Resilient biological hexavalent chromium removal with a two-stage, fixed-bed biotreatment system

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Abstract
Hexavalent chromium (Cr(VI)) can be biologically reduced to nontoxic and easily separable trivalent chromium (Cr(III)) without generating concentrated wastes. Using a 6–25 gpm pilot-scale two-stage, fixed-bed (FXB), biologically active carbon (BAC) treatment system, approximately 75 μg/L Cr(VI) was consistently removed to less than 7 μg/L with a 10-min empty-bed contact time. Potential Cr(VI)-reducing bacteria, including members from the Dechloromonas and Acinetobacter genera, were present in the system. The system was resilient, and 91% Cr removal was observed when the system was challenged with a 24-h phosphoric acid feed shutdown, a 3-day system shutdown, spiking Cr(VI) to 100 μg/L, or operating intermittently with regular shutdown periods of hours to days. The system recovered within 6 h after a 26-h acetic acid feed shutdown. Readily settling backwash wastewater was generated with characteristics similar to municipal wastewater. Overall, the results indicated that a two-stage, FXB BAC system can provide an effective and robust option for Cr(VI) removal.

KEYWORDS
backwash, backwash wastewater, biological, bioreactor, fixed-bed, hexavalent chromium, microbial community, robustness

1 | BACKGROUND

Inadequate access to clean drinking water is a globally pervasive problem. Amidst rapid population growth, urbanization, and climate change, water demand exceeds available freshwater resources in many locations, including California, Texas, and Oklahoma, which have recently experienced severe droughts. To address the water scarcity issue, a diverse water supply portfolio is required that considers leveraging all potential water sources. Groundwater has been recognized and utilized as a major drinking water source throughout the world. However, the presence of contaminants, such as nitrate, perchlorate, toxic trace elements (e.g., chromium [Cr], selenium [Se], uranium [U], and arsenic [As]), and volatile organic compounds (VOCs), often limits the use of groundwater for drinking water production unless adequately treated. Among the different classes of drinking water contaminants, toxic trace elements, particularly Cr, pose substantial operational challenges for drinking water treatment systems due to its wide occurrence and redox-sensitive mobilization characteristics.

Cr is one of the elements ubiquitously found in the earth’s crust. It is widely used in anthropogenic activities, including leather tanning, electroplating, wood preservation, and paint production. In general, improper waste disposal during and/or after chromite ore processing (Matern,
Trivalent chromium (Cr(III)) and hexavalent chromium (Cr(VI)) are the two stable chromium species present in natural aquatic environments (Bartlett, 1991). In water, Cr(III) exists as a cation, complexing with inorganic and organic ligands, and under circumneutral pH, Cr(III) can precipitate as Cr(III) hydroxides due to its low solubility. In contrast, Cr(VI) exists as either HCrO$_4^-$, CrO$_4^{2-}$, or Cr$_2$O$_7^{2-}$ anion depending on pH. Cr(VI) is very mobile and can be easily transported across cell membranes due to its structural similarities to sulfate and phosphate (Sugden & Stearns, 2000), whereas Cr(III) does not easily diffuse across cell membranes (Ramírez-Díaz et al., 2008).

Cr(III) is an essential micronutrient and is considered benign at concentrations found in natural water sources (Anderson, 1995; National Toxicology Program, 2008). In contrast, contradictory conclusions have been reported regarding the human health effects of Cr(VI) exposure through drinking water (Brandhuber et al., 2005) even though it has been identified as a carcinogen when inhaled (International Agency for Research on Cancer, 1990). Cr(VI) can be reduced to Cr(III) by thiol groups (e.g., glutathione and cysteine), reduced nicotinamide adenine dinucleotide phosphate and reduced nicotinamide adenine dinucleotide, and antioxidants (e.g., ascorbate). However, this may result in unstable products, such as pentavalent or tetravalent chromium, thiol radicals, or reactive ‘OH and ‘H$_2$O radicals (Liu & Shi, 2001; Shi & Dalal, 1989). The formation of these unstable and/or reactive byproducts has been linked to DNA damage and mutagenesis (Sugden & Stearns, 2000).

Under the National Primary Drinking Water Regulations, the U.S. Environmental Protection Agency (USEPA) regulates total Cr (i.e., Cr(III) and Cr(VI) combined) with a maximum contaminant level (MCL) of 100 μg/L. While a federal regulation does not exist for Cr(VI) in drinking water, the California Department of Public Health implemented an MCL of 10 μg/L. Cr(VI) on July 1, 2014, which was later removed on September 11, 2017, in response to a judgment issued by the Superior Court of Sacramento County, California. Currently, the USEPA is reviewing additional information on Cr(VI) toxicity, and utilities and public health officials are proactively investigating the feasibility of limiting Cr(VI) concentrations in drinking water to below the previously implemented MCL in California (i.e., 10 μg/L).

Cr(VI) can be removed from water either directly by using physicochemical treatment processes, such as adsorption, anion exchange, membrane filtration, and electrocoagulation or indirectly by chemically reducing Cr(VI) to Cr(III), which precipitates as Cr(III) solids. Weak base anion exchange, strong base anion exchange, and reduction/coagulation/filtration are some of the physicochemical processes that are known to effectively and consistently remove Cr(VI) to less than 5 μg/L with minimal water loss (Blute et al., 2014; McGuire, Blute, Seidel, Qin, & Fong, 2006). While effective, these physicochemical processes can be cost-prohibitive due to one or more of the following requirements: (1) additional treatment steps (e.g., pH adjustments), (2) disposal of resulting concentrated wastes, (3) large amount of chemicals, and (4) high energy. Biological treatment may provide an effective approach for Cr(VI) treatment that addresses some of these limitations.

Biological processes rely on enhanced growth and activity of microorganisms naturally occurring in the source water for contaminant removal. Multiple contaminants such as nitrate, perchlorate, As, U, and VOCs can be removed in a single unit process (Li et al., 2010; Upadhyaya et al., 2010), while achieving water recovery greater than 95% and minimizing energy and chemical costs. Often, the end products of biological treatment processes are innocuous, less toxic, or more easily separable than the parent compound. For example, nitrate and perchlorate are converted to N$_2$ gas and Cl$^-$, respectively, which are innocuous end products. Similarly, biological reduction of Cr(VI) and Se(VI) leads to the formation of less toxic and easily separable Cr(III) and Se$^0$ solids.

Despite the extensive literature on the biological reduction of Cr(VI) to Cr(III) (Dong et al., 2013; Lai et al., 2016), there is limited literature on biological Cr(VI) removal from groundwater sources using contact times typically practiced at a water treatment facility. Previous studies were conducted with high Cr(VI) concentrations (i.e., in mg/L) (Lai et al., 2016) or with a long contact time (Mamais et al., 2016; Panousi et al., 2017). Furthermore, previous studies failed to evaluate the resiliency of the treatment process or characterize the residuals of the treatment process.

