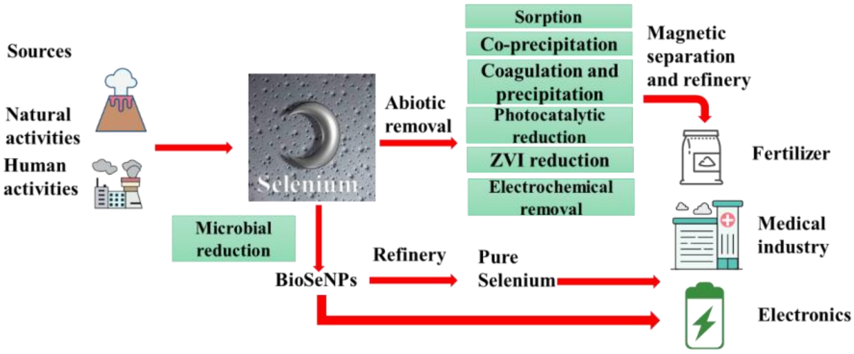
Graphical Abstract



Highlights:

- Biogeochemical cycling of Se presents opportunities for Se recovery
- Se recovery is urgent from both environmental and economic perspectives
- Bioreactor design and morphology control of BioSeNPs are critical for Se recovery
- Magnetic separation after remediation techniques is promising for Se recovery

Selenium (Se) recovery for technological applications from environmental matrices based on biotic and abiotic mechanisms

Zhongli Wang[1], Yanming Wang[2], Rachel L. Gomes[1], Helena I. Gomes[1]

[1] Food Water Waste Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

[2] Sustainable Process Technologies Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

*Corresponding author.

Zhongli Wang: Tel: +44 7925900241; E-mail: Zhongli.Wang@Nottingham.ac.uk; Zhongli.Wang.Xu@Outlook.com

Abstract:

Selenium (Se) is an essential element with application in manufacturing from food to medical industries. Water contamination by Se is of concern due to anthropogenic activities. Recently, Se remediation has received increasing attention. Hence, different types of remediation techniques are listed in this work, and their potential for Se recovery is evaluated. Sorption, co-precipitation, coagulation and precipitation are effective for low-cost Se removal. In photocatalytic, zero-valent iron and electrochemical systems, the above mechanisms occur with reduction as an immobilization and detoxification process. In combination with magnetic separation, the above techniques are promising for Se recovery. Biological Se oxyanions reduction has been widely recognized as a cost-effective method for Se remediation, simultaneously generating biosynthetic Se nanoparticles (BioSeNPs). Increasing the extracellular production of BioSeNPs and controlling their morphology will benefit its recovery. However, the mechanism of the microbial production of BioSeNPs is not well understood. Se containing products from both microbial reduction and abiotic methods need to be refined to obtain pure Se. Eco-friendly and cost-effective Se refinery methods need to be developed. Overall, this review offers insight into the necessity of shifting attention from Se remediation to Se recovery.

- **Keywords:** Biogeochemical cycling of selenium; Resource recovery; Selenium oxyanions reduction; Bioremediation.

1. Introduction

Selenium (Se) is crucial for industrial applications and an essential micronutrient for life [1]. Se semiconductor, photoconductor, photoelectrical, and catalytic properties play essential roles in the electronics industry, driving the market need for high purity Se [2, 3]. This element has a narrow range between beneficial and toxic (40 μg day^{-1}< beneficial < 400 μg day^{-1} < toxic) [4]. Se deficiency increases the risk of cancer [5]. However, excessive exposure to Se can cause acute poisonings, such as cardiovascular difficulties and chronic damage to mental and body health [6]. Both human and natural activities can cause Se contamination to environmental matrices, such as mining, petroleum refining, agricultural irrigation, and volcanic activities [7-9]. The extensive use of Se generated a widespread of Se contaminated wastewater, primarily containing soluble Se oxyanions, including selenate (SeO_4^{2-}) and selenite (SeO_3^{2-}) [6, 10].

Se is widely distributed in the Earth crust but with a low concentration (0.05–0.09 mg kg^{-1}), less than any other nutrient element. There is currently no ore from which Se can be mined as a primary product [11]. Currently, the main source of Se is the by-product of copper anode slime [12]. Prospective Se geogenic sources such as phosphorites, black shales and organic-rich sediments for Se supply have been proposed recently [13]. However, the natural occurrence of Se in these sources is not well understood, and the potential linkages between global biogeochemical Se cycling and Se recovery have received limited attention. Bridging these fields will reveal opportunities to support Se recovery and contribute to a resilient environment and circular economy thinking [14, 15].

Abiotic methods such as sorption, coagulation and precipitation are well recognized as effective Se removal techniques. However, they are rarely reported or discussed for Se recovery. These procedures followed by magnetic separation might provide another option for Se recovery [16]. Se removal through microbial reduction has received increased attention from researchers [17, 18]. In most studies, amorphous red Se nanoparticles in the colloidal form (BioSeNPs) were observed [19, 20]. Currently, most studies addressing Se remediation concentrate on the removal efficiency (the percentage of Se that is removed) and removal rate (the amount of Se that is removed in a specific time) of Se but ignore characterization of the Se containing product, which is critical for cost-effective Se separation and recovery [21].

Several reviews have been published on remediation approaches for Se [22-25], or biogenic synthesis of BioSeNPs [26, 27]. However, Se recovery was not fully explored even though there is potential to offset treatment costs and support a circular economy [23]. The main goals of this work are to highlight the importance of Se recovery, review Se remediation methods and their possibility to facilitate Se recovery. Abiotic Se remediation approaches followed by magnetic separation for Se recovery are proposed, and microbial Se reduction is highlighted in this review.

2. Se cycle, contamination, and bioaccumulation

Understanding Se cycles is the basis for understanding Se's environmental impact (Figure 1). Se's biogeochemical cycling can have implications for its recovery. Se normally exists in four valence states in the natural environment: Se(VI), Se(IV), Se(0), and Se(-II). Se(VI) and Se(IV) have high mobility as they are water-soluble and thus can pose health threats, while Se(0) is insoluble and less toxic [28]. Inorganic Se(-II) can be oxidized once it contacts oxygen, and most Se(-II) exists in organic forms such as selenocysteine (SeCys) and selenomethionine (SeMet), or as selenide mineral [28]. Three mechanisms control Se speciation (depending on microbial activities, redox conditions, pH): oxidation vs reduction, mineralization vs immobilization, and volatilization. They affect Se immobilization in the natural environment and Se remediation in wastewater [29]. Globally, 45,000 tons of Se is released into the environment from natural activities per year [30]. Natural sources of Se mainly include volcanic eruptions and biogeochemical processes of Se containing rocks [31]. Volcanoes eject massive amounts of toxic metal elements, including Se, into soils, water and the atmosphere [32]. About 76,000-88,000 tons of Se is released into the environment by human activities each year [30]. Major anthropogenic activities causing Se contamination are mining, fossil fuel combustion, fertilization, and precious metals processing such as copper, silver, and gold [33-36].

The lithosphere is the origin of Se (Figure 1). Rocks contain about 40% of the Earth’s crust’s total Se, mainly in sandstone, quartzite, and limestone [37]. Se can also be found in phosphatic rocks (e.g., phosphate rocks) and sulfur (S) containing rocks (e.g., chalcopyrite, pyrite) due to structural similarities between Se and P or S oxyanion [30, 38, 39]. Biogeochemical processes of rocks such as weathering, rock-water interactions, and biological activities can control Se migration from rocks to other phases and its distribution around the Earth [39]. Se concentration is elevated in the soil as Se fertilizer is adopted for tackling Se deficiency [36]. Some Se hyperaccumulating plants native to seleniferous soils accumulate Se up to 100-fold greater than other plants (15,000 mg·kg^{-1} dry weight) [40]. Various Se tolerant organisms may utilize Se rich plants, thereby facilitating Se transport into the food webs with subsequent cycling in other phases [40].

Annually, 14,000 tons of Se flow from the terrestrial system into the marine system through surface and groundwater [30, 41]. Mediated by microorganisms, Se(0) nanoparticles coated by biopolymer with colloidal stability (BioSeNPs) can be produced. In seawater, the presence of counter cations can substantially decrease the colloidal stability of BioSeNPs in contrast to freshwaters, which results in the concentration of Se on the sediment surface, representing an eventual sink for Se mobile pool [29]. Compared with surface water, groundwater normally contains higher concentrations of Se due to contact with rocks [30, 42]. Besides, Se in the deposited ash from volcanoes, mining and combustion would permeate into the water system through surface runoff and penetration.

