Effect of heavy metal co-contaminants on selenite bioreduction by anaerobic granular sludge

J. Mala, Y.V. Nancharaiah, E.D. van Hullebusch, P.N.L. Lens

1. Introduction

Selenium and sulfur belong to the chalcogen group (periodic table group 16), and have similar chemical behavior. Often, selenium oxyanion contamination occurs concomitantly with sulfate and heavy metals in different waste streams such as acid mine drainage, acid seeps, and agricultural drainage. There are limited studies on the microbial transformation of selenium oxyanions as compared to sulfur. Bioreduction of selenium oxyanions, particularly selenite, to elemental selenium can be achieved using both aerobic and anaerobic microorganisms. Thus, selenate (Se(VI)) and selenite (Se(IV)) reducing microorganisms could be potentially used for the bioremediation of selenium contaminated soils, sediments, industrial...
effluents, and agricultural drainage waters (Lenz et al., 2008; Nancharaiah and Lens, 2015a,b). However, the use of this strategy for practical applications may have important limitations because the microbial reduction processes as well as the fate of bioreduced selenium can be affected by the presence of co-contaminants such as heavy metals.

Heavy metals are toxic for microorganisms and cannot be biodegraded like organic pollutants. However, they can be transformed from mobile and toxic forms into immobile and less or non-toxic forms (Beyenal and Lewandowski, 2004; Nancharaiah et al., 2015, 2016). Both adsorption and redox conditions essentially control the mobility of these chemical species in natural environments. It has been well documented that heavy metals such as Cu(II), Zn(II) and Cd(II) can either be adsorbed (Demirbas, 2008) or precipitated as metal sulfide in anaerobic environments (Prasad and Jha, 2010). In contrast, their fate in selenium containing environment is poorly documented.

There is an increasing interest in the potential biotechnological applications of bacterial selenium oxyanion reduction as a green method for the production of metal selenide quantum dots (Ayano et al., 2013; Fellowes et al., 2013; Nancharaiah and Lens, 2015b). Among several metal selenides, mainly cadmium selenide (CdSe), zinc selenide (ZnSe) and lead selenide (PbSe) have attracted considerable attention due to their quantum confinement effects and size-dependent photoemission characteristics (Fellowes et al., 2013). Hence, microbial reduction of selenium oxyanions in the presence of heavy metals (e.g. Cd, Zn, and Pb) is very important for the development of efficient bioremediation processes and for the microbial synthesis of metal selenide quantum dots (Nancharaiah and Lens, 2015b).

The use of sulfate reducing bacteria in metal bioremediation processes has been widely reported, for example, bioprecipitation of selenium as metal sulfide for cadmium (White and Gadd, 1998), zinc and lead (Guo et al., 2010; Hien Hoa et al., 2007). However, to the best of our knowledge, there is no study on the effect of heavy metal co-contaminants on selenium oxyanion bioreduction or vice versa. Therefore, the objective of this work was to investigate microbial reduction of selenite in the presence of heavy metals. In this study, experiments were performed on selenite reduction by anaerobic granular sludge in the presence of different concentrations of three heavy metals, i.e. Cd(II), Zn(II) and Pb(II). Time course profiles of selenite removal along with the fate of bioreduced selenium and heavy metals were analyzed.

2. Methods

2.1. Source of biomass

Anaerobic granular sludge was collected from a full-scale upflow anaerobic sludge blanket (UASB) reactor treating paper mill wastewater (Industriewater Eerbeek B.V., Eerbeek, The Netherlands) and was utilized as the inoculum for all experiments. The anaerobic granular sludge was characterized in detail by Roest et al. (2005). The sludge was stored at 4 °C in an air tight jar under anaerobic conditions and used for selenite reduction experiments. All the experiments were performed in serum bottles under anaerobic conditions.

2.2. Selenite reduction experiments

The mineral medium used in selenite reduction experiments contained (mg/L): NH₄Cl (300), CaCl₂·2H₂O (15), KH₂PO₄ (250), Na₂HPO₄ (250), MgCl₂ (120), and KCl (250). Nitrilotriacetic acid (1 mg/mg heavy metal) was used as the chelating agent to prevent heavy metal precipitation. Sodium lactate (10 mM) was used as the carbon and electron source. Sodium selenite (Na₂SeO₃, 1 mM = 79 mg/L) was used as the source of selenium. The pH of the medium was adjusted to 7.3 with 1 M NaOH. The medium was distributed into 100 mL volume glass serum bottles as 70 mL aliquots. The serum bottles were inoculated with 0.7 g wet weight (0.2 g dry weight) of anaerobic granular sludge. The bottles were purged with N₂ gas for ~5 min and incubated at 30 °C on an orbital shaker set at 150 rpm for 9 d. All the experiments were performed either in duplicate or triplicate.