Although the biological reduction of Cr(VI) is thought to primarily result in Cr(III) hydroxides with low solubility, the presence of organic and inorganic Cr(III)-chelating ligands in groundwater can result in soluble Cr(III) complexes at circumneutral pH (Dong et al., 2013; Puzon, Roberts, Kramer, & Xun, 2005), which differ in mobility and recalcitrance depending on the ligand (Cao, Guo, Mao, & Lan, 2011; Puzon et al., 2008). Furthermore, chlorine (Chebeir & Liu, 2016; Lindsay, Farley, & Carbonaro, 2012) and, to a lesser extent, hydrogen peroxide (H$_2$O$_2$) (Luo & Chatterjee, 2010; Ye et al., 2017) may oxidize Cr(III) from both organic and inorganic complexes. Given the potential formation of Cr(III)–organic complexes and their reoxidation during downstream disinfection to potentially hazardous Cr(VI), the possibility of total chromium removal needs to be carefully assessed, along with...
contaminant removal, degradation kinetics, and process limitations when evaluating a biological treatment system.

A 10-month pilot study was conducted to (1) verify the effectiveness of a two-stage, fixed-bed (FXB) biotreatment system for Cr(VI) removal from groundwater, (2) assess system resiliency under challenged conditions, and (3) assess the residual characteristics. The results suggested that Cr(VI) can be effectively and consistently lowered from 75 to 100 μg/L to less than 7 μg/L with an empty-bed contact time (EBCT) as low as 10 min. The backwash wastewater (BWWW) had characteristics similar to municipal wastewater. Overall, the results showed that two-stage, FXB biotreatment can provide effective and robust Cr(VI) removal.

2 | MATERIALS AND METHODS

2.1 | Pilot skid

The pilot skid consisted of three 2-ft-diameter columns in series (Figure 1). Biological growth and contaminant removal typically occur in the first column (i.e., bioreactor), whereas the third column (i.e., biofilter) further polishes the effluent of the bioreactor, removing any residual electron donor (i.e., acetic acid [ACA]) or contaminants (e.g., nitrate) and turbidity. The biofilter also helps achieve the dissolved oxygen (DO) treatment goal when the bioreactor effluent (BR Eff) is supplemented with H₂O₂. The middle column, which can be utilized for degasification or aeration, was not used during this pilot study.

The bioreactor was packed with coconut shell-based granular activated carbon (GAC) (Cabot, Alpharetta, GA; effective size 1.0–1.2 mm; uniformity coefficient \( U_c \) ≤ 1.5) to achieve a bed depth of 54 in., whereas the biofilter contained 36-in. GAC (1.0–1.2 mm, \( U_c \) ≤ 1.5) over 18-in. sand (effective size 0.45–0.55 mm, \( U_c \) ≤ 1.5). The well water (raw water) was amended with an electron donor (i.e., ACA) and phosphoric acid (PHA) to enhance microbial growth in the system and fed to the bioreactor from the top. The BR Eff was supplemented with H₂O₂ and aluminum chlorohydrate (ACH) before feeding the biofilter from the top to maintain DO greater than 3 mg/L and turbidity less than 0.3 ntu in the biofilter effluent (BF Eff). The BF Eff was collected in a backwash tank and was used for backwashing the columns without any oxidant addition. The system was operated in a single-pass mode (i.e., without recirculation) throughout the study.

The pilot skid consisted of a human–machine interface, which facilitated on-site or remote pilot operation and monitoring. The skid was equipped with in-line monitoring and data logging for flow rate, head loss, DO, nitrate, and turbidity. It also included chemical feed systems for ACA, PHA, ACH, and H₂O₂. Provisions were also included for backwashing the bioreactor and biofilter based on either head loss accrual or runtime. In general, runtime dictated the backwash, and the bioreactor and biofilter were backwashed every 20–24 and 48 h, respectively, using the treated water without any oxidant addition.

2.2 | Performance monitoring

In-line analyzers were used to monitor flow, head loss across the bioreactor and biofilter beds, runtime, DO, nitrate + nitrite, and turbidity. A DO luminescent dissolved oxygen model (Hach, Loveland, CO) was used to determine DO levels with a method detection limit (MDL) of 0.02 mg/L. Hach’s Nitratex sc sensor was used for in-line nitrate + nitrite measurement with a 0.1 mg/L N MDL. Hach’s Ultraturb (Hach) was used for real-time turbidity monitoring. Besides the in-line analysis, raw water, BR Eff, and BF Eff grab samples were regularly collected for dissolved organic carbon (DOC) (method reporting limit [MRL] 0.3 mg/L), total Cr (MRL 1 μg/L), Cr(VI) (MRL 0.02 μg/L), total As (MRL 1 μg/L), sulfate (MRL 0.5 mg/L), and orthophosphate (MRL 0.01 mg/L P). USEPA methods 200.8 and 218.6 were used to determine total Cr and Cr(VI) in the grab samples. USEPA methods 365.1 and SM 5310C were used to determine phosphorus and DOC, respectively. To enhance the resolution of Cr(VI) monitoring through in-line measurement, a MetalGuard™ (Aqua Metrology Systems, Sunnyvale, CA) was connected to the system on day 117, and data collection started on day 137.

2.3 | Biological acclimation

Pilot testing started with a 20-min EBCT. Raw water (Table 1), containing 0.7 ± 0.3 (average ± standard deviation) mg/L nitrate-N and 75.1 ± 1.0 μg/L Cr(VI) (73.7 ± 2.7 μg/L total Cr), was fed to the bioreactor in a downflow mode after supplementing ACA and PHA. During the study, the raw water pH and temperature ranged from 7.6 to 8.4 standard units.

FIGURE 1 Process flow diagram for the pilot-scale system. The second column was bypassed during this study. BR Eff, bioreactor effluent; BF Eff, biofilter effluent; H₂O₂, hydrogen peroxide.
(SUs) and 10.1 to 26.9 (18.7 ± 3.7) °C, respectively. The ACA dose was determined based on a yield of 0.4 mg biomass chemical oxygen demand (COD)/mg ACA COD, and the phosphorus dose was selected based on a carbon (C) to phosphorus (P) molar ratio of 100:1. H₂O₂ and ACH were injected into the BR Eff to reoxygenate the water and achieve turbidity removal in the biofilter, respectively, before feeding the water into the biofilter in a downflow mode.

### 2.4 | Process optimization

Once near-complete biological acclimation was achieved, determined based on consistent Cr(VI) removal to below the target level, process optimization was undertaken from days 108 to 208. Process optimization included determining the lowest EBCT and chemical feed doses that would allow removing total Cr to less than 7 μg/L. The backwash protocol was modified, focusing on hydraulic performance over a runtime while maintaining less than 7 μg/L in the bioreactor and biofilter effluents.

2.5 | Sustained contaminant removal

With the optimized operating conditions (Table 2), sustained contaminant removal was demonstrated for over a month (i.e., from days 210 to 245). During this period, BWWW and microbial communities present in the bioreactor and biofilter were characterized. In addition, disinfection requirements and disinfection byproduct formation potential (DBPFP) were also assessed as described below.

