack of controlled antiscalant degradation may lead to uncontrolled precipitation and deposition of precipitate on conveyance pumps, pipes and outfalls (Crittenden et al. 2012; Fernández-Torquemada et al. 2005; Roberts et al. 2010). Establishing a ROC management technique at the nexus of desaturation and energy efficiency will overcome the techno-economic disposal challenge facing RO, allowing for expanded beneficial water extraction from impacted sources striving to attain ZLD/minimal liquid discharge (MLD).

Considering desalination implementation for Ag operations in particular is necessary to address salinity more broadly in the United States. When considering land area and usage in the United States, approximately half of all the land (1.2 billion acres) is dedicated farmland; additionally, the National Water-Quality Assessment (NAWQA) Project identified that Ag runoff is the leading cause for impacted water quality in streams and rivers and the third listed cause for lakes due to runoff (nonpoint source pollution), infiltration, and irrigation return flows (EPA 2025a). Vital Ag hubs in the United States, such as California's Central Valley, Central Kentucky's Headwaters, the Chesapeake Bay Watershed, the Great Lakes region, and the Upper Arkansas River Corridor (Hejase et al. 2022; Hussain et al. 2025; Jones et al. 2024; Skidmore et al. 2023; Stephenson et al. 2022), experience Ag pollution to local water sources from fertilizer, pesticides, soil amendments, and manure, which requires consideration for ROC management disposal for RO applications in those regions (EPA 2025a). Lack of planning for ROC discharge from sparsely distributed decentralized RO facilities may exacerbate already extensive salt accumulation due to importation, mobilization and application of soil amendments (CV-SALTS 2024; Nicolas et al. 2023; Whittemore et al. 2023) which have fallowed significant land areas (Hanak et al. 2019).

Biological reactions have been identified in RO related research, e.g., identifying means of denitrifying ROC (Ersever et al., 2007; Li et al., 2018), removing total nitrogen (N), P, and hardness from ROC using cultivated algae (Wang et al. 2016), and diatom silica metabolism in ROC (Gao et al. 2025). However, to the authors knowledge, no prior studies have investigated the potential for deactivation of antiscalant as a means of ROC desaturation via a novel aerobic biological treatment process. The study goals are: 1) test biological concentrate management (BCM) by determining carbon (C) source requirements and biological conditions that desaturate antiscalant, 2) identify if beneficial solids can be mined from ROC, 3) determine how much additional water can be extracted from ROC post BCM using second stage RO as option #1 for post-BCM treatment, and 4) treat BCM effluent with cationic ion exchange (IX) for additional water and resource mining using Arkansas River Water (ARW), followed by membrane desalting, with either NF treatment for sodium chloride separation and IX regeneration reuse (Korak et al. 2018) or RO treatment, as option #2 for post-BCM treatment.

2.0 Materials and Methods

2.1 Sample Collection and Water Quality

ARW was collected on March 27, 2024, near Garden City, Kansas in the Southwest Kansas Groundwater Management District Number 3. Samples were pulled to coincide with peak ARW conductivity (4.03 mS/cm), which is affected by controlled water releases from reservoirs in Colorado. Raw water quality is listed in table S1. Samples were collected in 3 60-liter high density polyethylene (HDPE) plastic drums and overnight shipped to the Denver Federal Center – Technical Service Center Water Treatment Laboratory (DFC WTL) where samples were stored at ambient temperature until treated. ARW was treated on April 22 and April 23, 2024 in two duplicate batches. The ARW was filtered using Inge Water Technologies Dizzer XL 0.9 MB 38 ultrafiltration (UF) membrane (Dupont, Wilmington, DE) for pre-treatment to remove suspended solids. The UF treated water was subsequently filtered using a brackish water RO membrane from Applied Membranes Inc. (Model No. M-B2540A) loaded in an Axeon RO unit with a single PVC-2540 pressure vessel to a recovery rate of 85% in a batch process using a cone bottom 40-liter HDPE tank. A proprietary polymer- and phosphonate-based antiscalant was used for silica and calcium sulfate scale mitigation. Based on UF filtered water quality and proprietary software that maximized recovery (85%), antiscalant was dosed at 3.0 mg/L. The resulting ROC conductivity was 16.83 mS/cm at 23.0 degrees Celsius (°C) and 16.84 mS/cm at 22.2 °C for batch 1 and 2, respectively. Resulting ROC water quality is listed in table 1. BCM batch reactors were run immediately upon ROC generation.

2.2 Biological Source and Sampling

Microbes dosed for BCM were collected from City of Boulder Water Resource Recovery Facility (WRRF) on April 17, 2024, from the end of the aerobic activated sludge basins as mixed liquor sample contained in a polyethylene 5-liter carboy. The WRRF employs conventional treatment techniques, i.e., physical separation, biological treatment for organics and N removal, ultraviolet light for disinfection, and solids treatment for resource recovery. The sample was brought back to the DFC WTL, where it was mixed and aerated. Vegetable derived glycerin ($C_3H_8O_3$) (USP food grade, 100% purity) was dosed as a C source to maintain microbial viability prior to BCM testing.

2.3 Antiscalant Characterization and Quantification

The antiscalant dosed was characterized by total P and acid hydrolyzable P/ortho P (reported as inorganic P) measurements and calculated organic P. This characterization classified initial antiscalant P fractions as inorganic and organic P. Furthermore, this testing monitored the extent of P reversion and antiscalant degradation over the hydraulic retention time (HRT) of the BCM batch reactors due to time and/or mixing conditions for up to 48 hours.

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An antiscalant concentration of 6.67 mg/L was dosed in duplicate 3 L of deionized (DI) water reactors to simulate theoretical ROC antiscalant concentrations. Standing mixers with 4-blade axial flow impellers (ONiLAB, City of Industry, CA), operated at 300 rpm, were used to homogenize and continuously mix reactors, with the terminus of impeller tips located 1/3 from the bottom of the reactor to ROC water level. Initial (Hour 0), 24 hours, and 48 hours grab samples were pulled from each reactor to measure total P and inorganic P. Samples were preserved in sulfuric acid and overnight shipped to Green Analytical Laboratories (GAL, Durango, CO) for analysis.

2.4 Biological Concentrate Management Batch Reactor

Three aerated batch BCM reactors were run in triplicate (over batch 1 and 2) at the DFC WTL on April 22 and April 23, 2024, at an HRT of 18 hours in 4-liter glass jars covered with an opening for gas release. ROC was dosed with activated sludge seed (seed). Seed preparation included filtering 100 mL of activated sludge through a Whatman glass microfiber filter with a nominal pore size of 0.7 μm to remove soluble total P from the microbial sample. The particulate seed captured on the filter was resuspended into ROC. $\text{C}_3\text{H}_8\text{O}_3$ was used as the substrate source to provide a readily biodegradable electron donor for oxidation. The $\text{C}_3\text{H}_8\text{O}_3$ dose into each reactor was calculated based off the C:N:P Redfield ratio of 106:16:1 for P assimilation (Arias-Paíć et al. 2022; Redfield 1934) using a measured soluble total P concentration of 0.60 mg/L P as the C dose basis. Twice the necessary C concentration, based on Redfield ratio, was dosed to ensure C was not reaction limiting. N was not dosed externally.

Three types of reactors were run, with two types of controls and the BCM reactor. Control – Type 1 was a reactor consisting of solely ROC without seed, $\text{C}_3\text{H}_8\text{O}_3$, aeration, or mixing as a means of quantifying stagnant ROC precipitation as a function of time. Control – Type 2 was a reactor that mixed and aerated the ROC and received no seed or $\text{C}_3\text{H}_8\text{O}_3$ doses. BCM reactors were dosed with filtered seed and $\text{C}_3\text{H}_8\text{O}_3$, while mixed and aerated over the 18-hour HRT. Table 2 summarizes the treatment conditions per reactor type. Control – Type 2 was replicated once due to limited concentrate availability, while the BCM reactor was run in triplicate to account for biological process variability.

ALS8 Aquatic Eco-Systems Sweetwater Air Diffusers (Pentair, London, UK) were connected to 0.5 L/min air pumps (Tetra, Blacksburg, VA) to aerate the indicated reactors and provide dissolved oxygen (DO) as the electron acceptor. After combining seed with the ROC (figure S1), the BCM reactors had an initial approximate volatile suspended solids (VSS) concentration of 0.50 g/L.

2.5 Ion Exchange Process

Purolite C100E was used for cation IX (CIX) treatment of UF filtered BCM effluent water. A 1-inch diameter schedule 40 polyvinyl chloride (PVC) column with a glass wool under-drain retained a 200 mL bed volume (BV) of resin as a means of cation removal exchanged with sodium (Na) in the CIX treated effluent. The operational parameters for the CIX treatment of

BCM treated water, regeneration, and rinse are outlined in table 3. Duplicate runs of UF filtered BCM water completed and the average results of the two runs are presented. CIX resin loading and recovery yields were determined based on integration of breakthrough and regeneration curves for samples taken every 0.5 BV.

2.6 Proposed Process Flow

Figure 1 outlines tested and proposed treatment trains for BCM as a means of enhanced water and mineral recovery through antiscalant inactivation. ROC would be treated by BCM, where precipitated solids would be recycled to sustain microbial community population and enhance precipitation with internally seeded gypsum. Solids removal would be principally achieved via sedimentation and polished by UF membrane filtration. Subsequent treatment could follow two proposed paths. The first option is RO treatment of the desaturated ROC for MLD. The second option is CIX treatment for hardness removal and mineral recovery during regeneration. NF treatment of the treated CIX water may then provide a recovered sodium chloride in the NF permeate as a regeneration solution.