Cases of Se pollution around the world and its threat to wildlife are listed in Table 1. In China, the biggest coal producer and consumer, Se released by coalfired power plants in 2020 was estimated to be 459.57 tons [43]. In industrial effluents and process wastewaters, Se concentrations ranging from 0.03 to 1.4 mg L^{-1} were detected due to its presence in crude oil [44]. In mining wastewaters, Se was found with concentrations up to 12 mg L^{-1} [45]. Se biofortification in agriculture for increasing human intake of Se was proposed and proved to be the most viable method for increased human consumption [40]. Se fertilizers have been adopted and increased the Se concentration in the soil, as not all added Se in the soil can be absorbed and used by plants [36]. Plants' uptake efficiency of Se varies from <1% to >50%, which is affected by Se speciation and soil properties [29]. Most of the Se in fertilizers remains in the soil and enters water bodies through soil leaching and surface runoff. Therefore, Se in wastewater increases Se concentration in aquatic or other compartments of the ecosystem without proper treatment. Many studies have reported that fish and birds die due to excessive intake of Se [29]. For example, 19 of the 20 fish species in a Se polluted lake in the US were eliminated [46]. In addition, animals with greater nutritional requirements in aquatic and terrestrial food webs may be overexposed to Se and poisoned [29]. Se contamination has become a concern because of its toxicity and bioaccumulative character in food webs. Thus, Se remediation is imperative [47].

3. Increasing market demand of Se and its circular economy

Due to its photosensitivity and semiconductor properties, Se is widely used in electronics, such as photocells and solar cells which represent about 30% of total Se demand [2, 3, 48]. High-purity Se is the primary and essential light-absorbing medium in photocopiers [49]. Se is also an important physical decolorizer and stain in the glass manufacturing industry, e.g., red lights at intersections are made with Se amended glass [50]. As a result of the continuous improvement in low-carbon energy development, there is an increasing demand for pure Se [51, 52]. For example, magnesium (Mg)-Se batteries have been developed to boost the kinetics of magnesium ions inside Se-based cathodes, as the electric conductivity of Se (1×10^{-3} S m^{-1}) is 25 orders of magnitude greater than that of S (5×10^{-28} S m^{-1}) [53]. BioSeNPs synthesized through microbial reduction have recently received increasing attention [26], and have been reported to be antibiotic, antimicrobial and anticancer agents [54, 55], adsorbent for metal, e.g., Cu, Zn, Cd, dyes and fertilizer, which can immobilize mercury (Hg) [56].

Se is an essential nutrient for humans and animals [36]. Selenoproteins and selenoenzymes are vital in thyroid hormone metabolism [57], immune function [58], and antioxidant defenses [59]. Oral supplements containing Se are popular, with various brands offering different dosages and Se species. Se effectively reduces cancer risk, inhibits oxidation, and supports the immune system [60]. Soil fertilization is one of the major agronomic practices for Se biofortification and plays an essential role in agriculture [61]. Se deficiency has been considered a global health issue that causes endemic diseases, e.g., Kashin-Beck disease in Eastern Siberia, Northern China and North Korea [62, 63]. A survey showed that half to one billion people are Se-deficient around the world [64]. For example, Denmark, Finland, New Zealand, eastern and central Siberia (Russia), and China contain minimal average amounts of Se in their soils [64]. Thus, agronomic biofortification through soil or foliar Se fertilizers has been studied and applied. For example, almost all fertilizers used in Finland since 1985 have Se because of a deficient Se intake in the 1970s (0.025 mg day^{-1}). Before Se supplementation of fertilizers started, the mean human plasma Se concentration in Finland was 0.89 µmol L^{-1}, with the mean plasma Se level reaching 1.4 µmol L^{-1} in the 2010s [65]. The reference range in the United States for plasma Se is about 0.87-2.14 µmol L^{-1} [66]. Serum or plasma Se concentrations are believed to achieve maximum glutathione peroxidases expression at 1.14-1.27 µmol L^{-1} [67]. Se fertilizers can increase the nutritional quality, including vitamin C, soluble protein, which has also been associated with antiviral resistance [68, 69].

Due to increased market demand, Se resources have become critical in recent years [13, 70]. Between 2002 and 2005, Se's (temporary) scarcity had a huge impact on market prices when the price of Se skyrocketed by a factor of 12 [71, 72]. Currently, according to the Shanghai Metals Market, the leading chemical supplier, high purity Se powder costs around 16-18 US$ kg^{-1} [13]. However, Se cannot be exploited through conventional ore exploration as it is extremely scattered. Currently, primary sources of Se are extraction from copper anode slimes and flue gas desulfurization effluents [48, 73]. Se concentrations can be as high as 12 mg L^{-1} in mining wastewater. If a median is taken to be 6 mg L^{-1}, with a recovery efficiency of 83.2%, 5 g Se could be obtained from 1 m^{3} wastewater [48]. The motivation for a cost-effective alternative resource of Se is evident, and economically feasible Se recovery technology is urgent.

4. Se remediation techniques and potential recovery

Se remediation techniques in wastewater can be classified into abiotic and biotic according to whether microorganisms are involved [74-76]. Abiotic Se remediation techniques, including sorption, co-precipitation, coagulation and precipitation, are well-recognized and can be combined with reduction in photocatalytic, zero-valent iron (ZVI), and electrochemical systems. In microbial Se remediation, different mechanisms such as sorption, reduction, transfer to organic materials, and volatilization by microorganisms coexist [77, 78]. Microbial reduction of soluble Se oxyanions to insoluble Se(0) is the dominating microbial Se removal mechanism. It has attracted increasing attention from researchers due to the formation of BioSeNPs and its low cost [74, 79].

Product separation is an indispensable step for achieving Se recovery. Two factors can be optimized for cost-effective BioSeNPs (product of microbial reduction) recovery. These are (1) the morphology of BioSeNPs through adjusting operating conditions of bioreactors and (2) settling by gravity through the configuration design of bioreactors [21]. Compared with BioSeNPs recovery, less attention has been paid to products obtained via the above abiotic Se remediation techniques, mainly because the BioSeNPs from microbial reduction can be applied directly as adsorbents and fertilizer [56, 80]. Combining magnetic separation is an option for achieving low-cost separation of Se containing products through abiotic techniques. However, no related work has been reported. The purity of the recovered Se containing product and its usage depends on the type of wastewater and the adopted technique. To meet the market demand for the high purity Se, recovered Se containing products from wastewater through both microbial reduction and non-biological methods need further refining.

There is limited information available in the literature on the capital and operating costs of Se remediation techniques. A comprehensive review from 2010 compares the available technologies at the time [79]. More recently, a cost evaluation of coagulation and precipitation for Se removal from wastewater using pre-hydrolyzed $FeCl_3$ at full scale was carried out. Reagent cost was estimated as 357 € kg^{-1} Se(IV) with Se(IV) concentration in the range of 30-100 μg L^{-1} [81]. For microbial reduction, the cost of treating 1 kg Se in a mesophilic and thermophilic UASB (up-flow anaerobic sludge blanket) reactor, respectively, is 0.51 and 1.06 € (Se(VI) concentration ranges from 0.78-3.9 mg L^{-1}) [82]. More effort is needed for the cost evaluation of Se remediation. Moreover, assessment of the whole process of Se recovery, including product separation and refining of different methods, should be carried out.

4.1. Abiotic techniques for Se remediation and potential recovery

This review focuses on recent progress about sorption, co-precipitation, coagulation and precipitation of Se oxyanions and their removal by ZVI, photocatalytic and electrochemical systems as abiotic Se remediation techniques. Magnetic separation is an important method usually employed in combination with other separation techniques for elemental recovery (Figure 2) [83-85]. Abiotic techniques combined with magnetic separation could be an option to recover Se from Se contaminated water due to its ease of recycling by simply using an external magnetic force. Compared with microbial recovery of Se, the purity of Se obtained via abiotic techniques followed by magnetic separation will be lower. This section focuses on exploring the technical possibility for implementing Se recovery and encouraging the development of related work.

4.1.1. Sorption for Se removal and potential recovery

Sorption based water treatment is a process through which a substance or a solute, initially present in the aqueous phase, is removed from that phase by accumulation at the interface between the aqueous phase and a solid phase [86]. Sorbents like activated aluminum, activated carbon, iron oxides, and nanoparticles, e.g., metal-organic frameworks and layered double hydroxides, are used for Se removal [87-93]. Sorption can be limited by the selectivity towards the target pollutant, as multiple pollutants exist in wastewater. For example, Se and arsenic (As) always coexist in the leachates of sedimentary rocks, and SeO_4^{2-} is more difficult to remove due to its more stable structure in aqueous solutions than SeO_3^{2-} [94-96]. Selectivity of the branched glutaraldehyde immobilized polyethyleneimine (PEI-GA) resins for Se(VI) in the Se(VI)-As(V) system has been studied [97]. These sorbents can selectively recover Se(VI) from the Se(VI)-As(V) system, especially at pH 2 (i.e., within 50 min, the sorption capacity reached 4.5 mmol g^{-1} PEI-GA (PEI/GA at a weight ratio of 4:1) resin for Se(VI)).