### 2.5.1 | BWWW characterization

Composite BWWW samples were collected on days 220 and 226 during a bioreactor or biofilter backwash to determine general water quality and settling characteristics of the wastewater. The BWWW composite sample was collected in a 40-gal container by splitting the 10-min fluidization period (30 gpm) into alternating segments of 10-s "collection periods" and 70-s "wasting periods." After collection, the wastewater was thoroughly mixed with a
1-in. polyvinyl chloride pipe. Total suspended solids, COD, Cr(VI), metals, and gross alpha were measured in the composite samples. Samples were also collected for toxicity characteristic leaching procedure (TCLP), soluble threshold limit concentration (STLC), and total threshold limit concentration (TTLC) analyses.

Settling characteristics were determined through jar testing with BWW WW from the bioreactor, biofilter, or a blend at 2:1 (v/v) using a six-paddle jar tester (Phipps & Bird, Richmond, VA). ACH doses ranging from 0 to 100 mg/L were used, and BWW WW settling characteristics were determined by measuring turbidity 2, 4, 8, and 16 min after adding the ACH.

### 2.5.2 Microbial community characterization

Media samples were collected on day 232 from the bioreactor and biofilter and shipped overnight on ice to the University of Texas at Austin. DNA was extracted, polymerase chain reaction amplification was performed, and multiplex 16S amplicon sequencing was performed on MiSeq (Illumina, San Diego, CA) after constructing a dual-index library (Kozich, Westcott, Baxter, Highlander, & Schloss, 2013). All MiSeq data were analyzed in quantitative insights into microbial ecology (Caporaso et al., 2010). After filtering the sequence reads to remove low-quality sequences and chimeras, the sequences were clustered into operational taxonomic units at 97% sequence identity (Edgar, 2010; Edgar, Haas, Clemente, Quince, & Knight, 2011). Taxonomy was assigned to each representative sequence to determine the phylogenetic affiliation of the bacteria present in the system by using the Ribosomal Database Project classifier (Wang, Garrity, Tiedje, & Cole, 2007) against the Greengenes reference database (McDonald et al., 2012).

### 2.6 Robustness testing

After sustained contaminant removal was demonstrated, the effects of operational challenges, including backwash events, chemical feed failure, system shutdown, Cr spiking, and intermittent operation, were assessed starting on day 215 to determine the robustness of the system.

#### 2.6.1 Effects of backwashing

Chromium removal was closely monitored immediately before and after a bioreactor or biofilter backwash during days 215–225 to evaluate the effects of periodic biomass removal during a backwash on system performance.

#### 2.6.2 ACA or PHA feed failure simulation

ACA or PHA feed was turned off for approximately 24 h on days 238 and 241, respectively, to determine the effects of potential full-scale chemical feed failure and system response upon resuming the feed. To capture the Cr trend immediately after resuming the feed, samples were collected after approximately 30 min, 1 h, 6 h, and 24 h.

#### 2.6.3 System shutdown simulation

The pilot system, including the chemical feeds, was completely shut down for a 3-day period starting on day 243 and the well water was diverted to the forebay. The water in the bioreactor and biofilter remained stagnant during the shutdown, and neither the bioreactor nor the biofilter was backwashed before the shutdown or after resuming the pilot operation. Cr(VI) and total Cr were closely monitored after restarting the system. To capture the Cr trend immediately after resuming the feed, samples were collected after approximately 30 min, 1 h, 6 h, and 24 h.

#### 2.6.4 Cr(VI) spiking

To assess the system response to an abrupt increase in raw water Cr(VI), a solution of potassium dichromate (Fisher Scientific, Hampton, NH) was injected into the influent line for approximately 4 days starting on day 247. A final influent concentration of approximately $100 \mu g/L$ was targeted. Cr(VI) and total Cr grab samples were collected from the BR Eff and BF Eff, and from the sampling port immediately above the bioreactor bed on day 249.

#### 2.6.5 Intermittent operation

The effectiveness of the system for a rural application with limited operator attention was evaluated by running the system under the following intermittent operating conditions from day 250 to day 301: (1) 7 days off followed by 7 days on (evaluated for approximately 4 weeks), (2) 68 h off followed by 100 h on (2 weeks), and (3) 60 min on followed by 60 min off for the first 12 h and off for the next 12 h (2 weeks). The columns were not drained during the shutdown, and the bioreactor or biofilter was not backwashed before the shutdown or after resuming the pilot operation.

### 3 RESULTS AND DISCUSSION

#### 3.1 Nitrate removal

Biological acclimation for nitrate removal was observed within 3 days, lowering the raw water nitrate (0.7 ± 0.3 mg/L N) to less than 0.1 mg/L N (Figure 2a). The raw
water, BR Eff, and BF Eff pH remained 8 ± 0.3, 7.9 ± 0.4, and 7.8 ± 0.3 SUs, respectively, during the study. The rapid acclimation is in agreement with previous studies, in which biological acclimation for nitrate removal occurred within 10 days with raw water nitrate concentrations more than 12 mg/L N (Li et al., 2010; Upadhyaya et al., 2010). As DO is the most preferred electron acceptor and was significantly higher in the raw water (5.3 ± 1.9 mg/L) than nitrate, complete DO reduction likely occurred before nitrate reduction, resulting in DO levels below the detection limit (i.e., <0.02 mg/L) in the BR Eff (Figure S2). The injection of 12–14 mg/L H2O2 allowed maintaining >3 mg/L DO in the BF Eff most of the time, except when the chemical feed was interrupted or the ACA was fed in excess.

3.2 | Chromium removal

MDL was not determined for the in-line analyzer in this study, but in general, Cr(VI) lab results matched the in-line Cr(VI) results (Figure S1). While Cr(VI) removal occurred through adsorption onto the GAC in the bioreactor and biofilter in the beginning, both BR Eff and BF Eff Cr(VI) and total Cr concentrations matched the influent concentrations within 12 days (Figure 2b). With the gradual establishment of Cr(VI)-reducing biological activity in the bioreactor, the BR Eff Cr(VI) started to decline after day 30. Cr(VI) removal through adsorption onto the GAC was confirmed once again when the top 6 in. of GAC in the bioreactor was replenished on day 54 after an accidental media loss while backwashing the bioreactor. While the system ran with the lower bioreactor bed depth for approximately 48 h before the media loss was realized, there were no apparent negative effects on system performance, and biological acclimation was uninterrupted after the exhaustion of the adsorption capacity of the newly added media.

With the gradual increase in biological Cr(VI)-removing activity, the BR Eff Cr(VI) gradually declined, and concentrations below the treatment target (i.e., 7 μg/L Cr(VI)) were observed once the system was acclimated around day 120. Although the bioreactor was not designed for filtration, Cr(III) species generated in the bioreactor were partially removed in the biofilter, resulting in 35–40 μg/L total Cr in the BR Eff. However, the biofilter, which was designed for particle and turbidity removal, further polished the BR Eff and retained the Cr(III) species present in the BR Eff (Figure 2b). This resulted in less than 7 μg/L Cr(VI) and total Cr in the BF Eff. The retention of the Cr(III) species in the bioreactor and biofilter was further confirmed while characterizing the bioreactor and biofilter BWWW (Section 3.7).