2.7 Analytical Methods

In-lab testing consisted of pH measurements using Hach probe PHC281 and conductivity measurements using HACH probe CDC401 (Hach, Loveland, CO). Total suspended solids (TSS) and VSS used Whatman 41 filter paper and Whatman glass microfiber filter (nominal pore size 0.7 μm), respectively. TSS and VSS were measured in accordance with Standard Methods (SM) 2540 D (APHA et al. 2023) and used to estimate fixed solids (i.e. gypsum) and microbial yields by calculating fixed suspended solids ($\text{FSS} = \text{TSS} - \text{VSS}$). Analytical samples filtered with 0.45 μm nylon filters and were sent to GAL to measure analytes shown in table S2.

CIX treated ROC analytical samples during treatment and regeneration were sent to the University of Colorado (CU) - Boulder for ICPMS metals analysis. Calcium (Ca), Cesium (Cs), Lithium (Li), Magnesium (Mg), Potassium (K), Rubidium (Rb), and Na were measured using EPA 6020B with both helium and hydrogen gas modes using an Agilent 7900 with an ultra-high matrix introduction system.

Per- and polyfluoroalkyl substances (PFAS) were measured by DHL Analytical (Round Rock, TX) on raw water, permeate, and concentrate samples (at 80% recovery of ARW) for perfluorohexanesulfonic acid (PFHxS), perfluorooctanesulfonic acid (PFOS), and perfluorooctanoic acid (PFOA).

Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM/EDS) was performed using a Hitachi SU3500 VP SEM with Oxford Instruments EDS at the CU-Boulder Colorado Shared Instrumentation in Nanofabrication and Characterization (COSINC) Laboratory. Batch 1 samples were gold sputter coated to minimize interference and improve image quality.

Next generation DNA sequencing was completed by Zymo Research following their ZymoBIOMICS® Targeted Sequencing Service (Zymo Research, Irvine, CA) on batch 2 reactor samples (post 18-hour HRT) and the activated sludge from City of Boulder WRRF. Samples were stored at -80 degrees Celcius until shipped on dry ice to Zymo Research for processing and analysis. The bacterial 16S ribosomal RNA gene was targeted with amplification of the V3-V4 region of the gene. The library was sequenced on the Illumina® Nextseq™.

2.8 Data Processing and Analysis

Thermodynamic modeling for scaling tendencies and pH and vapor surveys of ROC and BCM treated water was conducted using OLI Studio (version 12.0) Stream Analyzer. Bioinformatics analysis was completed by Zymo Research using the DADA2 pipeline (Callahan et al. 2016). Data visualization was completed using the tidyverse package in RStudio (R version 4.3.2) (R Core Team 2025; Wickham et al. 2019). Permeate and concentrate concentrations for RO and NF treatment were modeled with proprietary vendor software.

3.0 Results and Discussion

3.1. Antiscalant Characterization in Deionized Water

On average, total P concentrations from initial to 48-hour (final) measurements only changed 0.70%; therefore, total P is a valid surrogate measurement for antiscalant A under a hydraulic retention time (HRT) of less than 48 hours (figure 2) for waters with non-detectable concentrations of P. Surrogate antiscalant (total P) measurements indicated mixing was not a degradation mechanism of antiscalant A over this HRT. Furthermore, there were no major reversions of the P fraction composition, where the organic P fraction was sustained as the principal antiscalant P fraction over the course of 48 hours in mixed deionized water. The organic makeup of the antiscalant indicate a phosphonate antiscalant (Antony and Leslie 2014), as opposed to a phosphate and polyphosphate composition.

3.2. BCM Bench-Scale Batch Testing

3.2.1. Antiscalant Degradation

After an 18-hour HRT, the BCM reactor had visibly precipitated a significant quantity of solids, compared to the two types of controls, that visibly had very little precipitation, as shown in figure 3. Quantified as TSS, the Control – Type 1, Control – Type 2 and BCM reactors precipitated 0.0089 g/L, 0.14 g/L and 1.05 g/L of total suspended solids, respectively. Formation of precipitation yielded a decrease in ROC TDS that corresponded to antiscalant degradation, measured as Total P (figure 4).

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The BCM reactor yielded the greatest percent removal of antiscalant (88%) and TDS (16.2%), when compared to initial ROC conditions. Antiscalant, which interferes with nucleation and crystallization (Bond and Veerapaneni 2007), requires inactivation for controlled precipitation and solids recovery. Passive inactivation by means of antiscalant induction time could lead to inopportune precipitation, causing catastrophic pipe and equipment interferences at RO treatment facilities or ROC discharge locations. The Controls – Type 1 and 2, stagnant ROC and mixing and aerating ROC, respectively, indicate that an HRT of 18 hours or less is insufficient for induction time and mechanical mixing and aerating to control ROC desaturation. The comparable TDS removal between Control – Type 1 and 2 indicates nonlinearity between antiscalant degradation and TDS removal; however, further testing is required to confirm interdependence. In comparison, BCM antiscalant inactivation allows for desaturation of ROC with minimal additions of $C_3H_8O_3$ and aeration. The C_{removed} to P_{removed} ratio was 213:1 for the batch 1 BCM reactor, compared to the theoretical Redfield ratio of 106:1, indicating the $C_3H_8O_3$ dose could be further optimized, including the consideration of existing readily biodegradable COD in the ROC to reduce external dose requirements.

Biological antiscalant inactivation is a phenomenon previously observed in detrimental operation of RO membrane processes. Sweity et al. (2015) measured a decrease in total P as antiscalant corresponded to an increase in biological activity that induced biofouling of an RO membrane. Deactivation of antiscalant at the RO surface could cause solids deposition and catastrophic membrane failure, therefore, it is assumed that the antiscalant was not fully degraded from biofilm growth on the RO (Sweity et al. 2015). Utilizing microbes for antiscalant uptake is the basis of BCM; the postulated mechanism for inactivation is microbial P assimilation for cell growth, induced by C-P bond cleavage, due to limited P sources in the ARW (Quinn et al. 2007; Wanner 1994).

Microbially-induced Ca precipitation (MICP) via C metabolization (Ansari et al. 2020) and denitrification (Z. Wang et al. 2023) in Ca-rich medias is induced by nucleation and crystallization at the cell wall from intracellular Ca transport channel accumulation and / or from extracellular polymeric substances (EPS) production; however, contrary to the Wang et al. (2023) study of denitrification driven MICP in Ca-rich media, microbially denitrification is likely not occurring in the BCM aerated system due to the presence of DO and measured increases in nitrite/nitrate. Therefore, it is hypothesized the pathway for precipitation is antiscalant deactivation via microbial assimilation antiscalant derived total P.

P assimilation of phosphonate-based antiscalant is contingent on P-limited waters and ROC due to the greater bioavailability of ortho P compared to organic P as contained in antiscalant (Venkiteshwaran et al. 2018). An Ag drainage ROC water tested with the procedures and controls contained herein (data not shown) measured an ortho P concentration of 0.062 mg/L P had limited ROC precipitation compared to the ARW, which had a non-detectable amount of inorganic P (< 0.0215 mg/L P).

3.2.2. pH and Alkalinity

Increasing pH and decreasing alkalinity in Control – Type 2 (TSS = 0.14 g/L) and the BCM (TSS = 1.05 g/L) reactors (table S3) are hypothesized to have been induced by calcite precipitation. Confounding co-occurring reactions include air stripping of carbonic acid, due to system over aeration, which increased pH and induced calcite precipitation. Calcite precipitation consumes carbonate, thereby decreasing alkalinity and lowering pH. The aeration of the reactor reached saturation with an approximate DO concentration of 7 mg/L; however, DO saturation levels could be optimized and carbonic acid stripping, if occurring, minimized by controlling aeration to meet microbial requirements by maintaining a minimum DO concentration of 2 mg/L (Metcalf & Eddy Inc., 2013). The BCM reactor may have seen a larger consumption of alkalinity and a smaller increase in pH compared to Control – Type 2 due to the occurrence of nitrification inducing alkalinity consumption. The depletion of ammonia and increase in nitrate/nitrite also indicates the occurrence of nitrification / N assimilation for cell growth from a more abundant microbial community population. However, the consumption of alkalinity during nitrification in the BCM reactor would require an ammonia concentration 130 times greater than what was available in the ROC, which indicates alkalinity consumption is most likely occurring due to other mechanisms, such as calcite precipitation or induced by endogenous decay. Note that bench-scale testing limitations resulting in initial ROC alkalinity and pH variability complicate determining mechanisms for changes in measurements of these analytes remain unresolved. Due to passage of carbon dioxide gas across the RO membrane, while alkalinity undergoes concentration during constant recirculation and aeration when RO is operated at the bench scale, a larger scale test of continuous flow membrane treatment will represent a carbonate species equilibrium with greater reproducibility than RO batch treatment.