From environmental and circular economy perspectives, the use of Se saturated sorbent needs to be further processed, e.g., separating the saturated sorbent from water for Se recovery. Recently, the application of magnetic sorbent has drawn considerable attention because of the easy recycling by simply using an external magnetic force [98]. Se oxyanions sorption by magnetic sorbents is listed in Table 5, which shows the reported magnetic sorbents have better sorption capacity for Se(IV) than Se(VI). This might be due to the surface properties and functional group of sorbent [99]. In a reported work about the sorption of Se(IV) and Se(VI) at the goethite-water interface, it was suggested that Se(IV) forms a strongly bonded, innersphere bidentate complex [100]. In contrast, Se(VI) forms a weakly bonded, outersphere monodentate hydrated complex [100]. Six different hematite nanoparticles (na-Fe_2O_3), in terms of shape, size, and surface area, were used to assess how particle morphology affects the sorption capacity of nano-metal oxides for Se(VI) [93]. The results showed that surface area and size alone do not regulate the na-Fe_2O_3 sorption capacity of Se oxyanions. In contrast, the crystal surface structure affects both the adsorption capacity and mechanism. Explicitly, {0 1 2} facets (a crystal surface structure) promote adsorption of Se(VI) and Se(IV) over {1 1 0} facets. The absence of the {1 1 0} facet has a greater effect on Se(VI) adsorption than that of Se(IV). {1 1 0} and {0 1 2} facets bind Se(IV) via inner-sphere complexes with albeit {1 1 0} binds bidentate binuclear complexes, while {0 1 2} binds via bidentate mononuclear complexes. Se(VI) binds to na-Fe_2O_3 primarily through outersphere complexes with some proportion of innersphere complex dependent on the specific facet [93].

A strategy to enhance sorbents' capacity for Se(VI) to achieve efficient removal of total Se from wastewater containing both Se(VI) and Se(IV) is to combine selected sorbents with a material with a higher association constant for binding Se(VI), such as chitosan (3.048×10^{-3} for Se(VI) and 1.990×10^{-4} for Se(IV), respectively). Impregnating aluminum oxide (n-Al_2O_3) on chitosan beads (AICB, 0.0903 g n-Al_2O_3 g^{-1} chitosan) allowed to improve the adsorption capacity for Se(VI) from 9.35 mg g^{-1} n-Al_2O_3 to 20.11 mg g^{-1} AICB [91]. Further studies should be carried out for enhancing Se(VI) sorption by different magnetic sorbents. Moreover, whether chitosan affects magnetic sorbent's magnetic characteristics needs to be verified to achieve Se recovery via sorption combined with magnetic separation.

From the Se resource recycling perspective, biochar is an excellent sorbent and an agent for agricultural and environmental applications [94-96]. Compared with N and P, the sorption of Se by biochar has not received enough attention. Present studies using biochar for Se sorption aim to optimize the immobilization of Se in soil [101], and sorption of Se from aqueous solutions [102]. Several recent works focused on Fe-biochar for Se removal from water and soil [95, 101, 103]. In these studies, the modification of biochar by Fe(III) or ZVI considerably improves the sorption capacity of Se(VI) and Se(IV) from the water phase to the modified biochar. The application of Se saturated magnetic biochar as fertilizer might be an ideal solution as the recovery of high purity Se is challenging due to the presence of competitive anions such as PO_4^{3-}, SO_4^{2-}, and NO_3^-. However, no work focused on the application of Se saturated biochar as fertilizer has been reported.

A Se saturated sorbent-iron(III) modified zeolite (Fe(III)-MZ) has been tested as a soil supplement to cultivate *Pleurotus ostreatus* mushrooms [104]. In this work, the dried mushrooms showed that the amount of sorbed and organically transformed Se is greater (>200 μg g^{-1}) than in a control system (0.071 ± 0.01 μg g^{-1}). This finding proves that certain Se saturated sorbent can promote the sorption of Se by plants. However, factors such as the presence of other (toxic) pollutants and whether the sorbent is an environmentally friendly material must be carefully considered [105]. To achieve the application of recovered Se through adsorption/desorption, the desorption ability of Se saturated sorbents should be considered and evaluated in water/soil systems. However, the desorption ability of Se saturated sorbent, especially in soil, has received less attention than sorbents' adsorption ability.

Se release by Se loaded Fe(III)-MZ has been investigated in water and soil at different pH [105]. The results showed that the pH does not affect the Se release trend from Fe(III)-MZ in an aqueous solution. In contrast, the Se release proportion from Fe(III)-MZ increases with lower soil pH (the content of Se in the soil was 0.82 mg kg^{-1} and 0.67 mg kg^{-1}, and the release proportion was 13.84% and 11.39% when 0.50 g Se saturated Fe(III)-MZ was added into the soil at pH was 7.8 and 10.8, respectively). Another critical parameter is the amount of Se saturated Fe(III)-MZ applied. In this study, the content of Se in the applied soil reached 0.82 and 1.13 mg kg^{-1}, and the release proportion was 13.84% and 9.52 % when 0.50 and 1.00 g Se saturated Fe(III)-MZ was added at pH 7.8. This work demonstrated that Se release from a sorbent is affected by the conditions of desorption. However, Se's mobility in soil is complex. Many unanswered questions remain, e.g., how is it affected by the soil properties such as organic matter, texture, and microbial structure after its release from sorbents. Before actual application, the release of Se loaded on the sorbent must be evaluated.

4.1.2. Co-precipitation for Se removal and potential recovery

Co-precipitation, in this review, refers to the immobilization of a trace element in a mineral during the crystal growth of other elements. Barite ($BaSO_4$) can work as a host phase of Se in the natural environment [106, 107]. Se(IV) uptake by barite depends on pH, coexistent calcium ions (Ca^{2+}), and SO_4^{2-} concentration in the initial solution, possibly due to the effects on the chemical affinity and structural similarity of SO_4^{2-} and SeO_3^{2-}. Se(VI) uptake by barite is strongly inhibited by SO_4^{2-} in the initial solution due to the structural similarity of SO_4^{2-} and SeO_4^{2-} [106, 107]. Se species' incorporation into barite formed in marine sediment was discovered in a hydrothermal vent system near Okinawa [107]. This also explains why marine sediment is a pool of Se resources.

Se species' co-precipitation has also been reported during the formation process of minerals such as hematite (iron(III) oxide, Fe_2O_3, α-Fe_2O_3), goethite (α-FeO(OH)), magnetite (iron(II, III) oxide, $Fe(II)Fe(III)_2O_4$), and green rust [108-110]. Mineral phases containing reduced iron species (i.e., Fe(II)) can reduce Se oxyanions under anoxic conditions [111]. The Se and Fe(II) interaction leads to a nanoparticulate iron selenide phase (FeSe), which is oxidized and transformed into trigonal elemental Se during the gradual oxidation process of the aquatic system [111]. Se is retained regardless of whether the oxidation of the unstable iron oxides leads to the formation of pure magnetite or other iron oxide phases, e.g., goethite [111]. The possibility of Se incorporation into magnetic minerals followed by magnetic separation should be studied for Se recovery, especially for *in-situ* Se recovery. This will provide new insight into geochemical Se immobilization and mobilization.

4.1.3. Coagulation and precipitation for Se removal and potential recovery

Se removal can be achieved by coagulation and precipitation, a widely used water treatment process in drinking water plants to allow flocculation for precipitation [112]. The addition of a coagulant to the water will promote coagulation. Dissolved Se can be sorbed by destabilizing stabilized charged particles and forming agglomerates [86]. Aluminum (Al) and iron (Fe) salts, e.g., aluminum sulfate ($Al_2(SO_4)_3$), ferric sulfate ($Fe_2(SO_4)_3$) and ferric chloride ($FeCl_3$), are the most used coagulants. The Fe(III)-based coagulant was more effective than the Al^{3+}-based one in removing Se [113]. For example, the removal efficiency of Se(IV) by $FeCl_3$ can reach above 98% at dosages of more than 0.4 mmol Fe L^{-1} when the initial Se(IV) concentration was 250 μg L^{-1}. In comparison, the maximum removal efficiency of $AlCl_3$ was about 80% at the dosage of 1.2 mmol Al L^{-1} [113]. The removal of Se(IV) by coagulation was much more effective than that of Se(VI) [113]. For example, at the dosage of 0.4 mmol L^{-1} Fe or Al, the removal efficiencies of Se(IV) were twice as high as those of Se(VI) [113]. High coagulant dosage and weakly acidic pH conditions favored Se removal [113]. The coexistence of other anions impacts the removal [113, 114]. The negative influence on Se(IV) removal among the tested four oxyanions followed the order: $PO_4^{3-} > SiO_3^{2-} > CO_3^{2-} > SO_4^{2}$ due to each oxyanions' binding with the surface sites of metal hydroxides [113].

Electrocoagulation is a well-known technique for removing metalloids (including Se oxyanions) from wastewater [115, 116]. Electrocoagulation consists of generating a coagulant *in situ* through the dissolution of the metal anode while generating hydroxyl ions (OH^-) and hydrogen gas (H_2) at the cathode and anode, respectively. This process produces hydrous ferric oxide (HFO). Se(IV) is sorbed by HFO and its sorption efficiency changes with pH. Se(IV) will be removed from wastewater because SeO_3^{2-} can be sorbed onto metal oxyhydroxides, while SeO_4^{2-} presents low sorption and poor precipitation characteristics [117, 118]. This technique has been successfully tested in petroleum refining wastewater using a 1 L cylindrical acrylic cell [114]. Other chemical species such as PO_4^{3-} and SO_4^{2-} in the wastewater can reduce the removal efficiency of Se due to the competition for active binding sites of iron hydroxide formed in the electrocoagulation process, which lengthen the treatment time. The increased treatment time also increased the energy required per mg of removed Se. The increase in the current density has a notable effect on the removal efficiency. For 240 min of treatment, when the current density increases from 76.7 A m^{-2} to 153.4 A m^{-2}, the removal efficiency is almost doubled [114]. The next step should focus on how to upscale this technique to field application in terms of the configuration of the reactor, the applied current, and maintenance of the electrodes [119].