3.3 | Headloss accrual and backwashing protocol

With the overall treatment goal of maintaining less than 7 μg/L Cr in the BF Eff without any hydraulic issues during a bioreactor or biofilter run, the backwashing protocol was optimized during the biological acclimation period. Achieving a 35%–40% bed expansion and maintaining consistent clean-bed and terminal headloss were targeted. The tested air scour rates and duration ranged from 4 to 7 scfm and 5 to 7 min, respectively. Fluidization flow rates ranged from 25 to 35 gpm and was practiced for 8–12 min. The backwashing protocol listed in Table 2 allowed achieving the Cr removal treatment goal without any hydraulic issues.

After a backwash, headloss across the bioreactor or biofilter media bed gradually increased, reaching the highest...
level (Figure S3), likely due to the biomass growth and accumulation of solids. While terminal headloss remained considerably higher in the biofilter than in the bioreactor, the headloss accrual rate was typically faster in the bioreactor. This was not surprising as the DO and nitrate reduction occurred in the bioreactor. The higher terminal headloss observed in the biofilter likely resulted from the longer runtime (i.e., ~48 h) than that of the bioreactor (i.e., 20–24 h).

3.4 | Process optimization

Process optimization included determining effective backwashing protocol and the lowest EBCT and chemical feed doses. Backwash optimization considered both consistent hydraulic performance and Cr removal to less than 7 μg/L. The ACA optimization focused on achieving the treatment goal while maintaining minimal DOC in the effluent. Similarly, H$_2$O$_2$ and ACH dose optimization was undertaken by monitoring the BF Eff DO and turbidity levels, respectively.

While the system was started with an EBCT of 20 min (Figure 3a), lower EBCTs were evaluated starting on day 125. Lowering the EBCT to 13 min resulted in Cr(VI) breakthrough. This might have indicated that the system had not fully stabilized when the EBCT optimization was started. As the Eff DOC levels were very low (Figure 3b), the ACA dose was raised while continuing to lower the EBCT to rule out that the ACA limitation was not affecting Cr removal. At the lower EBCTs (the lowest EBCT was 6 min), an ACA dose greater than 15 mg/L did not help control the effluent Cr(VI), suggesting that the system was EBCT limited. Accordingly, the ACA dose was lowered to 14 mg/L on day 151, and the EBCT was

![Figure 3](image-url)

**FIGURE 3** Effluent hexavalent chromium (Cr(VI)) concentrations and dissolved organic carbon (DOC) levels during process optimization. (a) Effects of empty-bed contact time (EBCT) and acetic acid (ACA) on Cr(VI) removal. (b) Effluent DOC versus ACA dose. BF Eff, biofilter effluent; BR Eff, bioreactor effluent; Eff DOC, effluent-dissolved organic carbon

![Figure 4](image-url)

**FIGURE 4** Sustained chromium (Cr) removal. (a) hexavalent (Cr(VI)) and total Cr in the raw water, bioreactor effluent (BR Eff), and biofilter effluent (BF Eff) in the grab samples. (b) BR Eff and BF Eff Cr(VI) measured using the in-line analyzer and in the grab samples.
raised to 10 min on day 165. While the BF Eff Cr(VI) gradually declined with 10-min EBCT, the ACA dose was further raised to assess if the performance reestablishment could be expedited and if Cr(VI) could be lowered to below detection levels. To expedite the performance recovery, the EBCT was also raised to 12 min on day 173 (Figure 3a). The highest ACA dose of 80 mg/L resulted in 23–29 mg/L DOC (equivalent to 57–70 mg/L ACA) in the effluents (Figure 3b), suggesting that the system required only approximately 15–25 mg/L ACA. Once the system performance was completely reestablished, the EBCT and ACA dose were lowered to 10 min and 15 mg/L on days 189 and 208, respectively, without any negative effects on Cr(VI) removal.

Using a yield of 0.4 mg/L biomass COD per mg/L of ACA COD and a safety factor of 1.5, the ACA dose required for reducing ~1 mg/L N nitrate and ~6 mg/L DO was approximately 11 mg/L ACA. The optimal ACA dose determined during this study was not surprising given that multiple assumptions, including the yield, were incorporated when calculating the required ACA dose.

When starting the pilot operation, 2 mg/L ACH and 14 mg/L H₂O₂ were used. Process optimization suggested that 1.5 mg/L ACH and 12 mg/L H₂O₂ allowed maintaining less than 0.3 ntu turbidity and greater than 3 mg/L DO, respectively (Figures S4 and S5), for most of the testing period, except when the H₂O₂ and ACH feeds were interrupted. Lower DO and higher turbidity were also observed from day 180 to 200 due to the carry over of ACA into the biofilter and the associated aerobic growth.

Under the optimized operating conditions, the system consistently removed nitrate and Cr to below the detection limit (i.e., 0.1 mg/L N; data not shown) and less than 7 μg/L (Figure 4), respectively.

### 3.5 | Disinfection and DBPFP testing

Disinfection tests were performed with the raw water and BF Eff samples (Supplemental Information). The results suggested that effective disinfection was achieved with 2 mg min/L concentration*time (Table S1). DBP formation was not a concern (Figure S6) as very low levels of total trihalomethanes and haloacetic acid 5 were observed at the end of the 7-day incubation. This was expected as the raw water and BF Eff contained 0.3 ± 0.10 and 0.4 ± 0.3 mg/L DOC, respectively, after the process optimization, suggesting that the ACA was almost completely consumed.

![FIGURE 5](image-url)  
Effects of backwashing on hexavalent chromium (Cr(VI)) removal. The vertical solid and dotted lines represent the bioreactor and biofilter backwash events, respectively. BF Eff, biofilter effluent; BR Eff, bioreactor effluent

![FIGURE 6](image-url)  
Robustness testing: System response to simulated (a) 24-h acetic acid (ACA) feed failure and (b) 24-h phosphoric acid (PHA) feed failure. Average raw water hexavalent chromium (Cr(VI)) concentrations remained approximately 75 μg/L during the ACA and PHA feed failure testing. Total Cr levels in the BR Eff and BF Eff were not monitored during the ACA feed failure testing before resuming the ACA feed. BF Eff, biofilter effluent; BR Eff, bioreactor effluent
3.6 System robustness

To evaluate system robustness, challenge tests, including backwash events, simulated 26-h ACA feed failure, a 3-day system shutdown, Cr(VI) spiking, and intermittent operation, were conducted. During the robustness testing, raw water temperature and pH were 20.0 ± 2.3 °C and 7.9 ± 0.1 SUs, respectively.