3.2.3. DNA Sequencing

The next generation sequencing targeting the bacterial 16S rRNA gene identified microbial composition and 50 most abundant species identified for the activated sludge seeded, Control – Type 1, and the BCM reactors (figure S2). While some studies have been successful using specific strains of algae for ROC desalination with HRTs at or over 24 hours (Gao et al. 2025; Wang et al. 2016), our study found the most abundant microbial species post-BCM were either: saline tolerant (Park et al. 2014), soil derived, potentially from Ag inflows in ARW (Hantsis-Zacharov et al. 2008; Kirby et al. 2004), or common in wastewater due to the introduction of the activated sludge seed (Dueholm et al. 2022). Genera that have demonstrated C-P lyase activity were detected in the BCM reactor (e.g. *Rhodobacter* and *Pseudomonas*) (Agarwal et al. 2011; Schowanek and Verstraete 1990). Additionally, within the BCM reactor *Nitrosomonas* (ammonia-oxidizing bacteria within the top 50 most abundant genera) and *Nitrospira* (nitrite-oxidizing bacteria within the top 100 most abundant genera) were present and are required for complete nitrification, as hypothesized in section 3.2.2. The microbial community populations' relative abundances varied among the three samples. Due to the hypersaline nature of the ROC and lack of seeded activated sludge salinity assimilation, the saline tolerant microbes were postulated to experience the most growth / be the largest contributor to P assimilation (Lockwood et al. 2022). Future testing recommendations include monitoring bacterial growth after BCM seeding, C-P lyase gene presence, and alternative activated sludge seeds for microbial community population optimization.

3.2.4. Salt Precipitation

SEM/EDS images of the precipitated solids from batch 1 of Control – Type 2 and BCM reactors (figure 5) highlight that the control only precipitated Ca, oxygen (O), and C (indicating calcite [CaCO_3]), which could have solely been induced by an increase in pH due to carbonic acid stripping, and the BCM precipitated Ca, O, C, and sulfur (S) (indicating calcite and gypsum [$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$]). To confirm SEM/EDS and thermodynamic modeling results (figure S3) additional solids analysis testing is required. Consequently, BCM achieved an average 41% removal of Ca and 10% removal of sulfate from initial ROC concentrations. Control – Type 1 and 2 which experienced on average a 12% and 5% removal of Ca, respectively, and 4% removal of sulfate in both controls (table S4).

High purity precipitation of gypsum would be a beneficial by-product of BCM. Gypsum as an Ag soil amendment in saline and saline-sodic soil helps improve the sodium adsorption ratio (SAR) via Na/Ca exchange, which improves soil structure and water infiltration (Ahmed et al. 2015; Bello et al. 2021; Ghafoor et al. 2001). Gypsum application reduces salinity stress of the soil, which impacts growth and crop yield, depending on salinity tolerance (Aboelsoud et al. 2020; Ahmed et al. 2015). ARW entering Kansas from Colorado (the Upper Arkansas River Corridor) is salinity impaired by uranium and sulfate from natural geographic distribution, compounded by irrigation return flows, which infiltrate and contaminate groundwater, specifically the Ogalla-High Plains Aquifer (Buchanan et al. 2023; Whittemore et al. 2023). The return flows contain high concentrations of sulfate due to the application of gypsum on sodic and saline-sodic soils to significantly improve production of winter wheat, the largest production of the crop in the United States (Kansas Department of Agriculture, 2024; Ramamoorthy et al. 2021; Reed and Sorenson 1997). The Ogalla-High Plains Aquifer supports up to 80% of Kansas' water usage (Buchanan et al. 2023) and an estimated 30% of United States' Ag irrigation (NIFA and USDA 2025). The depletion of the aquifer has groundwater management districts exploring the feasibility of interstate water transfers as an alternative (Royse 2023), and consideration for managing salinity impacts from ARW using the best available technologies – RO and NF membrane separation. Therefore, the generation of gypsum via BCM will allow for a circular economy of treating ARW with the opportunity to sell RO permeate and the recovered gypsum back to local farmers for improved soil quality, resulting in larger yields and improved water consumption, while offsetting salt imports and associated costs with membrane treatment and BCM.

3.2.5. Increasing Gypsum Yields and Land Application

Utilizing a Kansas-based Ag laboratory (ServiTech, Inc., Dodge City, KS) for soil amendment analysis, it was determined that the precipitated solids post-BCM was 64% gypsum purity, assuming $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. To maximize gypsum purity while minimizing calcite, an unproductive byproduct, pH can be controlled to ≤ 7 with sulfuric acid based on thermodynamic modeling (figure S3) and when coupled with BCM aeration optimization ARW ROC precipitating Ca theoretically yields solely gypsum (without any calcite). The difference between theoretical solids yields and the post-BCM TSS concentration is indicative of additional precipitation required to decrease saturation to unity. The majority of the actual TSS fraction is fixed solids

(83%) for BCM reactors post treatment. Assuming most precipitated fixed solids are gypsum (with pH / aeration controls), BCM can produce ~125 kg of gypsum per million liters (ML) of ARK RO feed volume.

Mixed liquor VSS (MLVSS) concentration approximates biomass, and is dependent on solids retention time, substrate / nutrient availability, and environmental conditions. The presence of antiscalant in P limited systems can be modeled for the basis of $C_3H_8O_3$ (substrate) dose optimization solely considering antiscalant P concentration, DO and N requirements, and overall biomass yields per substrate dose using bioenergetics under standard conditions (Equations S1-S8) (Metcalf & Eddy Inc. 2013; Rittmann and McCarty 2001). The biomass yield (17% of TSS) in the mined gypsum requires biological stabilization for production of land applied biosolids that could then function as fertilizer mixed with gypsum. A portion of the solids would need to be recycled to maintain a microbial community population for antiscalant inactivation; however, included in the solids recycle would be precipitated gypsum. Additional testing is required to understand the effects of microbial and solids recycle on BCM. Recycle of gypsum precipitant could further enhance precipitation (Choi et al. 2021; McCool et al. 2012) in combination with BCM, thereby increasing yield of precipitated gypsum and/or decreasing HRT requirements.

3.2.6. Minimal Liquid Discharge

Assuming complete precipitation conversion to gypsum, the gypsum SI (where SI = 1 is at saturation) for the BCM reactor dropped from 3.00 as ROC to 2.08 post-precipitation as seen in figure 6. The precipitation of gypsum allows for an additional 45% water recovery from ROC through RO treatment based on modeling of post-BCM water quality, potentially increasing overall beneficial water recovery of ARW to 92% from 85% after a single pass through the BCM process nearing MLD/ZLD (Tong et al. 2025) (table S4). Desalting membrane permeate concentrations measured below EPA maximum contaminate levels (MCLs) for all inorganic chemicals monitored (EPA 2024); however, additional treatment, such as disinfection would be required for potable consumption. Using permeate for irrigation would be feasible, even for sensitive crop application, but could require coliform monitoring and disinfection (Ayers and Westcot 1994).

Although saturation unity was not achieved under current BCM conditions, TSS and VSS concentrations were measured 11 months post-BCM testing on a sample maintained at laboratory temperatures and conditions (20–25 °C) and resulted in only 0.28 g/L and 0.05 g/L, respectively, indicating a quasi-stable treated water. The acclimation of the microbial community composition encourages growth of halophiles, inhabitants of hyper saline environments, which are better suited for BCM due to the high ROC TDS. However, with having already reached an 88% reduction in antiscalant as total P during an 18-hour HRT, there may be a limit to the antiscalant availability to microbes for biological assimilation.

The recycle of precipitated gypsum with mechanical mixing could promote enhanced gypsum nucleation and crystallization in an aerated and pH-controlled water, limiting calcite formation, that will further decrease the gypsum SI for downstream treatment, such as CIX coupled with additional membrane treatment.

3.3. Trace Constituent Monitoring and Treatment

The post-BCM uranium concentration (0.422 mg/L) indicated uranium does not precipitate within this process. Additional uranium-specific treatment, such as anion IX (Flint et al. 2021), coagulation, lime softening, biosorption (Katsoyiannis and Zouboulis 2013), can subsequently treat significantly smaller feed flow rates. Limited PFAS testing indicated detectable concentrations of PFOA in the ROC at 80% recovery (table S5). Further testing is required at lower detection limits to understand the fate and transport of PFAS compounds and impacts to land application of gypsum and biosolids, and any additional required treatment.

3.3.1. Ion Exchange of BCM Treated Water

BCM treatment substantially reduces the Ca:Mg ratio present in the influent CIX water from 1:1 to 1:3 on an equivalent basis. The removal of Ca using CIX treatment on BCM treated water (influent water quality of 14.8 g/L TDS and 16.09 mS/cm conductivity) yielded a composite Ca concentration less than 2 mg/L, segmenting BVs from 0-15, prior to breakthrough commencement, which resulted in a Na dominant effluent (figure 7). Treated-CIX effluent was amenable to at least 75% NF recovery, which was volume limited, without antiscalant addition (table S4). CIX Mg, K, and Rb co-eluted prior to Ca breakthrough of BCM treated influent. Cs was undetected. Li, an important trace earth metal mined and recovered for rechargeable battery manufacturing (Smith et al. 2024; Tong et al. 2025), demonstrated lower selectivity with complete breakthrough prior to 5 BVs. The presence of Li in ARW ROC is likely due to Li soil abundance in western Kansas reaching upwards of 29 mg/kg (80th percentile in the contiguous United States) (Smith et al. 2024) accompanied with effective rejection of Li via RO membrane treatment (Korak et al. 2024). Loading the CIX resin to 15 BVs optimized operational efficiency, mostly eliminating Li chromatographic peaking, while almost completely removing K, Mg and Rb. Overall CIX removal was 98%, 93%, 35%, 98% and 95% of influent Ca, K, Li, Mg and Rb, respectively.