Magnetic seeding coagulation is a process where magnetic particles are added to coagulate with other particles to form magnetic flocs with improved settleability [120]. Magnetic seeding combined magnetic separation techniques have been used for heavy metal removal from wastewater since the 1970s [121, 122]. Magnetite (Fe_3O_4) is one of the most used magnetic seeds for water treatment [123]. Electrocoagulation has been reported to produce Fe_3O_4 particles using steel electrodes to form magnetic flocs, lowering the operating cost and the waste volume because this avoids preparing ferric/ferrous solutions at high-pH conditions [124]. Recently, magnetic seeding of Fe_3O_4 followed by magnetic separation has been applied in P recovery and As removal [125, 126]. Although coagulation and electrocoagulation can effectively remove Se oxyanions, magnetic seeding combined with magnetic separation has not been applied for Se removal and recovery [127]. The obtained Se containing flocs can be further processed for pure Se.

Sodium sulfide (Na_2S) is an effective precipitant for SeO_3^{2-} [128]. Removal/precipitation of Se with Na_2S from weakly acidic SO_4^{2-} solutions containing

300 mg L^{-1} of Se(IV) at 23 °C was achieved [128]. The precipitation reaction starts as soon as the Na_2S is added to the Se-bearing synthetic wastewater and completes within 10 min. The orange selenium sulfide (SeS_2) precipitates were aggregated and dense in an easily filterable precipitate. Elevation of pH above 7 leads to the SenS8−n solid solution structure breakdown and the formation of individual colloidal Se(0) particles [128]. The precipitation of SeO_3^{2-} by Na_2S and filtration of SeS_2 precipitates followed by pH elevation to release elemental Se might be a solution to achieve fast Se recovery from wastewater.

4.1.4. Photocatalytic systems for Se removal and potential recovery

Photocatalytic reduction is one of the most advanced wastewater treatment methods. It is potentially energy self-sufficient as it can use solar energy [129]. The mechanism of Se oxyanions reduction by TiO_2 is shown in Figure 3. To the authors' best knowledge, although diverse photocatalysts have been studied for aqueous oxyanions removal from water, the only well-studied photocatalyst for Se oxyanions is TiO_2, which was first studied by Sauki et al., in 1999 [130-132]. The existing literature has overlooked the role of other types of photocatalysts in exploring SeO_4^{2-} and SeO_3^{2-} reduction. In a recently published review, studies about photocatalytic reduction of SeO_4^{2-} and SeO_3^{2-} were summarized. However, they did not cover Se removal or recovery [132].

Different types of commercially available TiO_2 powder: Millennium PC500 (374 $m^2\ g^{-1}$), PC50 (53 $m^2\ g^{-1}$), and Degussa P25 (48 $m^2\ g^{-1}$) were tested for reduction of Se oxyanions to Se(0) [133]. Results showed that Millennium PC500, with the highest surface area, performed better sorption and photoreduction of Se oxyanions. Being sorbed on the surface of the photocatalyst is the prerequisite for photoreduction. In this process, all TiO_2 powders showed substantial sorption to SeO_3^{2-} and SeO_4^{2-} (i.e., 12.9 ±0.8 mg g^{-1} PC500 for 20 mg L^{-1} SeO_3^{2-}, 6.4 ±0.48 mg g^{-1} PC500 for 20 mg L^{-1} SeO_4^{2-}). Common co-existing anions, especially molybdate (MoO_4^{2-}) and SO_4^{2-}, can inhibit the sorption of SeO_4^{2-} on TiO_2 by competitive sorption [134-136]. However, there is no report on the sorption of SeO_4^{2-} on TiO_2 under the interference of other anions (e.g.,

NO_3^-, PO_4^{3-}, and metal oxyanions). Photocatalytic reduction of SeO_3^{2-} proceeded much faster than SeO_4^{2-} (i.e., 20 mg L^{-1} of SeO_3^{2-} needed 2 h for its complete removal from solution while 4 h were needed to remove 20 mg L^{-1} of SeO_4^{2-} with Millennium PC500 in [133]). The presence of common co-existing anions such as SO_4^{2-}, NO_3^-, PO_4^{3-}, and the reduction from SeO_4^{2-} to SeO_3^{2-} are big challenges of using TiO_2 for Se recovery in terms of the reduction efficiency of Se oxyanions and purity of the recovered Se product.

The endpoint of SeO_4^{2-} and SeO_3^{2-} reduction by TiO_2 can be Se(0) and/or Se(-II) as shown in Figure 3 [131, 137]. A challenge for Se recovery using TiO_2 is how to control the reduction's endpoint, which can be tackled by metal deposition on the TiO_2 surface and the addition of electron scavengers to the reaction system [137]. The noble metal deposit can affect the reduction potential of the electrons [137]. With a more positive reduction potential, the less likely the photogenerated electrons can reduce the Se(VI)/Se(0) reduction couple (E^0 = 0.5 V vs the standard hydrogen electrode (SHE)). For example, Ag, Au, Pt and Pd have varying work functions of -0.18 eV, 0.66 eV, 0.76 eV, and 1.06 eV vs SHE. Pd–TiO_2 catalysts allow greater product selectivity towards Se(0) than Ag-TiO_2, Au-TiO_2 and Pt-TiO_2 [137, 138]. Formic acid has been reported as the most effective organic scavenger for enhancing Se oxyanions photoreduction by TiO_2. Moreover, Se(0) was only produced in formic acid and was enhanced without oxygen in reported studies [131, 138, 139]. Although the final product has been proved to be controlled, the conversion efficiency of SeO_4^{2-} to Se(0) is still low, i.e., 40% for Pd–TiO_2 [137].

There is potential for Se remediation and recovery through photoreduction. However, this technique is not yet technologically and economically applicable for commercial scale as the most studied catalyst in Se removal-TiO_2 can only be activated by near UV irradiation (less than 5% of the total solar spectrum) [140]. Future work should explore Se reduction by different types of photocatalysts. It is also necessary to develop a photocatalytic system applied under visible and/or solar light irradiation for commercial scale Se remediation and recovery [140]. Another challenge in applying cost-effective photocatalytic reduction for Se recovery is how to improve the recovery of reduced Se products and used photocatalysts. A novel magnetic photocatalyst C-

TiO_2@Fe_3O_4/AC was recently prepared and had both C-TiO_2 and F_3O_4 loaded together onto magnetic activated carbon (AC). This magnetic photocatalyst could be an attractive choice due to its low band-gap of 2.535 eV, visible light catalytic activity, stable structure, and magnetic separation characteristics [141]. However, this photocatalyst has not been tested on Se removal and recovery.

4.1.5. Se removal, immobilization, and potential recovery by zero-valent iron (ZVI) system

Se removal can be achieved by chemical reduction as Se(0) is insoluble and less toxic than highly soluble Se(VI) and Se(IV) [142]. The most popular Se oxyanions reducing agent is zero-valent iron (ZVI) [142]. The application of ZVI in groundwater treatment began in the early 1990s when granular ZVI was first used in permeable reactive barriers (PRBs) systems [143, 144]. Compared to the conventional pump-and-treat technology, the ZVI-PRB technology is more efficient and substantially less expensive [145]. ZVI technology has been widely used in pilot and large scale field applications in the past few decades, as ZVI is readily available, relatively inexpensive, and nontoxic [146, 147]. Depending on the pH and redox potential, the endpoint of SeO_4^{2-} reduction can be SeO_3^{2-}, Se(0), and Se^{2-} [31]. Both chemical reduction and sorption by corrosion products occur during this process (Figure 4) [142]. From an environmental perspective, the identification of Se oxyanions reduction products and ZVI oxidation products can determine the transformation of ZVI to iron oxide and immobilization of Se(VI) in soils, sediments, and aquifers [142].

During the Se(VI) reduction process, ZVI is oxidized to Fe(II) and reacts with hydroxide (OH^-) to form ferrous hydroxide ($Fe(OH)_2$) at the corroding ZVI surface [142]. The $Fe(OH)_2$ can be further oxidized to green rust, magnetite, lepidocrocite, ferrihydrite, or goethite [148-151]. It has been reported that the main factor for Se(VI) reduction, sorption and iron corrosion coating was Se(VI) concentration [142]. With 10 mg L^{-1} Se(VI) concentrations as the initial concentration and 1 g L^{-1} ZVI as the electron donor, Se(VI) was completely reduced to Se(0)/Se(-II), and magnetite was formed. However, Se(VI)/Se(IV) was partially sorbed on the ZVI surface, and lepidocrocite was formed when initial Se(VI) concentrations were >50 mg L^{-1}. In addition, Fe(II) may have facilitated the autoreduction of lepidocrocite to magnetite [142]. From the viewpoint of electron transfer, magnetite can be considered a semiconductor (10^2–10^3 Ω^{-1} cm^{-1}) and is believed to facilitate the electron transfer from the ZVI core to the solid-liquid interface [152]. At the same time, lepidocrocite has poor conductivity (bandgap of 2.3 eV) and is mainly responsible for the passivation of ZVI [153]. However, lepidocrocite shows better sorption affinity for Se(VI) in the presence of Fe(II) [153]. Excessive generation of lepidocrocite would block the electron transfer pathway [154].