3.6.1 Effects of backwashing

Immediately after a bioreactor backwash, Cr(VI) in the BR Eff remained lower than 5 μg/L for approximately 3–4 h (Figure 5), likely due to partial exposure of GAC adsorption sites, and then spiked to as high as 8 μg/L. This indicated that the backwash negatively affected Cr(VI)-reducing microbial populations. However, the biofilter dampened the negative effects of bioreactor backwashing, maintaining the BF Eff Cr(VI) below 7 μg/L. Therefore, efforts were not made to further optimize the backwash protocol.

**FIGURE 7** Robustness testing: System response to a 3-day complete system shutdown. Average raw water hexavalent chromium (Cr(VI)) concentrations remained approximately 75 μg/L during the system shutdown testing. BF Eff, biofilter effluent; BR Eff, bioreactor effluent

**FIGURE 8** Robustness testing: System response to hexavalent chromium (Cr(VI)) spiking. Average raw water Cr(VI) concentrations remained approximately 75 μg/L during this testing. BF Eff, biofilter effluent; BR Eff, bioreactor effluent

**FIGURE 9** Robustness testing: System response to intermittent operation. (a) 7 days off, 7 days on. (b) 100 h on, 68 h off. (c) First 12 h off, then 1 h on followed by 1 h off for the next 12 h. BF Eff, biofilter effluent; BR Eff, bioreactor effluent; Cr(VI), hexavalent chromium
The additional Cr(VI) removal observed in the biofilter can be explained by the presence of aerobic Cr(VI)-reducing bacteria (Section 3.8). Anaerobic Cr(VI) reduction in the water column above the biofilter bed and potential anaerobic pockets within the biofilm likely helped lower the Cr(VI) concentration. The biofilter backwash resulted in temporary increases in the BF Eff Cr(VI), but the concentrations remained well below the target effluent concentration, except on day 215, when both bioreactor and biofilter were backwashed within 10 min of each other. Based on the results, when designing and operating a full-scale FXB system for Cr(VI) removal, it would be practical to make provisions to stagger the bioreactor and biofilter backwashes.

### 3.6.2 Effects of ACA feed failure

When the ACA feed was shut down on day 238, the BR Eff and BF Eff Cr(VI) gradually reached ~39 and ~10 μg/L within less than 80 min. Unfortunately, the in-line Cr(VI) analyzer failed, and Cr(VI) concentrations could not be determined during the no-ACA period. When the ACA feed was resumed, the effluent Cr(VI) concentrations matched the influent levels (Figure 6a). Once the ACA feed was reestablished, the system rapidly recovered, lowering the effluent concentrations to less than 10 μg/L within 6 h and reconforming biological Cr(VI) removal in the system.

### 3.6.3 Effects of PHA feed failure

Before the PHA feed was shut down on day 241, the BR Eff contained 45 and 4.8 μg/L total Cr and Cr(VI), respectively, whereas total Cr and Cr(VI) in the BF Eff were 7.0 and 6.6 μg/L, respectively (Figure 6b). Although Cr(VI) and total Cr were not monitored during the PHA feed shutdown period, when the PHA feed was reestablished, total Cr and Cr(VI) concentrations in the BR Eff and BF Eff remained similar to that before the shutdown, suggesting that Cr removal was unaffected when PHA feed was shut down for 24 h. As phosphorus requirement is typically very low for biomass growth, desorption of previously adsorbed phosphate likely supported microbial growth and activity during the no-PHA period. Furthermore, the possibility of using phosphorus present in the biomass or microbial products (e.g., extracellular polymeric substances [EPS] and soluble microbial products) cannot be ruled out.

### 3.6.4 Effects of complete system shutdown

The bioreactor and biofilter runtimes were 4.6 and 28.9 h, respectively, when the system was completely shut down on day 243 for a 3-day period. The raw water temperature ranged from 19.5 to 23 °C during this testing. The BR Eff and BF Eff contained less than 7 μg/L Cr(VI) (Figure 7), while total Cr remained 44 μg/L and less than 7 μg/L in the BR Eff and BF Eff, respectively. Immediately after restarting the system, approximately 18 and 22 μg/L Cr(VI) were observed in the BR Eff and BF Eff, respectively, but the system performance was reestablished within 3 h. With 12 mg/L H₂O₂, DO remained greater than 3 mg/L in the BF Eff (Figure S7) when the system operation resumed.

### 3.6.5 Effects of Cr(VI) spiking

To evaluate the system response to an abrupt increase in influent Cr(VI) concentrations, Cr(VI) spiking was conducted from day 247 to day 250, targeting 100 μg/L in the spiked influent. The in-line analyzer recorded 104 ± 13.9 μg/L Cr(VI) with considerable variability (Figure 8), likely because the analyzer was dedicated (for most of the time) and optimized for less than 10 μg/L Cr(VI) in the BR Eff and BF Eff. Given the short length (~10 ft) between the Cr(VI) injection port and the sample collection port, inadequate mixing was also, at least partly, responsible for the

| Analyte   | Unit | Bioreactor BWWW | Biofilter BWWW |
|-----------|------|-----------------|----------------|
|           |      | Day 220 A B     | Day 226 A B    | Day 220 A B |
| Cr(VI)    | μg/L | 17 3.3          | 7.6 8.4        | 1.7 ND      |
| COD       | mg/L | 250 240         | 210 210        | 230 360     |
| Total As  | μg/L | 4.6 5.4         | 5 5.6          | 96 100      |
| Total Cr  | μg/L | 140 150         | 160 170        | 9,500 10,000|
| TSS       | mg/L | 110 140         | 110 110        | 560 580     |
| Gross alpha | pCi/L | 7.5 N/A         | N/A N/A        | 870 N/A     |
| TDS       | mg/L | N/A N/A         | 320 330        | N/A N/A     |

Abbreviations: A and B, duplicate samples; As, arsenic; COD, chemical oxygen demand; Cr(VI), hexavalent chromium; N/A, not applicable; ND, nondetectable; TDS, total dissolved solids; TSS, total suspended solids.
variability in the in-line Cr(VI) results. The grab samples collected from the sampling port immediately above the bioreactor bed on day 249 contained 89 and 87 μg/L total Cr and Cr(VI), respectively. This was not surprising given that Cr(VI)-reducing bioactivity was expected in the water column and on the column wall above the bed. Slightly higher BR Eff Cr(VI) concentrations (i.e., 10.9 ± 4.9 μg/L) were observed during this testing, but the biofilter lowered Cr(VI) to 5.3 ± 2.8 μg/L in the BF Eff. Grab samples from day 249 contained 55 μg/L total Cr and 3.1 μg/L Cr(VI) were observed in the BF Eff. The additional Cr(VI) removal observed in the biofilter can be explained by the presence and activity of aerobic Cr(VI)-reducing bacteria (Section 3.8). However, as H₂O₂ is converted to DO when in contact with the GAC (Aguinaco, Pocostales, García-Araya, & Beltrán, 2011), it is likely that anaerobic growth occurred in the water above the bed. Furthermore, the possibility of small anaerobic pockets within the biofilm, especially in the lower section of the bed, promoting anaerobic Cr(VI) reduction cannot be ruled out.