3.3.2. Ion Exchange Regeneration and Selective Capture of Constituents

Regeneration of exhausted CIX resin allows for segmentation of elution peaks, where optimal constituent capture would be to collect between 0 and 3.5 BVs of the regenerant solution, as shown in Figure 8. While the regeneration co-elution of K, Li, Mg and Rb decrease constituent purity, thermodynamic modeling of the 0 to 3.5 BV segment indicates that raising pH to greater than 9 with sodium hydroxide (NaOH) would precipitate brucite ($\text{Mg}(\text{OH})_2$) of 98% purity, as shown in figure S4. Further treatment, such as evaporation, solvent extraction or other processes (Jang et al. 2017; Korak et al. 2024; Lee et al. 2024; Nisan et al. 2009; Tong et al. 2025), would be needed to address the remaining ions to maximize K, Li and Rb purity. From 1 ML of RO feed volume, approximately 52.5 kg, 5.0 kg, 0.026 kg, 142 kg, and 0.001 kg of Ca, K, Li, Mg, and Rb, respectively, could be recovered.

4.0 Conclusion

BCM as an ROC management technique can be implemented in salinity stressed locations, similar to the Upper Arkansas River Corridor and Ag hubs across the United States that account for half of the land mass, for treatment of Ag-impaired waters and similar saline water sources that are P limited. BCM reactors removed up to 88% of concentrated antiscalant as total P over 18 hours, resulting in 41% removal of Ca and 10% removal of sulfate. The precipitation of Ca and sulfate yielded a decrease in modeled ROC gypsum SI of 3.00 from to 2.08, based on high purity gypsum precipitation.

BCM implementation reduces salt importation (i.e., soil amendment addition) through direct mining of gypsum from ROC, while increasing beneficial water reuse by means of membrane separation followed by BCM at RO/NF membrane treatment facilities. Increased gypsum purity may be recovered with pH control ≤ 7 with sulfuric acid and aeration controls. The production of gypsum as a monetizable by-product of BCM presents the opportunity to reuse the salt in the same region that it was initially added as a soil amendment. BCM is one process that can limit salinity accumulation, thereby mitigating fallowing of farmland and aquifer contamination.

Additionally, the abundance of salts in the Upper Arkansas River Corridor provides an opportunity for mineral extraction and recovery; the application of BCM and CIX would significantly decrease the total volume for mineral recovery to ~97% smaller than the original volume being treated. As tested, CIX regeneration elution did not yield a high purity recovery and requires separation at additional costs. However, further treatment/separation via NF could offset salt requirements for CIX regeneration (i.e., evaporative recovery of NaCl and Na₂SO₄) while selectively recovering Li, K, Mg, and Rb to reach economic viability. Future applications of BCM can extract valorized salinity from farmland, taking steps to secure food production, while creating sustainable water source.

The application of BCM and a secondary RO process would reduce the influent volume by 92% required for uranium treatment of ARW, feasibly intercepting this constituent with a best available treatment technology, (e.g., IX) and potentially evaporating all remaining water. Providing alternative methods for ROC management gives flexibility to salinity-impacted communities and Ag hubs, such as California's Central Valley, Central Kentucky's Headwaters, the Chesapeake Bay Watershed, the Great Lakes region, and the Upper Arkansas River Corridor, to apply technologies with appropriate financial and environmental fit. BCM increases water and resource recovery to protect Ag, industrial, and municipal shared water supplies, while minimizing the importation salt loads into salinity-impaired farmland.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Disclaimer

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Supplemental Materials

Figures S1–S4, tables S1–S5, and equations (S1)–(S8) are available online in the ASCE Library (www.ascelibrary.org).

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Table 1.—ROC water quality for ARW at 85% recovery (batch 1, n=1)

Analyte	Units	ROC
Alkalinity, Total as CaCO ₃	mg/L	1,240
Alkalinity, Hydroxide as CaCO ₃	mg/L	ND
Alkalinity, Carbonate as CaCO ₃	mg/	200
Alkalinity, Bicarbonate as CaCO ₃	mg/L	1,040
Ammonia as N	mg NH ₃ -N/L	0.268
Barium	mg/L	0.1396
Calcium	mg/L	1,652
Chemical Oxygen Demand (COD)	mg/L	640
Chloride	mg/L	832
Conductivity	mS/cm	16.84
Fluoride	mg/L	5.44
Magnesium	mg/L	984
Nitrate/Nitrite as N	mg/L as N	6.04
pH	s.u.	8.05
Phosphorus, Total, Hydrolyzable	mg P/L	ND
Phosphorus, Total*	mg P/L	0.690
Potassium	mg/L	62
Silica (SiO ₂)	mg/L	76
Silicon	mg/L	35.6
Sodium	mg/L	2,764
Strontium	mg/L	30.44
Sulfate	mg/L	11,720
Uranium	mg/L	0.400

ND: Non-detectable

*Table S1 ARW total phosphorus was ND indicating that the ROC measured total phosphorus is due to antiscalant dosing.

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Table 2.—Reactor treatment conditions for ARW ROC

Reactor	Replicates	ROC Volume (L)	Filtered Seed Volume (L)	Glycerin Dose (mg/L)	Aerated (Y or N)	Mixed (Y or N)
Control – Type 1	2	3	0	0	N	N
Control – Type 2	1	3	0	0	Y	Y
BCM	3	3	0.1	325	Y	Y

Table 3.—CIX operational parameters for BCM treatment

Process	Flow (BV/hr)	Total Quantity (BV)	Solution
Treatment	25	20	UF filtered BCM effluent
Regeneration	4	11.5	10% NaCl in RO Permeate
Rinse	2	4	RO Permeate

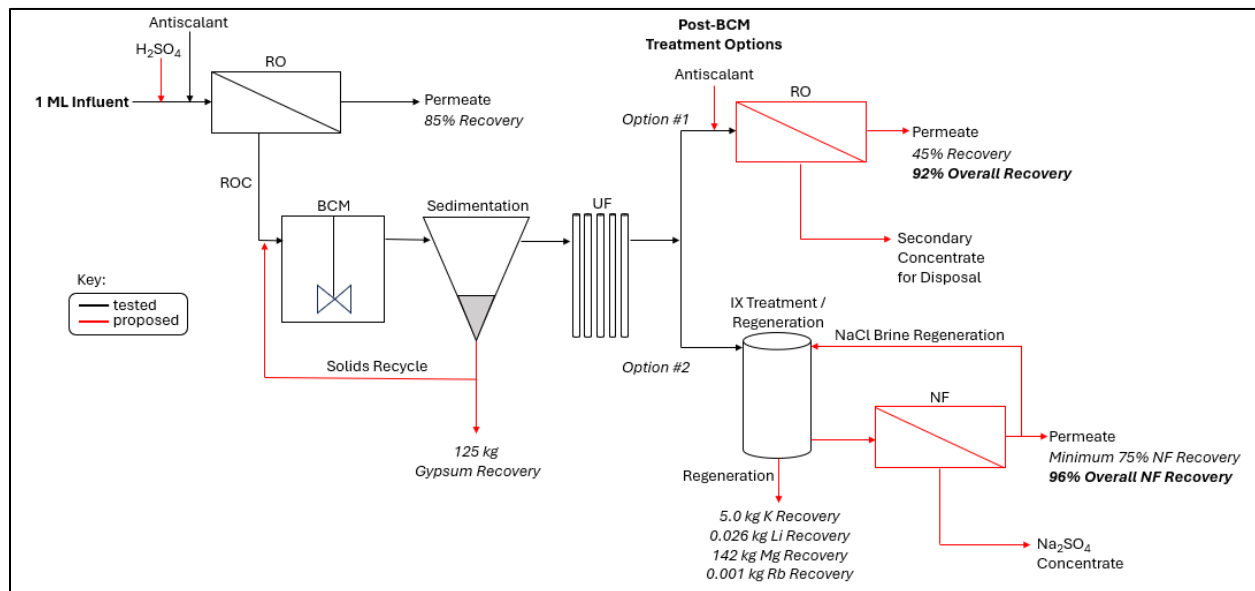


Figure 1.—Proposed treatment train with two options for post-BCM treatment processes. The processes outlined in black represent bench-scale testing performed for this study treating 1 million liters (ML) of ARK Water. The processes outlined in red represent proposed additions for pilot process testing and full-scale implementation.