The surface passivation of ZVI considerably restricts the application of ZVI technology. Acid washing, ultrasonication, H_2 reduction, microwave, nano-sized ZVI technology, and weak magnetic field have been developed to address this issue [155-160]. However, these techniques are far from satisfactory to implement in full-scale applications due to high capital and operational costs. Recently, using H_2O_2/HCl to conduct ZVI pre-corrosion allowed SeO_4^{2-} removal efficiency to improve from 65% to 95% in 8 h with Se(0) as a product [154]. In this study, the pathways of Se(VI) removal by pre-corroded ZVI were identified as the following processes in sequence: contact of Se(VI) with the solid surface, reduction of Se(VI) to Se(IV), immobilization of Se(IV) via inner-sphere complexation, further reduction of the immobilized Se(IV) to Se(0) in the solid phase. Finally, most Se (78.2%) was immobilized as Se(0) [154].

Based on the magnetic susceptibility of ZVI and Fe bearing minerals, several studies have assessed the suitability of magnetic separation following the ZVI amendment to remove heavy metals such as Cu, Zn, Cr from contaminated soils [161-163]. However, ZVI amendment combined with magnetic separation for Se recovery has not been reported. A magnetic separation process should be carried out to separate the residual ZVI particles and attached iron (hydr)oxides, thus minimizing the re-release risk of immobilized Se and achieving Se recovery [127].

4.1.6. Electrochemical systems for Se removal and potential recovery

Electrochemical systems have been employed to transform or destroy contaminants [164]. In these systems, one or more electrons are acquired on the cathode surface during direct current flow through the system (anode, cathode, and electrolyte solution). Generally speaking, the oxidation half-reaction occurs at the anode, while the cathode is where reduction occurs and electrons are gained [165]. Se oxyanions can be removed by direct electrochemical reduction on the cathode surface or by indirect chemical or physicochemical transformations in the electrolyte, depending on the anode material [117, 166-169]. Comparison and mechanisms of direct electrochemical reduction (DER) and indirect Se removal by electrochemical systems are illustrated in Figure 5.

In an electrochemical system with a sacrificial iron anode, iron dissolution is the dominant reaction on the anode (Figure 5) [166]. Depending on the electrolyte pH, the ferrous ions might subsequently form ferrous hydroxides ($Fe(OH)_2$) in a mixed cell [166]. The basic mechanisms of indirect Se removal have been investigated in batch electrochemical systems by comparing reactive iron anode and inert anode with a copper plate as the cathode in a bicarbonate medium (pH 7) [117]. SeO_4^{2-} removal in this system is due to the formation of $Fe(OH)_2$ precipitates instead of direct cathodic reduction. The SeO_3^{2-} reduced from SeO_4^{2-} can be further reduced to Se(0) or Se(II) [117]. Later, this electrochemical system was enlarged to a flow-through sand column incorporating a pair of electrodes (iron electrolysis) to simulate the *in situ* application in a permeable aquifer for SeO_4^{2-} remediation [170]. The removal rate of SeO_4^{2-} was proportional to the contact time and the yield of $Fe(OH)_2$ or ferrous carbonate. This study demonstrated the electrochemical system’s effectiveness in removing SeO_4^{2-} in a single well [170]. While the indirect electrochemical method can provide reliable Se removal performance for *in situ* remediation, solids that need management are produced. Se recovery from the generated solids can be a strategy to minimize the secondary pollution. Further research should be carried out to offset the management costs.

Direct electrochemical reduction (DER) has been intensively used in industrial Se plating (known as electrodeposition) for decades on metal surfaces, such as gold, silver, nickel, and iron [171]. Se oxyanions in the substrate are reduced to Se(0) during the DER process, forming a thin layer on the target metal surface [172]. A soft-template, cetyltrimethylammonium bromide (CTAB), had been used and synthesized single-crystalline Se nanotubes (10-30 μm) on the surface of a gold sheet electrode by cyclic voltammetry [173]. The advantages of using CTAB as a template are that it can be easily washed away from the products with hot water and can modify the morphology of produced Se(0) by changing CTAB concentration and electrochemical parameters of the system [172, 174].

Although Se ions can be successfully electrodeposited, the recovery ratio of Se is necessarily limited by the low Se concentration in wastewater. To enhance electrochemical Se recovery performance, a cyclone electrowinning reactor was employed to treat a strongly acidic copper refining wastewater (pH 0.3 and 3.8 mM Se). In this study, 97.6% of Se(IV) was successfully recovered via DER using low-cost stainless steel cathodes in 90 min with nano-sized and mesoporous Se(0) produced [167]. However, the Se electrochemical deposition mechanism is complex due to its several oxidation states, especially for environmental applications of Se removal and recovery [172]. To understand factors affecting DER performance for Se recovery, a three-electrode electrochemical system with gold as a working electrode was employed to evaluate Se reduction's thermodynamic and kinetic performance [175]. This work found that Se reduction via DER is a robust process that can deal with weakly acidic solutions (pH 4−7) containing 0.001−10 mM Se(IV). Se(IV) can be electrochemically reduced from the aqueous phase through either a four- or six-electron pathway. The former generates Se(0) directly attached to the electrode surface, and the latter produces Se(-II) that is subsequently converted to Se(0). The four-electron pathway is a surface-limited process below 70 °C. It terminates when the cathode is fully covered with the insulative amorphous Se(0).

Reducing SeO_4^{2-} to SeO_3^{2-} is a critical challenge in applying DER in wastewater or natural water treatment due to the necessity of anion structure change and the high activation energy required to break the Se=O double bond. Other oxyanions, e.g., SO_4^{2-}, NO_3^-, NO_2^-, PO_4^{3-}, and metal oxyanions that complex water matrices can trigger cathodic parasitic reactions to compete with Se removal via DER or lead to co-deposition with Se [175]. However, DER approaches offer several advantages over indirect electrochemical Se removal, including selective Se removal when the cathode potential is precisely controlled, less solids generation, and direct Se recovery on the cathode.

The major drawback of electrochemical systems is that electricity and working electrodes generate extra operation costs [204]. For example, operating costs of landfill leachate treatment amounted to 465.2 kWh m^{-3} (240 min of reaction time at 200 mA cm^{-2}) with a cost of 55.8 € m^{-3} influent, while for the combined microbial compartment with the electrochemical oxidative treatment, the total cost was 18.7 € m^{-3} [205]. However, Se removal by electrochemical systems requires less time than biotic methods. Moreover, it is cleaner and environmentally friendly than other abiotic methods. Future studies about reactor design optimization, electrode modification of electrochemical systems are also needed for more energy and cost-effective Se removal and recovery [175, 176].

4.2. Se remediation, BioSeNPs synthesis and recovery through microbial reduction

There are different mechanisms of Se oxyanions reduction and fabrication of BioSeNPs by different bacteria. Only a few species such as *Thauera selenatis*, *Enterobacter cloacae* SLD1a-1, and *Bacillus selenatarsenatis* SF-1 have been well studied regarding the enzymes involved in SeO_4^{2-} reduction [177]. However, microorganisms’ reduction shares four common steps for BioSeNPs formation (Figure 6): (i). Se oxyanions transportation into the cell; (ii) Se oxyanions reduction to Se(0); (iii) the exportation of Se(0) nuclei out of the cell; (iv) BioSeNPs assembly. Steps (i) and (iii) are not essential for forming BioSeNPs when the BioSeNPs form extracellularly [178]. For extracellular Se oxyanions reduction, only steps (ii) and (iv) are involved. The overall microbial Se oxyanions reduction process is illustrated in Figure 6.

4.2.1. Microbial Se oxyanions reduction and its affecting factors

The potential of microorganisms to mediate the Se cycle was first hypothesized in 1964 [179]. The reduction of SeO_4^{2-} to SeO_3^{2-} and Se(0) coupled with *Salmonella Heidelberg*'s aerobic growth was observed in 1966 [180]. Certain SeO_4^{2-} reducing bacteria can also perform SeO_3^{2-} reduction, which has a vital role in Se remediation and recovery [181, 182]. However, SeO_4^{2-} reduction has been shown to result in SeO_3^{2-} accumulation in bioreactors inoculated with certain single SeO_4^{2-} reducing bacteria [183, 184]. The understanding of bioreduction of Se oxyanions progressed in the 1980s and 1990s, with the recognition that sulfate (SO_4^{2-})-reducing bacteria (SRB) are also able to reduce SeO_4^{2-}, due to shared analogous biochemical and geochemical reactions [25, 181]. Since then, various microorganisms with Se oxyanions reduction ability through different pathways and forming Se(0) at different locations have been identified and separated (Table 2) [23, 181, 185].