### 3.6.6 Effects of intermittent operation

While the 3-day complete system shutdown demonstrated that the system was minimally affected by the one-time long-term shutdown, three different intermittent operating conditions were evaluated to determine the applicability of the system in rural areas with limited operator attention. Except the long-term intermittent shutdown (i.e., 7 days off followed by 7 days on), the BR Eff Cr(VI) concentrations remained less than 7 μg/L (Figure 9). During the long-term intermittent shutdown, BR Eff Cr(VI) remained as high as 30 μg/L. However, regardless of the intermittent operating conditions evaluated, further polishing was observed in the biofilter, which lowered the BF Eff Cr(VI) concentrations to below the treatment target. This demonstrated that the system can be reliably applied in a rural area with minimal operator attention.

Overall, these results demonstrated the robustness with respect to Cr(VI) removal over a wide range of operating conditions and water quality characteristics.

### 3.7 BWWW characteristics

COD levels in the BWWW ranged from 210 to 290 mg/L, suggesting that the BWWW had characteristics similar to municipal wastewater (Table 3). As expected, the biofilter BWWW contained high Cr and As concentrations. Furthermore, jar testing results (Figure 10) showed that the solids present in the wastewater can be effectively separated within 8 min by supplementing ACH, and additional water can be recovered and retreated, if needed.

Very low As and Cr levels were observed in the TCLP analysis (Table 4), suggesting that As and Cr leaching from

![Figure 10](image-url)
the BWWW will not be of concern. The STLC analyses showed the presence of metals in the bioreactor and biofilter BWWW at concentrations lower than the levels regulated by the California Code of Regulations (CCR, Title 22, Division 4.5) (Table 4). However, As and Cr in the biofilter BWWW exceeded the respective TTLC limits, possibly necessitating the blending of bioreactor and biofilter BWWW at a full-scale treatment plant. To assess the potential final concentrations in the blended BWWW, a mass balance analysis was conducted using a blending ratio of 2:1 (v/v) (i.e., 2 volumes of bioreactor BWWW to 1 volume of biofilter BWWW) as the bioreactor and biofilter were backwashed every 20–24 and 48 h, respectively. The results suggested that the blended BWWW would have concentrations well below the TTLC limits (i.e., approximately 44 mg/kg As and 1,600 mg/kg total Cr). Therefore, when designing a full-scale biological Cr(VI) treatment plant, it will be prudent to make provisions for blending and settling the bioreactor and biofilter BWWW. This will enhance water recovery as the supernatant from the settling chamber can be redirected to the bioreactor for retreatment.

### Microbial community

Biomass samples were collected from the bioreactor and biofilter on day 232, when Cr(VI) in the BR Eff and BF Eff was 1 and 2.6 μg/L, respectively. The microbial community analyses confirmed that Cr(VI) reduction occurred through the growth and activity of Cr(VI)-reducing bacteria (Table 5). *Proteobacteria* and *Bacteroidetes* were the dominant phyla, with *Betaproteobacteria* and *Gammaproteobacteria* as the most abundant bacterial classes in the bioreactor and biofilter. *Dechloromonas*, *Acinetobacter*, and *Zoogloea* were the most dominant genera in the bioreactor, whereas *Acinetobacter*, *Zoogloea*, and *Azohydromonas* (from *Comamonadaceae* family) were the most abundant genera in the biofilter. *Dechloromonas* falls within the *Rhodocyclaceae* family, which was previously identified as one of the dominant bacterial families in anaerobic Cr(VI)-removing batch reactors. Members from the *Dechloromonas* genus can remove multiple inorganic contaminants, including perchlorate (Coates & Achenbach, 2004; Li et al., 2010), nitrate (Li et al., 2010; Upadhyaya et al., 2010), and selenium (Knight & Nijenhuis, 2002). Bacteria from this genus have also been previously reported in chromium-removing systems (Chung, Nerenberg, & Rittmann, 2006). The presence of

| Table 4 | Results of soluble threshold limit concentration (STLC), total threshold limit concentration (TTLC), and toxicity characteristic leaching procedure (TCLP) analysis of the bioreactor or biofilter backwash wastewater (BWWW) |
|---------|-------------------------------------------------------------------------------------------------|
| STLC results (mg/L) | TTLC results (mg/kg) | TCLP results (mg/L) |
| Reg. limits | Bioreactor BWWW | Biofilter BWWW | Reg. limits | Bioreactor BWWW | Biofilter BWWW | Reg. limits | Bioreactor BWWW | Biofilter BWWW |
| Arsenic | 5 | <0.044 | <0.044 | 50 | <36 | 59 | 5 | <0.044 | <0.044 |
| Chromium | 5 | 0.032 | 1.1 | 2,500 | 286 | 4,100 | 5 | 0.43 |
| Mercury | 0.2 | 0.0005 | 0.00039 | 20 | <0.0057 | <0.0059 |
| Barium | 100 | 0.079 | 0.15 | 10,000 | 1.3 | 23 |
| Cadmium | 1 | <0.027 | <0.027 | 100 | <0.13 | <0.13 |
| Lead | 5 | <0.041 | <0.041 | 1,000 | <0.13 | <0.13 |
| Selenium | 1 | <0.07 | <0.07 | 100 | <0.3 | 0.46 |
| Silver | 5 | <0.014 | <0.014 | 500 | <0.13 | <0.085 |

Note: Reg. limits—regulatory limits as per California Code of Regulations (CCR), Title 22, Division 4.5.
**Table 5** Microbial community present in the bioreactor and biofilter

| Phylum            | Class           | Order          | Family           | Genus               | Bioreactor (%) | Biofilter (%) |
|-------------------|----------------|----------------|------------------|---------------------|----------------|---------------|
| Bacteroidetes     | Flavobacteriia | Flavobacteriales | Cryomorphaceae   | Fluvicola           | 2.6            |               |
|                   |                |                | Flavobacteriales | Flavobacterium      | 5.6            | 1.7           |
|                   |                |                | Weeksellaceae    | Cloacibacterium     | 4.7            |               |
| Sapromspirae      | Saprospirales  | Chitinophagaceae| Unclassified     | Chitinophagaceae    | 2.0            | 2.9           |
| Proteobacteria    | Alphaproteobacteria | Rhizobiales | Unclassified Rhizobiales | Rhizobium         | 8.0            |               |
|                   |                |                | Rhizobiaceae     | Unclassified        | 1.6            | 4.6           |
|                   |                |                | Weeksellaceae    | Cloacibacterium     | 2.9            |               |
| Betaproteobacteria| Burkholderiales | Comamonadaceae | Unclassified     | Comamonadaceae      | 7.7            | 1.0           |
|                   |                |                | Comamonadaceae   | Azohydromonas       | 1.2            | 13.3          |
|                   |                |                | Comamonadaceae   | Hydrogenophaga      | 4.2            | 1.0           |
|                   |                |                | Oxalobacteraceae | Unclassified        | 3.4            | 1.9           |
|                   |                |                | Rhodocyclaceae   | Unclassified        | 2.9            |               |
|                   |                |                | Rhodocyclaceae   | Dechloromonas       | 25.0           | 5.7           |
|                   |                |                | Rhodocyclaceae   | Zoogloea            | 9.5            | 14.5          |
| Deltaproteobacteria| Desulfuromonadales | Geobacteraceae | Geobacter         |                     | 1.2            |               |
|                   |                |                | Myxococcales     | Unclassified        | 2.5            |               |
| Gammaproteobacteria| Pseudomonadales | Moraxellaceae  | Acinetobacter     |                     | 23.6           | 22.9          |
|                   |                |                | Xanthomonadaceae | Pseudoxanthomonas   | 2.3            |               |

**Dechloromonas** as the most abundant genus in the bioreactor can be explained by the fact that the majority of the Cr(VI) was removed along with nitrate in the bioreactor.