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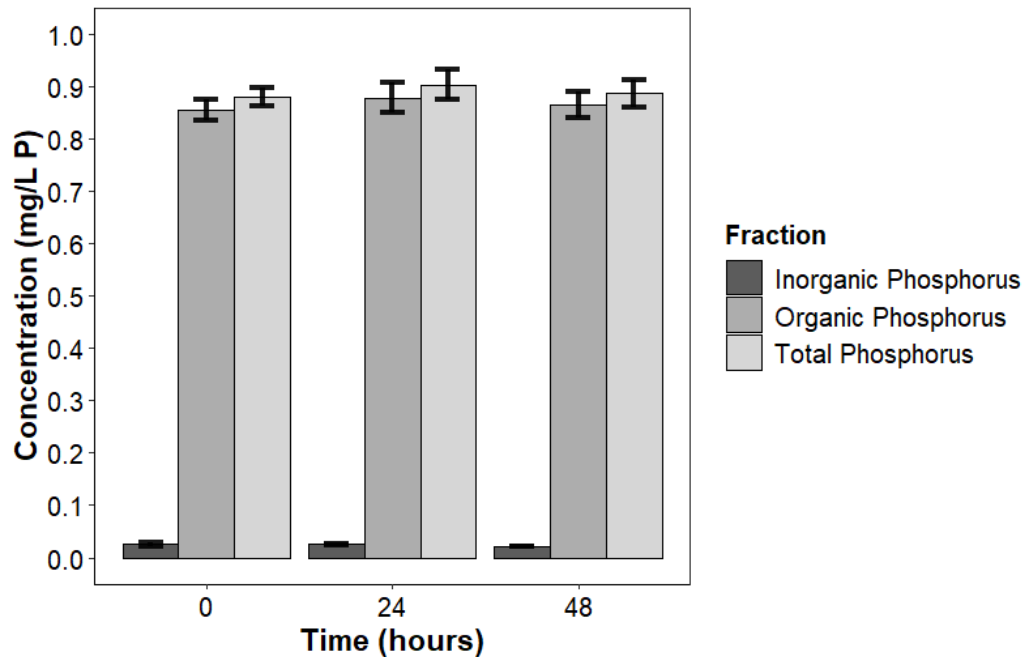


Figure 2.—6.67 mg/L antiscalant dosed in DI water measured at initial (hour 0), 24 hours, and 48 hours as Inorganic P, Organic P, and Total P fractions (n=2) under mixed conditions. Inorganic P fraction at 48 hours was non-detect (method detection level [MDL] <0.0215 mg/L P). Error bars represent minimum and maximum values.

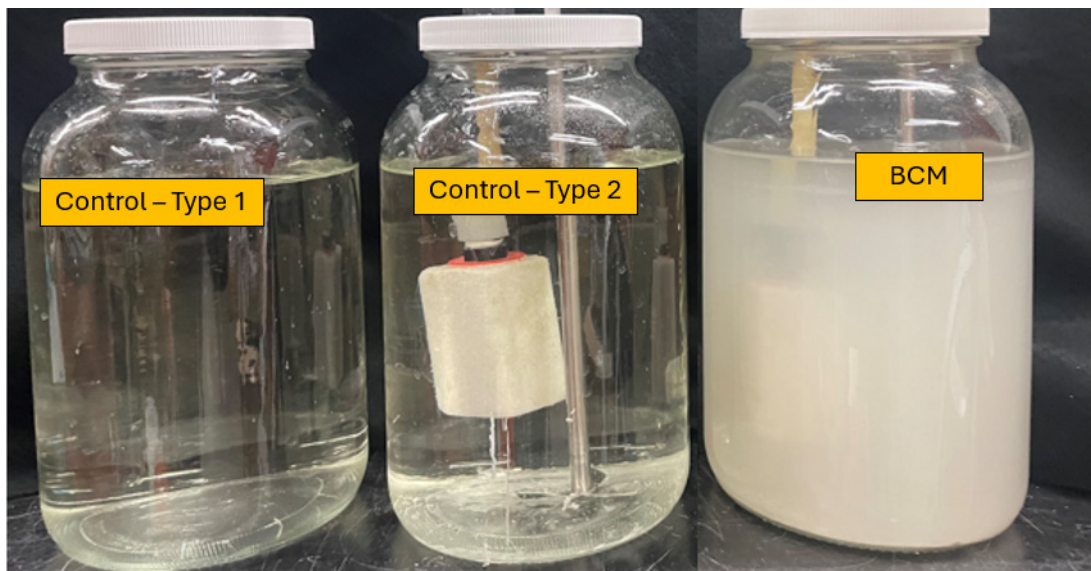


Figure 3.—Control - Type 1 (n=2), Control - Type 2 (n=1), and BCM (n=3) reactors after an 18-hour HRT for batch 1 testing.

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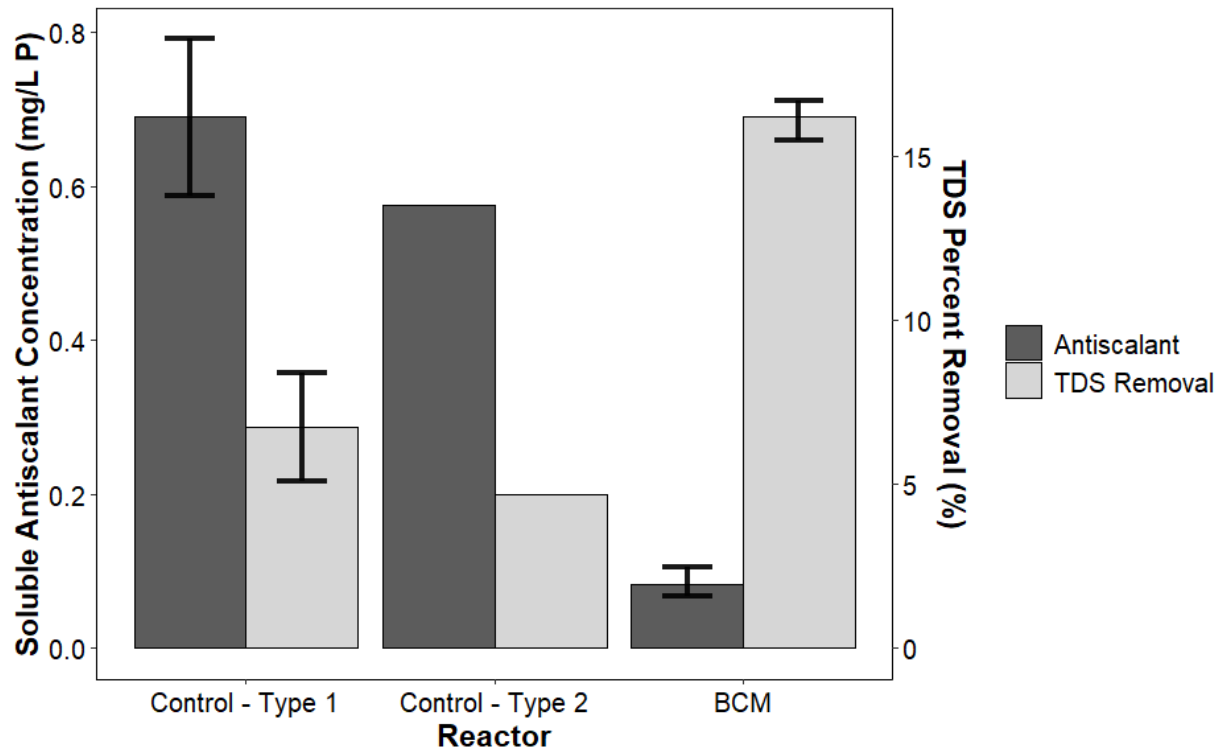


Figure 4.—Antiscalant concentration measured as soluble total P (mg/L) and TDS Removal (%) for Control – Type 1 (n=2), Control – Type 2 (n=1), and BCM (n=3) reactors for batch 1 and 2. Error bars represent minimum and maximum measurements.

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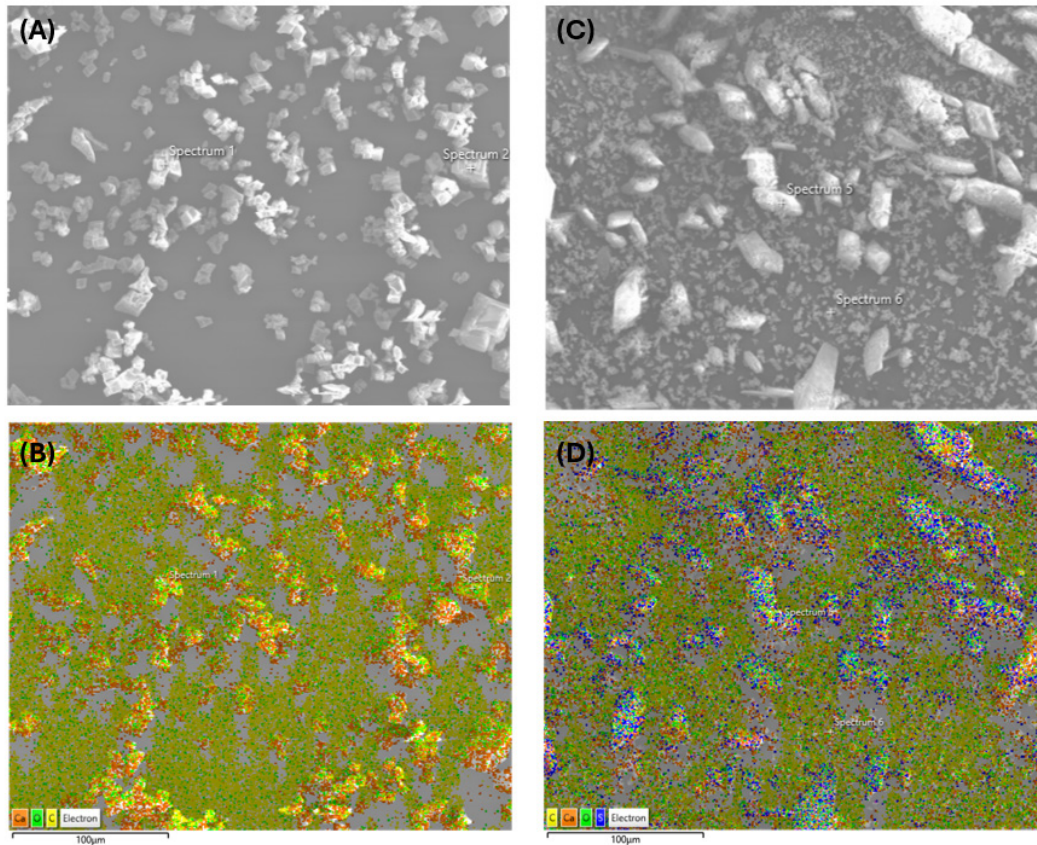


Figure 5.—SEM/EDS image of precipitant: (a and b) Control – Type 2 reactor; and (c and d) BCM batch 1 reactor. Yellow corresponds with detection of C, orange corresponds with detection of Ca, green corresponds with detection of O, and blue corresponds with detection of S.