The reduction of SeO_4^{2-} can be inhibited by other electron acceptors, with SO_4^{2-} and NO_3^- being the most studied coexistent pollutant in Se reduction [186]. It has been reported that SO_4^{2-} in wastewater inhibits SeO_4^{2-} reduction by bacteria such as *Comamonas testosteroni S44* [187]. In addition to SO_4^{2-}, NO_3^- is also often abundant in wastewater [188-190]. In a study about a pure culture (though species not identified) isolated from a freshwater marsh, SeO_4^{2-} was used as an electron acceptor only when NO_3^- was absent [189]. However, not all bacteria performing SeO_4^{2-} reduction can be inhibited by NO_3^-. For example, the presence of NO_3^- did not inhibit SeO_4^{2-} reduction in SeO_4^{2-}-grown *Thauera selenatis* as it synthesizes independently NO_3^- and SeO_4^{2-} reductases in different locations within the cell [191]. Besides SO_4^{2-} and NO_3^-, SeO_4^{2-} reduction is also inhibited by the presence of other electron acceptors, such as O_2, CrO_4^{2-}, or MnO_2 [186].

Another challenge in using a single microbial strain to remove Se from wastewater through reduction is that Se often coincides with the high salinity in industrial wastewaters [77]. In Se refinery wastewater, typical concentrations of Se and salinity range from 13.2 to 74.0 mg L^{-1} and 6-7%, respectively [192]. Inhibition of Se reduction caused by salinity was observed for *Pseudomonas stutzeri* NT-I, with reduction efficiency for SeO_4^{2-} and SeO_3^2 considerably decreased from 100 % at 0.5 % (w/v) NaCl to 40% at 2% (w/v) NaCl [193]. Thus, it is crucial to select suitable strains with Se oxyanions reduction ability in target wastewater under certain operating conditions, e.g., *Pseudomonas stutzeri* NT-I has been reported to reduce SeO_4^{2-} to Se(0) efficiently without prolonged accumulation of SeO_3^{2-} under aerobic conditions [193].

Mixed cultures from activated sludge have been adopted for treating SeO_4^{2-} containing mine wastewater (containing 3 % (w/v) NaCl) with excessive acetate as the electron donor under oxygen-limited conditions, with 98% of 395 mg L^{-1} soluble Se was removed within 7 d [19]. The composition of the microbial community shifted to overcome salinity inhibition. Besides, there is a synergy between bacteria in diverse and complex bacterial communities that resist environmental changes and reduce SeO_4^{2-} reduction inhibition when multiple pollutants are present in the wastewater [194-196]. Besides activated sludge, mine site soils and sediments have also been utilized as microorganism resources [197]. Enriched mixed cultures from a metal mine site continuously receiving SeO_4^{2-} containing wastewater have been studied for their ability to reduce and remove dissolved Se from a concentrated brine solution containing NO_3^-, SO_4^{2-}, and other salts (235 mg L^{-1} N, 1730 mg L^{-1} SO_4^{2-}, and 1.87 mg L^{-1} Se) [197]. Successful Se removal with NO_3^- and SO_4^{2-} present was achieved by the symbiotic relationship between the enriched microorganisms and the addition of ZVI [197]. The dominant species of the enriched microorganisms include *Clostridium*, *Sphaerochaeta*, *Synergistes*, and *Desulfosporosinus* species [197].

Other factors affecting microbial Se oxyanions reduction performance include pH, initial Se concentration of the wastewater, and operation conditions of bioreactors such as hydraulic retention time (HRT), dosage of electron donor (reducing agent) and temperature. Different bioreactors' operations under different conditions with their performance are listed in Table 3. However, it is hard to compare the Se oxyanions reduction performance in various types of bioreactors with different inoculum as the enrichment of bacteria or the microbial community is either too complex or not well documented. The complex factors described above can affect bacteria or the microbial community in actual water bodies and must be addressed for scaling up. In extensive research on Se oxyanions reduction using mixed culture as inoculum, e.g., activated sludge, contaminated/uncontaminated soil or sediment, the structure of the microbial community changed with different operating conditions and thus affected Se oxyanions reduction performance [19, 74, 79, 81, 82, 193-197]. Compared with selecting pure cultures or specific consortia as seed for bioreactors, a preliminary work of enriching and isolating functional microbial consortium as inoculum from mixed cultures, shaped by target contaminated water under certain operating conditions that require low maintenance cost is a better solution. In this way, the inhibition effects of other contaminants in actual wastewater can be overcome, and the financial requirements can be satisfied.

4.2.2. Mechanism of microbial reduction of Se oxyanions and synthesis of BioSeNPs

In this review, BioSeNPs (biologically produced Se nanoparticles coated by biopolymer) are considered Se recovery products through bioreduction without further refining treatment. Microorganisms (bacteria and fungi) have been reported in BioSeNPs synthesis and Se recovery (Table 4). Different bacteria or fungi have different Se oxyanions reduction pathways and mechanisms, which might influence Se oxyanions reduction rate, BioSeNPs formation location, size and shape, which consequently affect the separation of BioSeNPs [198, 199]. For example, extracellular polymeric substances (EPS) coated BioSe-Nanospheres (diameters between 20 and 50 nm) showed a 91.6 ± 0.5 % settling efficiency in fresh lake water. In contrast, EPS coated BioSe-Nanorods (lengths between 300 and 700 nm with a median of 570 nm) displayed a settling efficiency of 97.1 ±0.5 % [199].

The transportation of SeO_4^{2-} and SeO_3^{2-} into cells is the first step of Se metabolism [200]. Transporters for structurally similar oxyanions, e.g., SO_4^{2-} and PO_4^{3-}, can uptake Se oxyanions [201, 202]. SeO_4^{2-} and SeO_3^{2-} can enter the *E. coli* cells through the sulphate permease system (cysA, cysU, cysW) [203, 204]. Through engineering PO_4^{3-} transporters from *Saccharomyces cerevisiae* into *Rhodotorula glutinis* X-20, Se content in the cell was increased by 21.1% and reached 5349.6 μg g^{-1} with SeO_3^{2-} as the Se source [202]. However, the Se uptake pathway is not well documented, and no specific Se oxyanions uptake system has been reported. From the perspective of Se recovery, reducing the Se uptake by cells may enhance the production of extracellular BioSeNPs, which might be achieved by gene regulation and modification.

Several reviews have summarised the Se oxyanions reduction processes by bacteria [182, 205, 206]. It is well recognized that microbial SeO_4^{2-} reduction to Se(0) can be represented by equations (1) and (2). The reduction of SeO_4^{2-} and SeO_3^{2-} can occur both intracellularly and extracellularly mediated by reductase and other biomolecules (Figure 6) [177]. The bioreduction of SeO_4^{2-} to SeO_3^{2-} is primarily catalyzed by either a soluble or membrane-bound selenate reductase (Ser) [182]. In comparison, the microbial conversion of SeO_3^{2-} to Se(0) is widely recognized as a detoxification strategy, whereby the toxic and soluble Se is converted to solid Se(0). During the detoxification process, various biomolecules, including glutathione, glutaredoxin, and siderophores, facilitate the conversion of SeO_3^{2-} to Se(0) [182]. There are also reported studies using extracted biomolecules such as cytochrome c, glutathione, and β-carotene as reductants to synthesize Se nanostructures at room temperature [207-209]. EPS, which contains various functional groups including carboxyl, phosphoric, amine, and hydroxyl groups, also has an unrevealed function in extracellular Se oxyanions reduction [187-191]. The reduction of SeO_3^{2-} by EPS has been confirmed [194]. However, the specific component in EPS and enzyme responsible for Se oxyanions reduction is still poorly understood and documented. Further studies should be conducted to reveal the Se oxyanions reduction enzyme, biomolecule and EPS components for low-cost Se recovery through large scale cell-free reduction of Se oxyanions.

$$SeO_4^{2-} + 2e^- + 2H^+ \rightarrow SeO_3^{2-} + H_2O \qquad (1)$$

$$SeO_3^{2-} + 4e^- + 6H^+ \rightarrow Se(0) + H_2O \qquad (2)$$

For steps (iii) and (iv), there are different opinions. It has been proposed that BioSeNPs are formed by binding amorphous Se(0) and protein Se factor A (sefA) before being exported by *Thauera selenatis* (Figure 6) [210]. For *Stenotrophomonas maltophilia*, it has been suggested that the Se(0) is produced intracellularly and exported outside the membrane. Then amorphous BioSeNPs is formed [211]. Although some authors claim that larger selenospheres are formed through Ostwald ripening until caped by agents such as EPS and protein, larger selenosphere formation from Se(0) is not well studied [23, 178, 212]. Moreover, how the BioSeNPs are exported through the membrane is still unknown [23, 178]. Although there is not enough research concentrating on the fabrication and exporting process of BioSeNPs, protein and enzyme involvement may substantially influence the morphology of BioSeNPs [213]. Bacterial SeO_3^{2-} reduction by *Azospirillum brasilense* was studied using the efflux pump inhibitor carbonyl cyanide m-chlorophenylhydrazone (CCCP). In this case study, only intracellular Se crystallites were produced because CCCP blocked the membrane export of Se(0) nuclei [214]. From the perspective of Se recovery, bacteria with efflux pump overexpression can boost the presence of extracellular BioSeNPs. In the most reported cost-effective Se removal studies, mixed cultures, e.g., activated sludge and sediment, were employed as microorganism resources, especially for *in situ* remediations [215, 216]. In this case, mechanisms discussed above, including intracellular/extracellular Se oxyanions reduction and BioSeNPs assembly, occur [215, 216].