Members of *Acinetobacter* are well described for the intracellular reduction of Cr(VI) to Cr(III) under aerobic conditions (Ahmad, Zakaria, Khasim, Alias, & Ismail, 2010; Bhattacharya, Gupta, Kaur, & Malik, 2014; Dermou & Vayenas, 2007). Bacteria related to the *Comamonadaceae* family likely reduce Cr(VI) to Cr(III) under aerobic conditions (Lai et al., 2016).

### 4 | CONCLUSION

This pilot study demonstrated the effectiveness of a two-stage, FXB biotreatment system for Cr(VI) removal from drinking water sources. Approximately 75 μg/L Cr(VI) was consistently lowered to less than 7 μg/L. Irrespective of the raw water Cr(VI) concentrations, highly efficient Cr(VI) reduction was achieved in the bioreactor, while the Cr(III) species generated in the bioreactor were effectively retained in the biofilter. The system was resilient and was not affected by a 24-h phosphorus feed failure, a 3-day system shutdown, Cr(VI) spiking, or intermittent operation. The system rapidly recovered (i.e., within 6 h) after a 26-h ACA feed shutdown. Potential Cr(VI)-reducing bacteria, including members of the *Dechloromonas* and *Acinetobacter* genera, were identified in the bioreactor and biofilter. The BWWW generated during the treatment process was readily settleable and had chemical compositions similar to a municipal wastewater. Overall, the results indicated that a
two-stage, FXB biotreatment system can provide an effective and sustainable approach for Cr(VI) removal.

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REFERENCES

Aguinaco, A., Pocostales, J. P., García-Araya, J. F., & Beltrán, F. J. (2011). Decomposition of hydrogen peroxide in the presence of activated carbons with different characteristics. Journal of Chemical Technology and Biotechnology, 86(4), 595–600. https://doi.org/10.1002/jctb.2560

Ahmad, W. A., Zakaria, Z. A., Khasim, A. R., Alias, M. A., & Ismail, S. M. H. S. (2010). Pilot-scale removal of chromium from industrial wastewater using the ChromBac system. Bioresource Technology, 101(12), 4371–4378. https://doi.org/10.1016/j.biortech.2010.01.106

Anderson, R. A. (1995). Chromium and parenteral nutrition. Nutrition, 11, 83–86.

Bartlett, R. J. (1991). Chromium cycling in soils and water: Links, gaps, and methods. Environmental Health Perspectives, 92, 17–24.

Bhattacharyya, A., Gupta, A., Kaur, A., & Malik, D. (2014). Efficacy of Acinetobacter sp. B9 for simultaneous removal of phenol and hexavalent chromium from co-contaminated system. Applied Microbiology and Biotechnology, 98, 9829–9841. https://doi.org/10.1007/s00253-014-5910-5

Blute, N., Wu, X., Cron, C., Abueg, R., Froelich, D., & Feng, L. (2014). Hexavalent chromium treatment implementation in Glendale, Calif. Journal AWWA, 106(3), 160–175.

Brandhuber, P., Frey, M., McGuire, M., Chao, P. F., Seidel, C., Amy, G., … Banerjee, K. (2005). Low-level hexavalent chromium treatment options: Bench-scale evaluation. Water Research Foundation, Project #2814, 214.

Cao, X., Guo, J., Mao, J., & Lan, Y. (2011). Adsorption and mobility of Cr(III)-organic acid complexes in soils. Journal of Hazardous Materials, 192(3), 1533–1538. https://doi.org/10.1016/j.jhazmat.2011.06.076

Caporaso, J. G., Kuczynski, J., Stombaugh, J., Bittinger, K., Bushman, F. D., Costello, E. K., … Knight, R. (2010). QIIME allows analysis of high-throughput community sequencing data. Nature Methods, 7(5), 335–336. https://doi.org/10.1038/nmeth0510-335

Chebeir, M., & Liu, H. (2016). Kinetics and mechanisms of Cr(VI) formation via the oxidation of Cr(III) solid phases by chlorine in drinking water. Environmental Science and Technology, 50, 701–710. https://doi.org/10.1021/acs.est.5b05739

Chung, J., Nerenberg, R., & Rittmann, B. E. (2006). Bio-reduction of soluble chromate using a hydrogen-based membrane biofilm reactor. Water Research, 40, 1634–1642. https://doi.org/10.1016/j.watres.2006.01.049

Coates, J. D., & Achenbach, L. a. (2004). Microbial perchlorate reduction: Rocket-fueled metabolism. Nature Reviews. Microbiology, 2(7), 569–580. https://doi.org/10.1038/nrmicro926

Dermou, E., & Vayenas, D. V. (2007). A kinetic study of biological Cr(VI) reduction in trickling filters with different filter media types. Journal of Hazardous Materials, 145(1–2), 256–262. https://doi.org/10.1016/j.jhazmat.2006.11.017

Dong, G., Wang, Y., Gong, L., Wang, M., Wang, H., He, N., … Li, Q. (2013). Formation of soluble Cr(III) end-products and nanoparticles during Cr(VI) reduction by Bacillus cereus strain XMC-6. Biochemical Engineering Journal, 70, 166–172. https://doi.org/10.1016/j.bej.2012.11.002

Edgar, R. C. (2010). Search and clustering orders of magnitude faster than BLAST. Bioinformatics, 26(19), 2460–2461. https://doi.org/10.1093/bioinformatics/btq461

Edgar, R. C., Haas, B. J., Clemente, J. C., Quince, C., & Knight, R. (2011). UCHIME improves sensitivity and speed of chimera detection. Bioinformatics, 27(16), 2194–2200. https://doi.org/10.1093/bioinformatics/btr381

International Agency for Research on Cancer (1990). Monographs on the evaluation of carcinogenic risks to humans. In Chromium, nickel, and welding (Vol. 49). Geneva, Switzerland: IARC.

Knight, V. K., & Nijenhuis, I. (2002). Degradation of aromatic compounds coupled to selenium reduction. Geomicrobiology Journal, 19(1), 77–86.