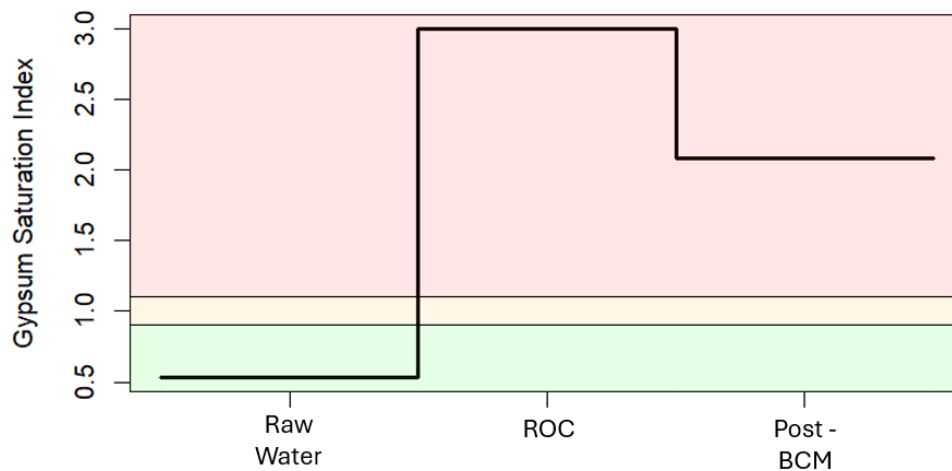


Figure 6.—Gypsum SI changes of ARW as raw water (batch 1, n=1), 85% recovery ROC (batch 1, n=1), and post-treatment with BCM (Post-BCM) (batch 1 and 2, n=3) with the red zone indicating supersaturation, the yellow zone indicating saturation, and the green zone indicating under saturation.

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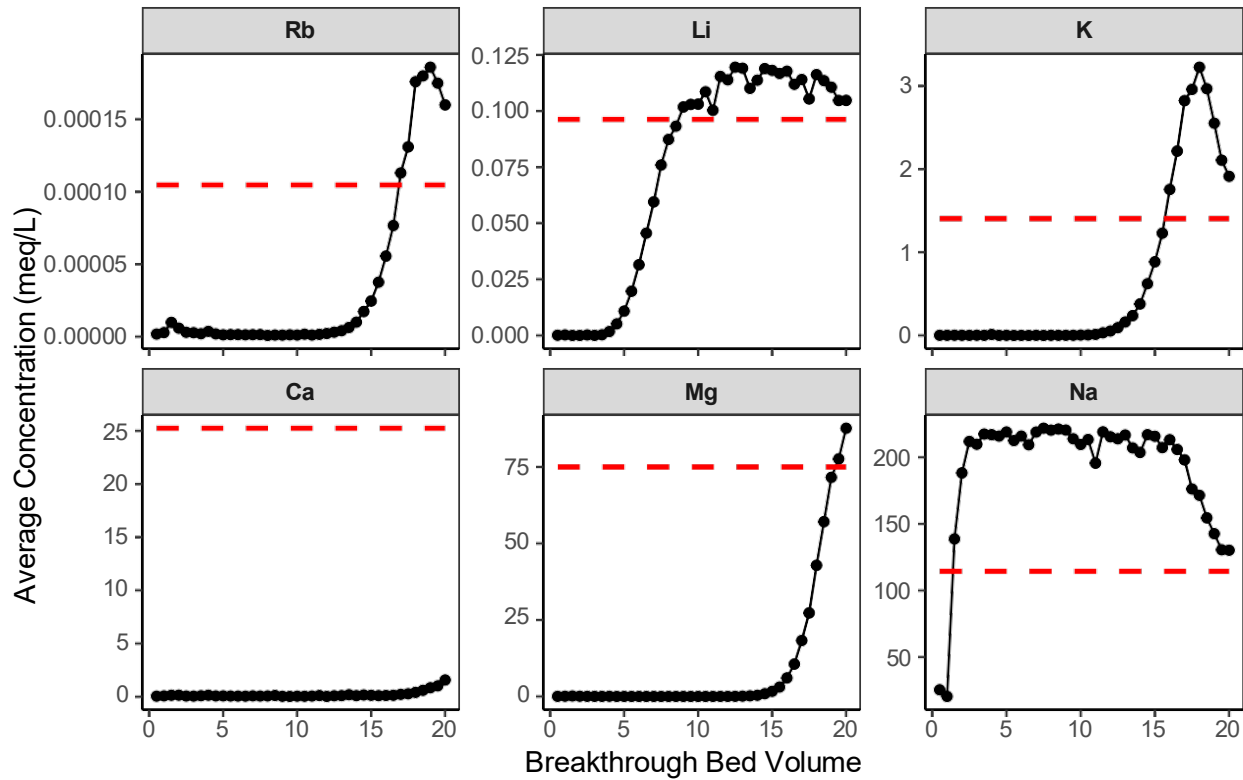


Figure 7.—Breakthrough curves (n=2) for Rb, Li, K, Ca, Mg, Rb, and Na of BCM treated influent water over 20 BVs (composited every 0.5 BV). The red dashed line represents the influent CIX concentration. Effluent concentrations above the red dashed line indicate chromatographic peaking.

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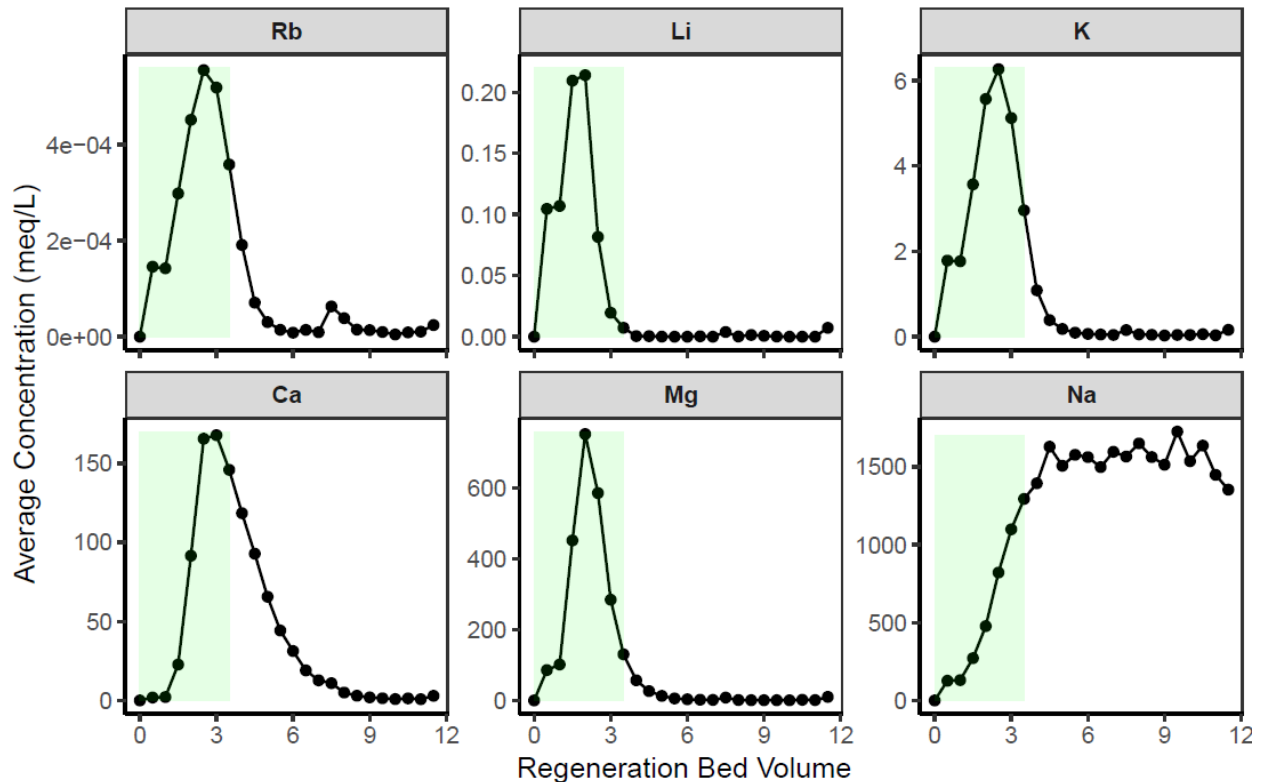


Figure 8.—Regeneration curves (n=2) of Rb, Li, K, Ca, Mg, Rb, and Na of BCM treated influent water over 12 BVs (composited every 0.5 BV). The shaded green box represents BVs 0-3.5 captured for mineral recovery.