4.2.3. BioSeNPs production and its recovery from wastewater

The recovery of BioSeNPs from wastewater is attracting attention from researchers worldwide [12, 217, 218]. However, other pollutants such as PO_4^{3-}, S, Ca, especially metal ions in wastewater, can be trapped with the BioSeNPs [199, 219]. The purity of the recovered Se depends highly on the type of wastewater, which might affect its application. It has also been reported that the recovered BioSeNPs produced by *Pseudomonas stutzeri* NT-I from synthetic wastewater were composed mainly of organic matter and 11-14 mass% Se(0) (biomass unseparated) [219]. For obtaining pure Se, the refining of recovered BioSeNPs from wastewater is necessary.

The BioSeNPs are produced both intracellularly and extracellularly, especially when using mixed cultures [220]. Part of the Se will be trapped in the biomass, and separating the entrapped BioSeNPs for Se recovery can be achieved through cell lysis followed by filtration or centrifugation [221]. However, cell lysis is energy-intensive and involves chemicals that lead to further environmental contamination [220]. A solution to avoid breaking cells is using microbes to reduce Se(0) to volatile methylated selenides and then using chemicals (e.g., nitric acid) to collect the selenides [222]. However, the produced selenides are toxic. To improve Se's recovery efficiency, purity and avoid cell lysis of Se accumulated in the cell or volatile methylated selenides production, maximizing the extracellular production of BioSeNPs is necessary [220].

Different physiological states of growing cell culture, their gradual changes, and the medium components also influence both the Se oxyanions reduction process and BioSeNPs synthesis [223]. Two *Azospirillum brasilense* strains (Sp7 and Sp245) were studied to reduce SeO_3^{2-} to BioSeNPs [214]. Extracellular BioSeNPs can be attained by using bacterial cultures at the end of the logarithmic growth phase (sometimes called the log phase or the exponential phase, a period characterized by cell doubling) [214]. The obtained BioSeNPs sizes depended on the initial Se concentration (~25–80 nm in diameter at 5–10 mM selenite). This study showed that the formation of extracellular BioSeNPs requires normal bacterial metabolic activity [214]. Studies aiming at maximizing microbial Se recovery should test the microorganisms at different conditions to maximize the production of extracellular BioSeNPs.

Certain bacteria can produce extracellular BioSeNPs only. For example, *Bacillus safensis* JG-B5T was reported to reduce SeO_3^{2-} to BioSeNPs extracellularly with decreased colloidal stability than BioSeNPs produced by anaerobic granular sludge and *B. selenatarsenatis* which enables a higher settling efficiency [224]. For instance, at a Na:Se mass ratio of 23 and neutral pH, the ζ-potential of BioSeNPs produced via anaerobic granular sludge and *B. selenatarsenatis* was -35 mV. In comparison, at a much lower Na:Se mass ratio of ~0.80 and neutral pH, ζ-potential was close to -10 mV for BioSeNPs produced by *B. safensis* JG-B5T. The lower colloidal stability of the BioSeNPs produced by *Bacillus safensis JG-B5T* has a strong relationship with the high toxicity of SeO_3^{2-} which induces stress in the microorganisms, making less extracellular protein coating on Se(0). However, in this study, no decrease of total Se and increase of SeO_3^{2-} were observed when SeO_4^{2-} was the only electron acceptor present during the incubation of *Bacillus selenatarsenatis*, which means *Bacillus safensis JG-B5T* is not capable of reducing SeO_4^{2-}. Although BioSeNPs were produced extracellularly in this study, direct cell contact was essential for SeO_3^{2-} reduction by *Bacillus safensis JG-B5T* [224].

A fungus isolated from a soil sample, identified as *Aspergillus terreus*, was used for cell-free extracellular synthesis of SeNPs [225]. Spherical particles with an average size of 47 nm were formed by adding a culture supernatant of *Aspergillus terreus* to SeO_4^{2-} and SeO_3^{2-} solution [225], avoiding the intracellular reduction of Se oxyanions and the formation of SeNPs. Through this cell-free method, the purity of Se in the recovered SeNPs might be enhanced, which can reduce the cost of refining SeNPs to get pure Se [219, 224]. Moreover, the recovery of the final Se production is simplified as no biomass was present and thus no need for the separation of biomass and Se. However, the authors did not adequately describe the produced BioSeNPs, *i.e.,* purity of Se and the functioning enzymes and metabolites in the supernatant.

In the effluent of most studied bioreactors treating Se containing wastewater, BioSeNPs have a diameter of up to 400 nm instead of large crystals [23]. This characteristic and the coated polymer layer allow BioSeNPs to display colloidal properties and remain in the bioreactor liquid phase [23]. The colloidal stability of BioSeNPs also leads to further treatment because part of the BioSeNPs is still present in the effluent and cannot meet the discharge regulatory guidelines. The BioSeNPs from the matrix can be separated by adding chemicals through coagulation and flocculation [226, 227]. Adjusting the pH and/or addition of counter cations is a straightforward method to enhance the settleability of BioSeNPs, which can further decrease the Se concentration in the effluent [72]. For Se removal from the effluent, lower zeta potential means lower cost of chemicals for separating colloidal BioSeNPs [72]. Further research on Se bioremediation should optimize BioSeNPs separation for effective Se removal. However, for Se recovery, adding chemicals will hamper the purity of recovered Se. Physical solid-liquid-biomass separation (i.e., centrifugation, filtration or gravity sedimentation) of BioSeNPs resulting from microbial reduction, which is more eco-friendly as there is no extra addition of harsh chemicals, is influenced by BioSeNPs properties such as size, density and crystal structure [21, 199]. Combining BioSeNPs sedimentation and well-designed configuration of bioreactors, enabling liquid, biomass, and BioSeNPs separation is an optimal method for low-cost Se recovery.

Various morphologies of BioSeNPs have been observed (Table 2) through Se oxyanions reduction by bacteria or fungi. The size of the Se(0) particles produced by microorganisms grows until capped by agents such as proteins, polysaccharides, phospholipids or EPS, which coated the Se(0) with a layer of biopolymer (BioSeNPs). The production of larger particles with higher density (crystalline Se: 4.81 g mL^{-1}) from Se with lower density (amorphous Se: 4.27 g mL^{-1}) is a crucial step to enable easy BioSeNPs sedimentation for Se recovery [21]. In batch and fed-batch reactors using anaerobic activated sludge, grey crystalline hexagonal acicular BioSeNPs were obtained at pH 7, 8 and 50 ℃, while at pH 6, 7, 8 and 9 combined with a temperature lower than 30 ℃, red amorphous nanospheres were dominant [21]. Relatively pure hexagonal Se(0) crystals, which can settle under gravity, were produced in a batch reactor treating an influent containing 120 mg L^{-1} Se(VI) with ethanol as the electron donor and carbon source at 30 ℃ (pH 7) [217]. However, in this study, Se(VI) concentration is much higher than Se(VI) concentration used in other works and common wastewater (Table 1). Moreover, the presence of relatively pure hexagonal Se(0) crystals might be due to the long incubation as the morphology of the BioSeNPs was observed after 229 days [188]. Amorphous BioSeNPs (181 ± 40 nm), produced by *Shewanella* sp. strain HN-41 under anaerobic conditions, were found to transform into extensive, long and thin, polycrystalline Se nanowires and nanoribbons (>100 mm × 57 nm) rapidly in 80% DMSO, a polar aprotic solvent, after 12 h of incubation at 30 ℃ via dissolution–recrystallization processes [228]. This might be an option for resembling amorphous BioSeNPs in the effluent to crystalline BioSeNPs by gravity for Se recovery.

To achieve low-cost Se recovery, reactor design to enable liquid-solid separation is critical. An inverse fluidized bed (IFB) reactor containing low-density floatable biosupport material was investigated [229]. In this reactor, biofilm is formed on the biological carrier material and remains on the top of the reactor. Due to fluidization, BioSeNPs are separated from the biomass and settled at the bottom, so the BioSeNPs are easy to recover. When the IFB operated with hydraulic retention time (HRT) of 24 h and 48 h (influent SeO_3^{2-} concentration of 0.1 mM), 94% and 99% of Se was removed, respectively. Around 45% of Se was recovered as BioSeNPs in both cases. The extended residence time allows agglomeration of amorphous BioSeNPs into larger crystalline BioSeNPs, and the sedimentation rate to the bottom of the reactor is faster. However, small BioSeNPs (< 45 nm) generally do not settle at the bottom of the reactor and get washed out along with the effluent stream and a large part of Se was trapped in biomass, which was not determined in this work. For the separation of treated water, BioSeNPs and biomass, a system with the combination of a fixed bed biofilm reactor, a novel bacterium-nanoparticle separator containing a titled poly-ethylene sheet, and a tangential flow ultrafiltration module was investigated [230]. The three units in the system worked in synergism to achieve separation and recovery. The tangential flow ultrafiltration module retained the biomass in the system, which increased the biomass retention time and allowed for more biomass decay through which intracellular BioSeNPs could be released and recovered. BioSeNPs aggregates were separated from bacterial aggregates due to their different interactions with a tilted polyethylene sheet in the bacterium−BioSeNPs separator. BioSeNPs aggregates stayed on the polyethylene sheet while bacterial aggregates settled to the bottom of the separator [230]. The potential of rotating biological contactor, rotating horizontal packed bed bioreactor, moving bed biofilm reactor to complete Se recovery in the single-stage process have also been discussed in a review paper [194]. However, no work on the use of these bioreactors for Se recovery has been published.