2.3. Effect of heavy metals on selenite reduction

Selenite reduction experiments described above were performed in the presence of heavy metals. Stock solutions of heavy metals were prepared by dissolving 1 g/L of CdCl₂, ZnCl₂, or PbCl₂ in ultrapure water. Heavy metals were added to serum bottles individually at different concentrations (10, 30, 50, 70, 90, 150, 300 and 400 mg/L). To avoid precipitation, Pb concentrations were used up to a maximum of 150 mg/L. Liquid samples were collected at regular time intervals for analyzing lactate, selenite, elemental selenium, total selenium and heavy metals. After 9 d of incubation, biomass was subjected to microwave-assisted acid digestion for measuring the total metal (Cd, Zn or Pb) and selenium concentration. Appropriate controls were setup by incubating serum bottles containing only mineral medium and sodium lactate with selenium and heavy metals, but without the biomass.

2.4. Kinetics of heavy metal removal

The heavy metal (Cd, Zn and Pb) removal kinetics were analyzed by fitting the data using the pseudo-first order rate expression based on the solid capacity as given below:

\[ \frac{dq_t}{dt} = k_1(q_e - q_t) \]  

where \( q_t \) and \( q_e \) are the amount of metal biosorbed per unit weight of biosorbent (mg/g dry weight) at equilibrium and at any time \( t \); respectively, and \( k_1 \) is the rate constant of pseudo-first order sorption (min⁻¹). After applying the initial and boundary conditions, for \( t = 0 \) and \( q_t = 0 \), the integrated form of the above equation becomes:

\[ \log(q_e - q_t) = \log(q_e - q_{i}) - \frac{k_1}{2.303} t \]

In contrast to the pseudo-first order model, the pseudo-second order kinetic model predicts the behavior over the whole range of adsorption and is widely used by many researchers because it provides a more appropriate description than the first order equation (Volesky and Holan, 1995). It can be expressed in linear form as:

\[ \frac{t}{q_t} = \frac{1}{k_2q_e^2} + \frac{t}{q_e} \]

where \( q_t \) is the amount of the sorbate on the sorbent at time \( t \) (mg/g), \( k_2 \) is the equilibrium rate constant of pseudo-second order sorption kinetics (g/mg.min) and \( q_e \) is the equilibrium uptake (mg/g) (Volesky and Holan, 1995). The pseudo-first and -second order constants were determined by plotting \( \log(q_e - q_t) \) against \( t \) and \( t/q_t \) against \( t \), respectively (Cordero et al., 2004).

2.5. Analytical methods

The concentration of Cd, Zn and Pb was analyzed using an atomic absorption spectrophotometer (AAS) (PerkinElmer Model Analyst 200). Liquid samples were first filtered through a 0.45 µm cellulose acetate syringe filter (Sigma Aldrich, USA) and then the filtrate was analyzed for residual heavy metals after
acidifying with concentrated nitric acid (pH < 2) to prevent metal precipitation and adsorption onto surfaces.

For Se (IV) analysis, a modified spectrophotometric method was followed (Dao-bo et al., 2013). Briefly, liquid samples collected at different time points were centrifuged at 37,000g for 15 min to remove the suspended cells and Se(0) particles. The supernatant (1 mL) was mixed with 0.5 mL of 4 M HCl, and then with 1 mL of 1 M ascorbic acid. After 10 min of incubation at room temperature, the absorbance was determined at 500 nm using an UV–Vis spectrophotometer (Hermle Z36 HK).

Se(0) was collected from the liquid phase by centrifuging at 37,000g for 15 min. After centrifugation, the supernatant was separated and the total selenium concentration in the supernatant was measured using a graphite furnace AAS (SOLARAR MQZe, unity lab services USA). The pellet was re-suspended in Milli-Q water and the Se concentration was determined using the same graphite furnace AAS. Aqueous selenide (HSe⁻) concentration was calculated by subtracting concentrations of selenite in solution from the total Se (selenium + selenide) in solution by following Pearce et al. (2009).