SUPPLEMENTAL INFORMATION: Mining Reverse Osmosis Concentrate with
Biological Concentrate Management: Beneficial Water and Mineral Extraction
from a Salinity Impaired Surface Water

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Table S1.—Average ARW concentration and sample size (n) from the Southwest Kansas Groundwater Management District No. 3.

Analyte	Units	n	Average Concentration
Alkalinity, Total as CaCO ₃	mg/L	3	154 ± 50
Alkalinity, Hydroxide as CaCO ₃	mg/L	3	<10 ± 0
Alkalinity, Carbonate as CaCO ₃	mg/L	3	11 ± 1
Alkalinity, Bicarbonate as CaCO ₃	mg/L	3	146 ± 58
Barium	mg/L	2	<0.050 ± 0.000
Boron	mg/L	2	0.629 ± 0.000
Calcium	mg/L	3	249 ± 45
Chloride	mg/L	3	151 ± 5
Conductivity	mS/cm	1	4.03
Fluoride	mg/L	2	0.97 ± 0.00
Iron	mg/L	2	<0.050 ± 0.000
Lithium	mg/L	1	<0.500
Manganese	mg/L	2	<0.020 ± 0.000
Magnesium	mg/L	3	153 ± 11
Nitrate as N	mg/L as N	2	2.46 ± 0.00
pH	s.u.	1	7.60
Phosphorus, Total	mg P/L	2	<0.050 ± 0.000
Potassium	mg/L	3	10.5 ± 0.3
Silica (SiO ₂)	mg/L	3	18.3 ± 1.5
Silicon	mg/L	3	8.53 ± 0.69
Sodium	mg/L	3	476 ± 8
Strontium	mg/L	3	5.03 ± 0.23
Sulfate	mg/L	3	2,167 ± 127
Total Dissolved Solids	mg/L	2	3,470 ± 0
Uranium	mg/L	1	0.060

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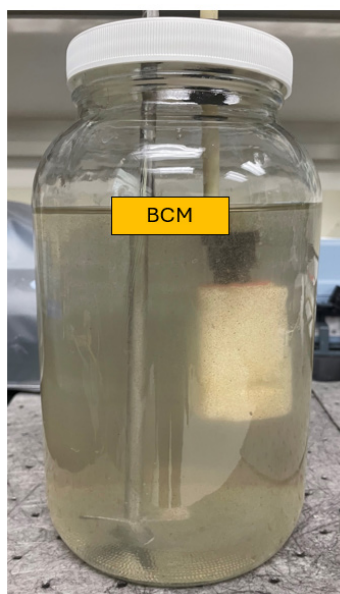


Figure S1.—Batch 1 BCM reactor after combining seed with ARW ROC prior to mixing.

Table S2.—Analytes and methods for water quality measurements by GAL

Analyte	Method
Alkalinity, Total	SM 2320B
Ammonia	EPA 350.1
Barium 200.2 by ICPMS	EPA 200.8
Calcium 200.2 by ICP	EPA 200.7
Chloride by IC	EPA 300.0
COD	EPA 410.4
Fluoride by IC	EPA 300.0
Lithium 200.2 by ICP	EPA 200.7
Magnesium 200.2 by ICP	EPA 200.7
Nitrate/Nitrite as N	EPA 353.2
Phosphorus, Total	EPA 365.1
Phosphorus, Hydrolyzable	EPA 365.1
Phosphorus, Organic	Calculation
Potassium by ICP	EPA 200.7
Silicon 200.2 by ICP	EPA 200.7
Silica 200.2 by ICP	Calculation
Sodium 200.2 by ICP	EPA 200.7
Strontium 200.2 by ICP	EPA 200.1
Sulfate by IC	EPA 300.0
Uranium 200.2 by ICPMS	EPA 200.8

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Table S3.—Average temperature, pH, total alkalinity and conductivity values for the ROC (n=2), Control – Type 1 (n=2), Control – Type 2 (n=1), and BCM (n=3) reactors from batch 1 and 2 over 18 hours.

	ROC				Control - Type 1			
Time	Temperature	pH	Total Alkalinity	Conductivity	Temperature	pH	Total Alkalinity	Conductivity
Hour	Degrees Celsius	s.u.	mg/L CaCO ₃	mS/cm	Degrees Celsius	s.u.	mg/L CaCO ₃	mS/cm
0	22.6 ± 0.4	8.05 ± 0.01	1,240	16.84 ± 0.01	22.6 ± 0.4	8.05 ± 0.01	--	16.84 ± 0.01
1	--	--	--	--	22.1 ± 0.0	8.05 ± 0.04	--	16.77 ± 0.03
18	--	--	--	--	22.0 ± 0.3	8.07 ± 0.00	926 ± 76	16.97 ± 0.14
	Control - Type 2				BCM			
Time	Temperature	pH	Total Alkalinity	Conductivity	Temperature	pH	Total Alkalinity	Conductivity
Hour	Degrees Celsius	s.u.	mg/L CaCO ₃	mS/cm	Degrees Celsius	s.u.	mg/L CaCO ₃	mS/cm
0	22.5	8.03	--	16.88	21.9 ± 0.4	8.07 ± 0.03	--	16.79 ± 0.02
1	21.8	8.39	--	16.76	21.7 ± 0.0	8.31 ± 0.11	--	16.67 ± 0.03
18	21.9	8.69	558	16.52	21.3 ± 0.5	8.23 ± 0.13	304 ± 16	16.09 ± 0.26

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Table S4.—Water quality after tested and proposed treatment stages with EPA MCL standards as a comparison. IX treated effluent concentrations represent average concentration prior to breakthrough at 15 BVs

Analyte	Units	First Stage RO Permeate	BCM Treated Effluent (Filtered)	Second Stage RO Permeate*	Second Stage RO Concentrate*	IX Treated Effluent	NF Permeate**	NF Concentrate**	EPA MCL
		n=1	n=3	modeled data	modeled data	n=2	modeled data	modeled data	
Alkalinity, total as CaCO ₃	mg/L	ND	304	1.057	553	304*	168	713	--
Alkalinity, hydroxide as CaCO ₃	mg/L	ND	ND	0.0	0	ND*	0	0	--
Alkalinity, carbonate as CaCO ₃	mg/L	ND	50	0.0	91	50*	4.59	44.1	--
Alkalinity, bicarbonate as CaCO ₃	mg/L	ND	254	1.057	462	254*	163	669	--
Ammonia as N	mg NH ₃ -N/L	ND	ND	--	--	--	--	--	--
Barium	mg/L	ND	0.052	0.0	0.095	--	--	--	2
Calcium	mg/L	0.852	980	0.028	1,782	1.69	0.016	6.7	--
Chloride	mg/L	9.89	814	2.578	1,480	814*	719	1,100	--
Chemical oxygen demand (COD)	mg/L	13	1,099	--	--	--	--	--	--
Fluoride	mg/L	0.032	3.00	0.008	5.45	3.00*	3.56	2.81	4
Lithium	mg/L	ND	0.67	0.001	1.21	0.434	0.049	1.59	--
Magnesium	mg/L	0.52	933	0.023	1,695	1.63	0.01	6.49	--
Nitrate/nitrite as N	mg/L as N	0.464	6.98	0.078	12.7	6.98*	6.98	6.98	10, 1**
Phosphorus, total, hydrolyzable	mg P/L	--	ND	--	--	--	--	--	--
Phosphorus, total	mg P/L	ND	0.083	0.0	0.151	0.083*	0.010	0.078	--
Potassium	mg/L	0.231	57.7	0.045	105	3.28	0.324	12.1	--
Rubidium	mg/L	--	0.01	--	--	0.0003	--	--	--
Silica (SiO ₂)	mg/L	0.323	73.1	0.395	133	73.1*	57.9	119	--
Silicon	mg/L	0.151	34.2	0.185	62.1	34.2*	27.1	55.6	--
Sodium	mg/L	12	2,667	2.249	4,848	4,556	594	21,152	--
Strontium	mg/L	ND	22.2	0.001	40.4	--	--	--	--
Sulfate	mg/L	31.6	10,567	0.169	19,212	10,567*	75	42,043	--
Uranium	mg/L	0.0001	0.444	0.0007	0.807	0.444*	0.004	1.76	0.03