Kozich, J. J., Westcott, S. L., Baxter, N. T., Highlander, S. K., & Schloss, P. D. (2013). Development of a dual-index sequencing strategy and curation pipeline for analyzing amplicon sequence data on the miseq illumina sequencing platform. Applied and Environmental Microbiology, 79(17), 5112–5120. https://doi.org/10.1128/AEM.01043-13

Lai, C., Zhong, L., Zhang, Y., Chen, J., Wen, L., Shi, L., … Zhao, H. (2016). Bioreduction of chromium in methane-based membrane biofilm reactor. Environmental Science and Technology, 50, 5832–5839. https://doi.org/10.1021/acs.est.5b06177

Li, X., Upadhyaya, G., Yuen, W., Brown, J., Morgenroth, E., & Raskin, L. (2010). Changes in the structure and function of microbial communities in drinking water treatment bioreactors upon addition of phosphorus. Applied and Environmental Microbiology, 76(22), 7473–7481. https://doi.org/10.1128/AEM.01232-10

Lindsay, D. R., Farley, K. J., & Carbonaro, R. F. (2012). Oxidation of Cr(III) to Cr(VI) during chlorination of drinking water. Journal of Environmental Monitoring, 14(7), 1789–1797. https://doi.org/10.1039/c2em00012a

Liu, K. J., & Shi, X. (2001). In vivo reduction of chromium(VI) and its related free radical generation. Molecular and Cellular Biochemistry, 222, 41–47.

Luo, Z., & Chatterjee, N. (2010). Kinetics of oxidation of Cr(III)-organic complexes by H2O2. Chemical Speciation and Bioavailability, 22(1), 25–34. https://doi.org/10.3184/095422909X12548400846521

Mamais, D., Noutsopoulos, C., Kavallari, I., Nyktari, E., Kaldis, A., Panousi, E., … Nasioka, M. (2016). Biological groundwater treatment for chromium removal at low hexavalent chromium concentrations. Chemosphere, 152, 238–244. https://doi.org/10.1016/j.chemosphere.2016.02.124

Matern, K., Weigand, H., Singh, A., & Mansfeldt, T. (2017). Environmental status of groundwater affected by chromite ore processing residue (COPR) dumpsites during pre-monsoon and monsoon seasons. Environmental Science and Pollution Research, 24, 3582–3592. https://doi.org/10.1007/s11356-016-8110-2
McDonald, D., Price, M. N., Goodrich, J., Nawrocki, E. P., DeSantis, T. Z., Probst, A., ... Hugenholtz, P. (2012). An improved Greengenes taxonomy with explicit ranks for ecological and evolutionary analyses of bacteria and archaea. The ISME journal, 6(3), 610–618.

McGuire, M. J., Blute, N. K., Seidel, C., Qin, G., & Fong, L. (2006). Pilot-scale studies of hexavalent chromium removal from drinking water. Journal AWWA, 98(2), 134–143.

Novak, M., Martinkova, E., Chrastny, V., Stepanova, M., Sebek, O., Andronikov, A., ... Komarek, A. (2017). The fate of Cr(VI) in contaminated aquifers 65 years after the first spillage of plating solutions: Aδ53 Cr study at four central European sites. Catena, 158(July), 371–380. https://doi.org/10.1016/j.catena.2017.07.004

National Toxicology Program (NTP). (2008). Technical Report on the Toxicology and Carcinogenesis Studies of Sodium Dichromate Dehydrate in F344N Rats and B6C3F1 Mice (Drinking Water Studies). NTP TR 546, US Department of Health and Human Services, Washington.

Panousi, E., Mamais, D., Noutsopoulos, C., Mpertoli, K., Kantavelou, C., Nyktari, E., ... Kaldis, A. (2017). Biological groundwater treatment for hexavalent chromium removal at low chromium concentrations under anoxic conditions. Environmental Technology (United Kingdom), 3330, 1–9. https://doi.org/10.1080/09593330.2017.1393013

Puzon, G. J., Roberts, A. G., Kramer, D. M., & Xun, L. (2005). Formation of soluble organo-chromium(III) complexes after chromate reduction in the presence of cellular organics. Environmental Science and Technology, 39(8), 2811–2817. https://doi.org/10.1021/es048967g

Puzon, G. J., Tokala, R. K., Zhang, H., Yonge, D., Peyton, B. M., & Xun, L. (2008). Mobility and recalcitrance of organo-chromium(III) complexes. Chemosphere, 70(11), 2054–2059. https://doi.org/10.1016/j.chemosphere.2007.09.010

Ramírez-Díaz, M. I., Díaz-Pérez, C., Vargas, E., Riveros-Rosas, H., Campos-García, J., & Cervantes, C. (2008). Mechanisms of bacterial resistance to chromium compounds. Biometals, 21(3), 321–332. https://doi.org/10.1007/s10534-007-9121-8

Shi, X., & Dalal, N. S. (1989). Chromium(V) and hydroxyl radical formation during the glutathione reductase-catalyzed reduction of chromium(VI). Biochemical and Biophysical Research Communications, 163(1), 627–634.

Siddique, A., Zaigham, N. A., Mallick, K. A., Mumtaz, M., & Saied, S. (2008). Geochemical and geostatistical investigations of chromium pollution in groundwater. Water Environment Research, 80(2), 149–153. https://doi.org/10.2175/106143007X220824

Sugden, K. D., & Steams, D. M. (2000). The role of chromium(V) in the mechanism of chromate-induced oxidative DNA damage and cancer. Journal of Environmental Pathology, Toxicology and Oncology, 19, 215–230.

Upadhyaya, G., Jackson, J., Clancy, T. M., Hyun, S. P., Brown, J., Hayes, K. F., & Raskin, L. (2010). Simultaneous removal of nitrate and arsenic from drinking water sources utilizing a fixed-bed bioreactor system. Water Research, 44(17), 4958–4969. https://doi.org/10.1016/j.watres.2010.07.037

Villalobos-aragón, A., Ellis, A. S., Armienta, M. A., Morton-bernea, O., & Johnson, T. M. (2012). Geochemistry and Cr stable isotopes of Cr-contaminated groundwater in León valley, Guanajuato, Mexico. Applied Geochemistry, 27, 1783–1794. https://doi.org/10.1016/j.apgeochem.2012.02.013

Wang, Q., Garrity, G. M., Tiedje, J. M., & Cole, J. R. (2007). Naïve Bayesian classifier for rapid assignment of rRNA sequences into the new bacterial taxonomy. Applied and Environmental Microbiology, 73(6), 5261–5267. https://doi.org/10.1128/AEM.00062-07

Ye, Y., Jiang, Z., Xu, Z., Zhang, X., Wang, D., Lv, L., & Pan, B. (2017). Efficient removal of Cr(III)-organic complexes from water using UV/Fe(III) system: Negligible Cr(VI) accumulation and mechanism. Water Research, 126, 172–178. https://doi.org/10.1016/j.watres.2017.09.021

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