3. Results

3.1. Effect of Cd, Zn and Pb on selenite reduction by anaerobic granular sludge

Selenite removal by anaerobic granular sludge was monitored as a function of time in the presence of Pb, Zn and Cd separately at different concentrations and in the absence of heavy metals (Fig. 1A–C). At lower initial concentrations of Pb and Zn (10–70 mg/L), selenite was completely reduced within 5 d of incubation. At higher initial concentrations of Pb and Zn (>90 mg/L), selenite was not complete, but more than 92% was still removed (Fig. 1B and C). Overall, the presence of Pb and Zn in the medium did not exert a significant inhibition on the selenite reduction. In the presence of Cd, complete reduction of selenite was observed in 7 d at initial concentrations of 10–70 mg/L. However, Cd showed a strong inhibition on selenite reduction at initial concentrations higher than 150 mg/L and approximately 65–48% of 1 mM selenite was reduced (Fig. 1A).

Fig. 1D–F shows lactate consumption in the presence of different initial heavy metal concentrations. There was no significant effect of Pb and Zn on the lactate consumption at any of the Pb and Zn concentrations investigated. Also, Cd did not show any significant effect on lactate consumption at low initial concentrations (10–30 mg/L). However, with an increase in initial Cd concentration (70–400 mg/L), lactate consumption was inhibited: almost 40–80% lactate was not consumed and available in the medium, even at the end of the 9 d incubation period.

The elemental selenium production was visually evident by the appearance of a red color during the incubation period. Control serum bottles setup without the granular sludge did not show any decrease in selenite concentration and appearance of red color. Fig. 2A shows that production of red elemental Se was much higher in the presence of Cd as compared to Zn or Pb. It also shows that formation of elemental Se was increased with increased initial Cd concentration. However, the formation of elemental Se started decreasing again from 50 mg/L Cd onwards. In contrast, production of elemental Se was much less at lower Pb and Zn concentrations and then started increasing at concentrations >90 mg/L, but decreased again from 150 mg/L onwards (Fig. 2A).

The concentration of aqueous selenide (HSe⁻) was relatively higher in the presence of Cd as compared to Pb and Zn (Fig. 2B). Similar to elemental Se, the HSe⁻ present in the liquid phase increased with the Cd concentration and reached a maximum at 50 mg/L Cd and decreased thereafter. The production of HSe⁻ was much less in the presence of Pb and Zn. At higher heavy metal concentrations (>150 mg/L), the formation of HSe⁻ was not observed.

The difference in selenium loading in the biomass under different conditions is shown in Fig. 3A. The selenium content of the biomass increased with an increase in the metal concentration up to 90 mg/L and then gradually decreased with a further increase in metal concentration. For Pb, 90–90% of selenium was available in the biomass, while for Zn, the selenium concentration in the biomass decreased from 90% to 75% with increasing initial Zn concentration. The Cd concentration had the most significant effect on the selenium association with the biomass (Fig. 3A). A gradual increase in selenium concentration in the biomass from 50% to 80% was associated with an increase in initial Cd concentration from 10 to 90 mg/L, and then the selenium concentrations in the biomass decreased at higher initial Cd concentrations. At 400 mg/L Cd, the selenium concentration in the biomass was only 38% (Fig. 3A).

3.2. Kinetics of heavy metal removal

The time course of Cd, Zn and Pb removal by anaerobic granular sludge is shown in Fig. 4. There was no significant effect of the initial metal concentration on the heavy metal removal efficiency at lower concentrations (10–90 mg/L). After 9 d of incubation, the Pb and Zn concentrations were decreased to below 2 mg/L in the liquid phase, resulting in more than 97% removal of metals. For Cd, more than 90% metal was removed from an initial concentration of 150 mg/L. However, at a metal concentration of 150 mg/L, the metal removal efficiency decreased to 86% for Pb, while removal efficiencies were 81% for Zn and 87% for Cd at 400 mg/L metal concentration. It was also clear from Fig. 3B that 80–90% of the initial Pb was associated with the biomass. For Zn and Cd, although 80–90% of the metal was biosorbed at lower concentrations (10–90 mg/L), the removal efficiency started to decline with a further increase in initial metal concentration.