*Assumed conserved through the IX column

*Modeled at 45% recovery

**Nitrate = 10 mg/L, Nitrite = 1 mg/L

**Modeled at 75% recovery

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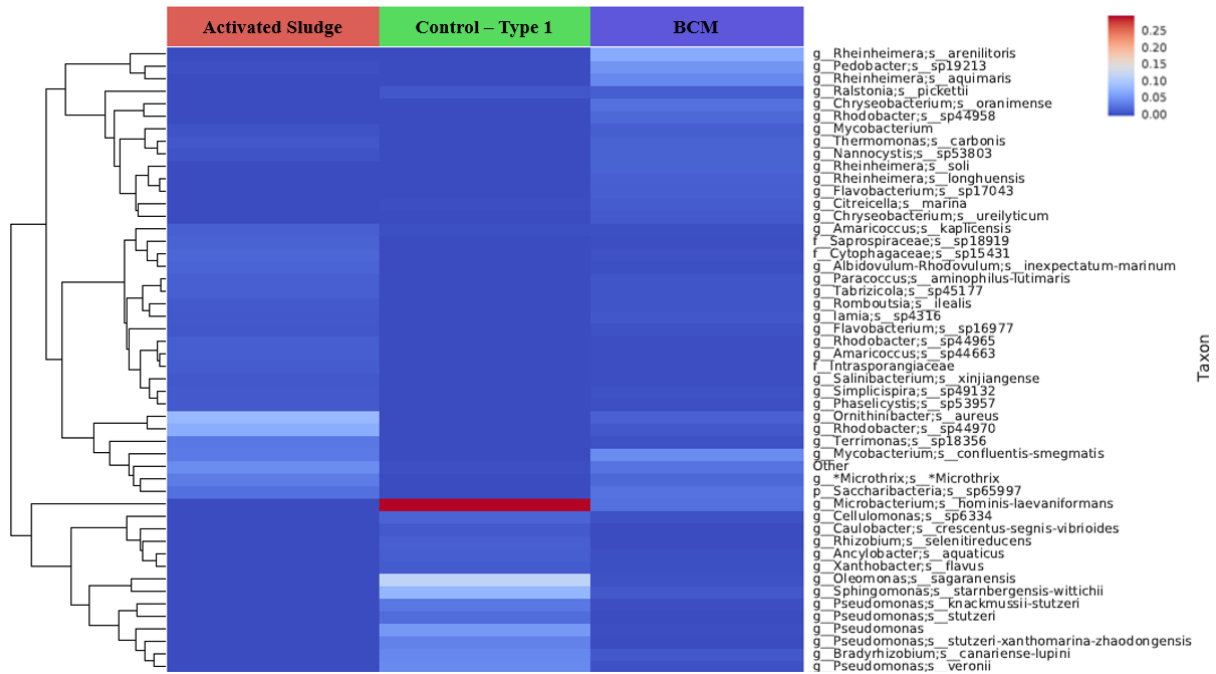


Figure S2.—Heatmap of the microbial composition of the Activated Sludge (upon sampling), Control – Type 1 (post 18 hours), and batch 1 BCM (post 18 hours) at the species level with the top fifty most abundant species identified as relative abundance. Hierarchical clustering was completed using Bray-Curtis dissimilarity with similar distributions grouped together.

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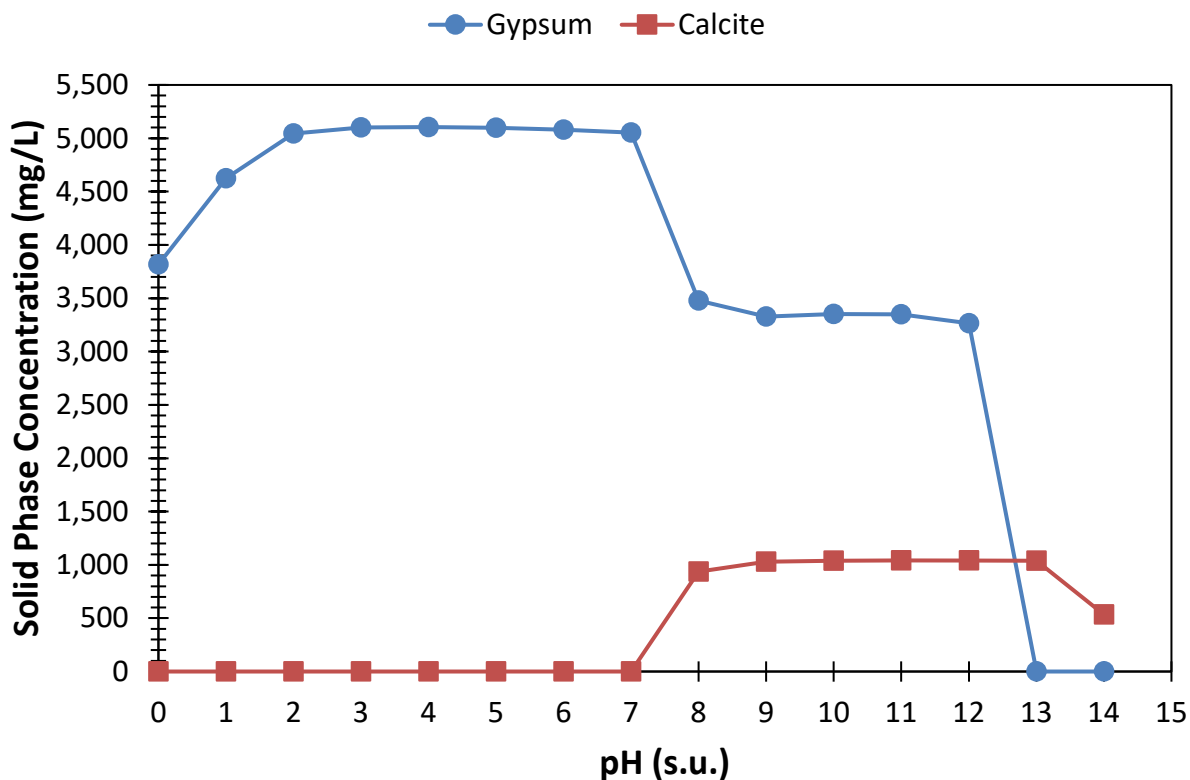


Figure S3.—Thermodynamic modeling (OLI Studio) of the solid phase concentration of gypsum ($\text{CaSO}_4 \cdot \text{H}_2\text{O}$) and calcite (CaCO_3) over increasing pH values with sulfuric acid (H_2SO_4) as the pH titrant acid and sodium hydroxide (NaOH) as the pH titrant base.

Table S5.—Preliminary PFAS concentrations for PFHxS, PFOS, and PFOA at 80% recovery of ARW

Analyte	Units	Raw Water	Permeate	ROC
Perfluorohexanesulfonic acid (PFHxS)	ug/L	<0.00430	<0.00450	<0.00430
Perfluorooctanesulfonic acid (PFOS)	ug/L	<0.00430	<0.00450	<0.00430
Perfluorooctanoic acid (PFOA)	ug/L	<0.00170	<0.00180	0.00300

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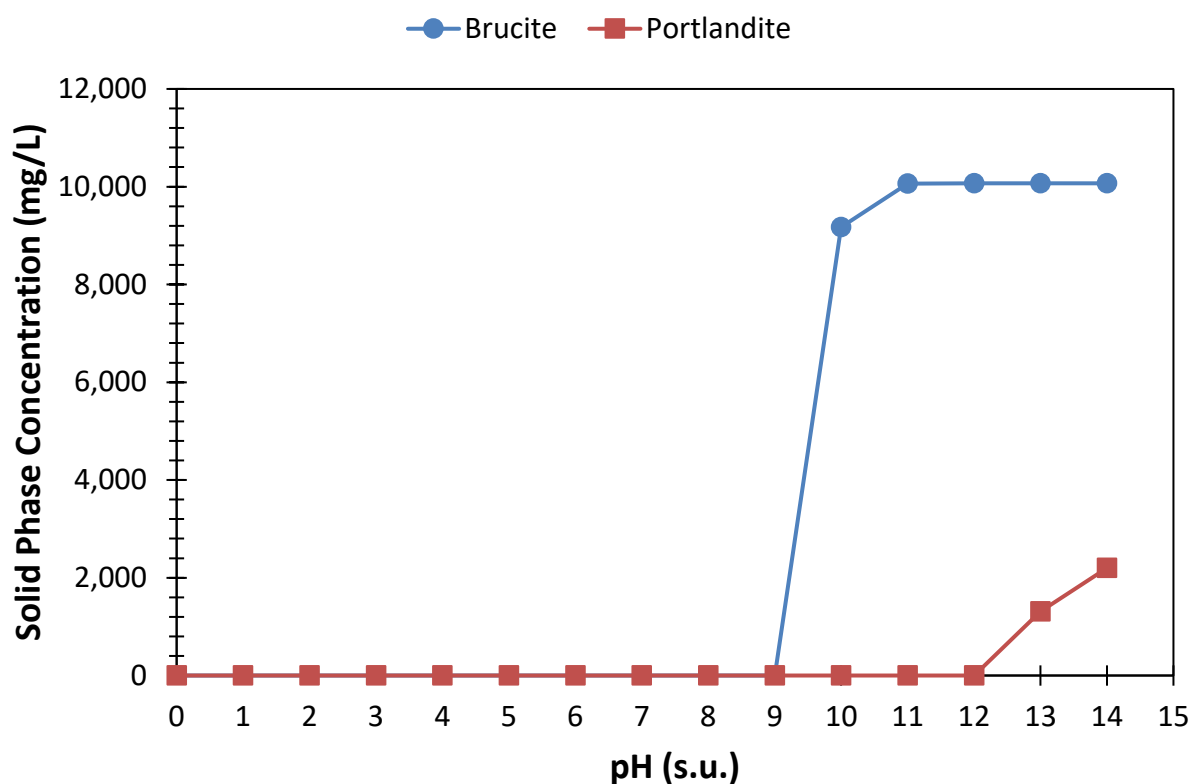


Figure S4.—Thermodynamic modeling (OLI Studio) of the solid phase concentration of brucite ($\text{Mg}(\text{OH})_2$) and portlandite ($\text{Ca}(\text{OH})_2$) over increasing pH values with hydrochloric acid (HCl) as the pH titrant acid and NaOH as the pH titrant base.