In order to describe the biosorption process of Pb, Zn and Cd to the biomass, the kinetic data were described using the pseudo-first order and pseudo-second order rate equations. The correlation coefficients ($R^2 < 0.95$) for the pseudo-first order kinetic constants were much lower than the pseudo-second order kinetic model ($R^2 > 0.95$), suggesting that the pseudo-second order kinetic model fitted the biosorption data better (Table 1). Table 1 shows the pseudo-second-order kinetic rate constant $k_2$ (pseudo-second order rate constant; mg/g min) and $q_e$ (sorption capacity; mg/g) values, with the calculated $q_e$ being close to the experimental data, the pseudo-second order equation predicted equilibrium adsorption values more precisely than the first-order one. The biosorption capacity of the anaerobic granular sludge increased with increasing metal concentration. When the initial metal concentration increased from 10 to 400 mg/L, the $q_e$ increased from 1.01 to 34.84 mg g⁻¹ for Cd and 1.03 to 32.89 for Zn. Similar results were observed in case of Pb: the biosorption capacity increased with an increase in initial metal concentration. However, for initial concentrations exceeding 150 mg/L Pb, the metal cations began to precipitate in the medium prior addition to biomass. The rate parameter $k_2$ listed in Table 1 also indicated the biosorption of metals decreased at higher initial metal concentrations.

3.3. Selenium and heavy metal mass balances

The selenium mass balance was estimated from the obtained measurements at the end of the 9 d incubation. The mass balance was based on Se measurements and by assuming that the total initial selenium supplied as selenite (79 mg/L) was converted partly to Se(0) and HSe⁻ and partitioned between the liquid and biomass phases. Se in the liquid phase was distinguished in terms of resid-
ual selenite (Se(IV)), biogenic elemental Se (Se(0)) and selenide (HSe⁻/C0). The Se associated with the biomass was considered as total Se and no effort was made to distinguish between different selenium species, as this requires specialized speciation techniques as XANES and XAFS which were out of the scope of this study.

The percentage ratio of total selenium partitioned between the liquid and biomass phase could be accounted to about 85–94% of the supplied selenium for all three heavy metals studied.

Similarly, the mass balance of Cd, Zn and Pb was determined. Heavy metal concentrations in the liquid phase were measured at regular intervals during the incubation period. However, the total metal concentration measured at the end of the incubation period includes the metal present in the medium and metal present in biomass. For Pb and Zn, the percent ratio of total final metal to the supplied initial metal was 88–94% while for Cd, it varied from 80% to 87%.

**Fig. 1.** Selenite reduction (A–C) and lactate consumption (D–F) profiles by anaerobic granular sludge in the presence of different concentrations of the heavy metals Pb, Zn, and Cd. To avoid precipitation, Pb was used only up to 150 mg/L. Legend symbols are inside the panel (A).
4. Discussion

4.1. Effect of heavy metals on selenite reduction

This study shows that heavy metals, particularly Pb and Zn, did not significantly inhibit selenite reduction by anaerobic granular sludge at 30 °C and pH 7.3 using lactate as electron donor. In contrast, Cd at higher concentrations (>150 mg/L) was inhibitory to the selenite bioreduction (Fig. 1A). The time-course of selenite removal revealed a pattern consisting of two distinct phases. At the beginning, the removal occurred rapidly indicating the biosorption of the selenite ion, followed by a second phase wherein removal was by the uptake and bioreduction of selenite by the biomass. The inhibitory effect of Cd on selenite reduction confirms the more toxic nature of Cd to bacterial metabolism compared to Pb and Zn (Guo et al., 2010). At higher Cd concentrations (150 mg/L), heavy metal removal was comparatively lower resulting in higher Cd(II) concentrations in the aqueous phase. The free metal ion concentration available in the aqueous phase eventually exerts toxicity to microorganisms and inhibits selenite bioreduction (Bartacek et al., 2008). However, the toxicity of the heavy metal dependents on several other factors, including metal type and speciation, type of microorganisms, species composition of microbial community and their defense mechanisms (Ayano et al., 2013; Bartacek et al., 2008; Kieu et al., 2011). For example, Cd, Zn and Pb at concentrations of 20 mg/L, 25 mg/L, and 75 mg/L, respectively are toxic to sulfate reducing bacteria (SRB) in batch experiments (Hao et al., 1994). Another report on heavy metal bioremediation by a mixture of SRB showed that Zn had significantly less toxic effects on SRB with inhibition caused only at 400 mg/L Zn (Zhou et al., 2013). This suggests that SRB are more sensitive to heavy metal toxicity than the selenite reducing population present in the anaerobic granular sludge investigated in this study.

There are no studies on the effect of heavy metals on anaerobic selenate or selenite reducing bacteria. Recently, selenite reduction and formation of CdSe by *Pseudomonas* sp. was reported under aerobic growth conditions (Ayano et al., 2013). *Pseudomonas* sp. isolated through an enrichment process was able to grow and carry out selenite reduction even at 3660 mg/L Cd (Ayano et al., 2014). This is to the best of our knowledge the only study which investigated Cd resistance and selenite reduction in the presence of Cd using *Pseudomonas* sp. in aerobic conditions. No studies have been done so far on the effect of heavy metals on selenite reduction by pure or mixed cultures under anaerobic conditions.
CdSe is thermodynamically more favored than ZnSe and PbSe formation (Pearce et al., 2008). In addition, the Cd–Se bond strength in CdSe is much higher than the Zn–Se bond strength in ZnSe (Sung et al., 2006). In an analogous sulfide system, it was suggested that Zn is more likely than Cd to form oxide/hydroxide phases, because of the relatively small difference in the solubility products of ZnS and ZnO/Zn(OH)₂ (O’Brien and McAleese, 1998). Pb has a similar chemical behavior like Zn. Under the experimental conditions, formation of Pb carbonate or oxide precipitates is more likely rather than sulfide or selenide phases (Hesterberg et al., 1997; O’Day et al., 2000). However, in the presence of 90 mg/L Pb and Zn onwards, an increase in elemental Se and HSe⁻ was observed (Fig. 2). It is likely that higher concentrations of Zn and Pb interfered with the selenite removal mechanisms, particularly with biosorption. Thus, more selenite present in the liquid phase was converted to relatively higher amounts of Se(0) and Se(−II) in the aqueous phase by bioreduction by the microorganisms present in the anaerobic granular sludge.

Simulation by Visual MINTEQ software confirmed the formation of HSe⁻, which reacts with Cd, Zn or Pb available in the medium to form CdSe, ZnSe or PbSe, respectively. Charge differences of all the simulation models were less than 5% which supports the applicability for the experimental system. According to the simulation, all the HSe⁻ is used to form metal selenides when the aqueous heavy metal concentration equals or exceeds the available HSe⁻. A similar behavior for consumption of biogenic sulfide for heavy metal precipitation as metal sulfides was reported by Villa-Gomez et al. (2012).

From Fig. 3 it is clear that more than 90% of the added Pb and Zn along with selenium were present in the anaerobic granular sludge, which could be in the form of PbSe or ZnSe, respectively. Another reason could be that a large amount of selenite was reduced rapidly to elemental selenium and the heavy metals adsorbed on these Se(0) nanoparticles lead to the precipitation of elemental selenium (Jain et al., 2015).

4.3. Fate of heavy metals

The time-course measurements (Fig. 4) demonstrated that removal of heavy metals by anaerobic granular sludge occurred rapidly at the beginning through biosorption, which is a spontaneous process and thereby often occurs very fast (Volesky, 2001; Yuan et al., 2009). It also reveals that the bioremoval of heavy metals had a second removal phase probably via intracellular accumulation (Yuan et al., 2009) or as metal selenide precipitate (Fellowes et al., 2013) or sorption onto Se(0) (Jain et al., 2015). Indeed, the heavy metals are not inhibiting the microbial metabolism, as Se bioreduction continued during the incubation in the presence of even high initial heavy metals concentrations (Fig. 1A–C).

Heavy metal removal data fitted well using the pseudo-second order equation with R² values of >0.99 (Table 1). The results predict the behavior over the entire study range, with a chemisorption mechanism involving valency forces through sharing or exchange of electrons between sorbent and sorbate being the rate controlling step (Choi et al., 2009). The experimental results showed an increase in metal adsorption capacity (Table 1) while the removal efficiency decreased with an increase in initial metal ion concentration (Fig. 4). The initial increase in metal adsorption capacity resulted from the increase in driving force, i.e. concentration gradient due to adsorption. The decrease in the heavy metal removal efficiency at elevated concentrations might be due to the saturation of binding sites for adsorption (King et al., 2008; Yang et al., 2010). The rate parameter k₂ (Table 1) derived from fitting experimental data indicated that the biosorption at higher metal concentrations is slower due to the competition for binding sites.
4.4. Proposed selenium removal mechanism in the presence of heavy metals

Based on the results presented above, a mechanism for the removal of selenite and heavy metals through different processes is proposed (Fig. 5). Granular sludge became red due to the formation of Se(0) in the granular sludge and precipitation of Se(0) formed in the aqueous phase by bioreduction of selenite in the presence of heavy metals, using lactate as electron donor. The removal of heavy metals is mainly driven by biosorption onto the granular sludge (Volesky, 2001; Yuan et al., 2009). Adsorption of heavy metals onto Se(0) nanoparticles can partly contribute to the removal of the heavy metals from aqueous phase as well. Subsequent reduction of Se(0) will form HSe\(^{-}\) which precipitates with heavy metals to form metal selenides. Depending on the size and surface properties, the formation of metal selenides both in the granular sludge and in the aqueous phase is expected. To further evaluate the chemical environment of heavy metals, especially whether the metals are sorbed onto the Se(0) nanoparticles or bound as metal selenides (e.g. CdSe), further speciation studies are required using X-ray absorption spectroscopic techniques e.g. XANES and EXAFS. Nevertheless, the results presented in this paper show for the first time the effect of heavy metal co-contaminants on the microbial selenite reduction and the fate of bioreduced selenium in anaerobic granular sludge.

### Table 1

Second-order kinetics constant for the biosorption of Pb, Zn and Cd on anaerobic granular sludge.

<table>
<thead>
<tr>
<th>Initial metal concentration (mg/l)</th>
<th>(q_e)</th>
<th>(k_2)</th>
<th>(R^2)</th>
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<tr>
<td></td>
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<tr>
<td>400</td>
<td>34.84</td>
<td>32.89</td>
<td>–</td>
</tr>
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</table>

\(q_e\) – Adsorbed metal ion quantity per gram of biomass at equilibrium (mg g\(^{-1}\)).

\(k_2\) – Second-order adsorption rate constant (g mg\(^{-1}\) min\(^{-1}\)).

\(R^2\) – Correlation coefficient.

4.5. Practical implications

Heavy metals are common co-contaminants with selenium oxyanions in different selenium containing waste streams (Table S1, Supplementary data). The present study demonstrated that bioreduction of selenite by anaerobic granular sludge is possible, even in the presence of high (up to 400 mg/L) concentrations of heavy metals. The results obtained here are useful for the development of a selenium oxyanion-reducing bioreactor to simultaneously remove selenium oxyanions and heavy metals from wastewaters. The majority of studies on selenium wastewaters noted the presence of colloidal Se(0) in the effluents of bioreactors, necessitating post-treatment prior to discharge. It is to be noted that this information is based on microbial reduction of selenium oxyanions performed in the absence of heavy metal co-contaminants. In this study, most (~90%) of the added selenium and heavy metals were associated with the biomass (~90%), which will increase the Se removal efficiency of the UASB bioreactor and will thus make the post-treatment redundant. It is desirable to investigate the treatment of selenium oxyanions in bioreactors in the presence of heavy metal co-contaminants in order to ascertain the fate of Se under long term operating conditions. Furthermore, the anaerobic sludge was able to reduce selenite up to selenide in the presence of heavy metals, which opens perspectives to develop a novel microbial synthesis process to produce metal...
selenium nanoparticles by combining bioremediation approaches to convert environmentally problematic waste streams to ‘high-end’ saleable products like metal chalcogenide quantum dots (Pearce et al., 2008).

5. Conclusion

This work showed the effect of Cd, Zn and Pb on the microbial reduction of selenite. Both elemental selenium and selenite were bioreduced by anaerobic granular sludge. Production of aqueous fractions of Se(0) and HSe– were much higher in the presence of Cd as compared to Pb and Zn. The majority of the bioreduced selenium and heavy metals were associated with the anaerobic granular sludge.

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Appendix A. Supplementary data

Heavy metals are common co-contaminants with selenium oxianions in different selenium containing waste streams. Table S1 gives an overview of selenium and metal concentrations in different waste streams. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2016.01.064.

References