4.3 Refinery of Se containing products

To obtain pure Se, the recovered Se containing products from wastewater treatment need refining [219]. The most used method for getting pure Se from anode slime, currently the primary source of Se, is chemical Se refining. The whole procedure can be summarized into three steps: (i) characterization of the recovered product; (ii) separation of the impurities; (iii) conversion of the captured Se to Se(0) by reduction [73, 231, 232]. The aim of step (i) is to identify the elemental composition of the recovered Se containing product using X-ray diffraction analysis (XRD). Step (ii) can be achieved by adding various leaching agents such as mineral acids and sodium hydroxide [73, 232], or roasting (including oxidation, sulfate, and soda) [233-235].

Although as high as 99% pure Se can be obtained through chemical refining, it has the following disadvantages: complex process, large reagent consumption, low yield, and production of severe pollution [231]. Physical methods such as zone refining and vacuum distillation have been studied for Se refining [231]. However, high concentrations of volatile impurities (1.12% of Te, 0.06% of Cu, and 0.01% Pb) have hindered the purification of Se [231]. An approach combining chemical impurity separation and vacuum distillation was studied, and 70% Se was purified to 99.998% [231]. In this study, hydrogen peroxide (H_2O_2) converted the impurity phases in the Se sludge slurry, thereby decreasing impurities' volatilization in the later distillation process. A vacuum distillation process was carried out to extract Se efficiently, and high-purity Se was collected in the volatile component [231]. These refinery methods provide the basis to develop cost-effective and eco-friendly Se refining from Se containing solids, including BioSeNPs through microbial reduction and Se containing sludge through abiotic methods followed by magnetic separation.

Only oxidizing roasting has been adapted for the refinery of BioSeNPs obtained through microbial reduction of Se oxyanions in synthetic wastewater by P*seudomonas stutzeri* NT-I with a purity of 99% [219]. The detailed procedure is to evaporate Se to gaseous selenium dioxide (SeO_2) from solid at 700 °C or higher temperature with pure oxygen, precipitate SeO_2 at 340 °C or lower temperature. The solid SeO_2 is dissolved in water to produce a SeO_3^{2-} solution, then subjected to a reduction process by applying sulfite gas to obtain purified Se [219]. For other Se containing products obtained through abiotic techniques, no refinery study has been reported. More studies about eco-friendly and cost-effective Se containing product refining for high purity Se should be carried out.

5. Conclusions and future perspectives

Se is a valuable and scarce resource that plays an essential role in industries. However, it cannot be exploited through ore exploration. Because of the intensive human activity and uncontrolled natural activities, mounting Se contamination offers the opportunity to remediate and recover it for reuse, given the increasing demand for pure Se for electronics and medical applications. Microbial recovery of Se nanoparticles has gained substantial attention as BioSeNPs can be obtained. Se recovery through microbial reduction can be boosted by enhancing Se oxyanions' extracellular reduction and larger size BioSeNPs production by manipulating reaction conditions. The production of BioSeNPs with density for sedimentation by gravity, combined with well-designed bioreactors allowing liquid-solid separation, is an optimal solution to achieve low cost Se recovery. Notably, the cost-effective recovery of Se with high purity is limited by its concentration and the existence of other pollutants in wastewater. Compared with abiotic Se remediation methods, microbial reduction needs a longer time for incubation and bacterial growth. At the same time, abiotic Se remediation techniques, e.g., coagulation and precipitation, reduction by ZVI followed by magnetic separation, can be an option for Se recovery. From both Se remediation and recovery perspectives, the coexistence of other pollutants, including sulfate, phosphate, nitrate, is a major challenge. The development of cost-effective and eco-friendly refinery methods for recovered Se containing products has not received enough attention.

This work has reviewed the widespread microbial Se reduction, proposed abiotic Se remediation techniques in combination with magnetic separation for Se recovery, and suggested the development of refinery methods for recovered Se product. The attractive microbial reduction and proposed abiotic Se remediation techniques followed by magnetic separation have shed light on Se recovery from wastewater. However, pilot and full scale applications of Se recovery from wastewater are largely absent in the literature. Only a few papers have demonstrated Se recovery at laboratory scale. To achieve and maximize Se recovery through microbial reduction, future research should consider the following points: (i) the performance of microbial Se reduction should be evaluated on a case-specific basis before scaling up as it can be affected by wastewater type, selected inoculum, and operation conditions; (ii) the mechanism of Se oxyanions reduction to BioSeNPs formation needs to be further explored, and extracellular production of BioSeNPs should be boosted; (iii) biological reduction technology and physio-chemical technology can be combined for easy separation of the formed BioSeNPs. The combination of abiotic Se remediation techniques and magnetic separation may be an option for achieving Se recovery with the following aspects needing to be addressed: (i) verification and development of the magnetic separation combined with different abiotic Se remediation techniques; (ii) identification and evaluation of the recovered Se product via different abiotic methods. To provide pure Se to the market, the produced Se containing product from wastewater needs further refining. The goal of a cost-effective and eco-friendly refinery method for recovery Se containing products requires further attention.

6. Acknowledgements

Zhongli Wang would like to acknowledge the support from the China Scholarship Council (CSC) and the University of Nottingham. H.I. Gomes acknowledges the University of Nottingham for her funding through an Anne McLaren Fellowship and the Fondazione CON IL SUD through the project MATCHER (2018-PDR-01165). We thank four anonymous reviewers for their comments which have improved the manuscript.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

[1] M. Sakamoto, H.M. Chan, J.L. Domingo, M. Kubota, K. Murata, Changes in body burden of mercury, lead, arsenic, cadmium and selenium in infants during early lactation in comparison with placental transfer, Ecotoxicology and environmental safety, 84 (2012) 179-184.

[2] Y.H. Ribeiro, D.G. David, M.V. da Silva, Z.N. da Rocha, Analysis and Growth Modeling of CuInSe 2 Films by Electrodeposition for Photocell Applications, Brazilian Journal of Physics, (2021) 1-14.

[3] A. Kumar, Impact of selenium composition variation in CZTS solar cell, Optik, 234 (2021) 166421.

[4] W.H. Organization, Trace elements in human nutrition and health, World Health Organization, 1996.

[5] L. Foster, S. Sumar, Selenium in the environment, food and health, Nutrition & Food Science, (1995).

[6] S. Etteieb, S. Magdouli, M. Zolfaghari, S. Brar, Monitoring and analysis of selenium as an emerging contaminant in mining industry: A critical review, Science of the Total Environment, 698 (2020) 134339.

[7] A.D. Lemly, Aquatic selenium pollution is a global environmental safety issue, Ecotoxicology and environmental safety, 59 (2004) 44-56.

[8] G.H. Floor, E. Marguí, M. Hidalgo, I. Queralt, P. Kregsamer, C. Streli, G. Román-Ross, Study of selenium sorption processes in volcanic ash using Total Reflection X-ray Fluorescence (TXRF), Chemical Geology, 352 (2013) 19-26.

[9] L. Twidwell, J. McCloskey, P. Miranda, M. Gale, Technologies and potential technologies for removing selenium from process and mine wastewater, Proceedings of the Recycling, Waste, Treatment and Clean Technology (REWAS), San Sebastian,

Spain, (1999) 5-9.

[10] A.M. Gustafsson, M.R.S. Foreman, C. Ekberg, Recycling of high purity selenium from CIGS solar cell waste materials, Waste management, 34 (2014) 1775-1782.

[11] M.M. Rodriguez, V.C. Rivero, R.J. Ballesta, Selenium distribution in topsoils and plants of a semi-arid Mediterranean environment, Environmental Geochemistry and Health, 27 (2005) 513-519.

[12] O. Otsuka, M. Yamashita, Selenium recovery from wastewater using the selenate-reducing bacterium Pseudomonas stutzeri NT-I, Hydrometallurgy, 197 (2020) 105470.

[13] V. Funari, H.I. Gomes, D. Coppola, G.A. Vitale, E. Dinelli, D. de Pascale, M. Rovere, Opportunities and threats of selenium supply from unconventional and low-grade ores: A critical review, Resources, Conservation and Recycling, 170 (2021) 105593.

[14] J.T. Trimmer, D.C. Miller, J.S. Guest, Resource recovery from sanitation to enhance ecosystem services, Nature Sustainability, 2 (2019) 681-690.

[15] A.P. Velenturf, P. Purnell, Resource recovery from waste: Restoring the balance between resource scarcity and waste overload, Sustainability, 9 (2017) 1603.

[16] S.F. Evans, M.R. Ivancevic, J. Yan, A.K. Naskar, A.M. Levine, R.J. Lee, C. Tsouris, M.P. Paranthaman, Magnetic adsorbents for selective removal of selenite from contaminated water, Separation Science and Technology, 54 (2019) 2138-2146.

[17] L. Lortie, W. Gould, S. Rajan, R. McCready, K.-J. Cheng, Reduction of selenate and selenite to elemental selenium by a Pseudomonas stutzeri isolate, Appl. Environ. Microbiol., 58 (1992) 4042-4044.

[18] J.-H. Luo, H. Chen, S. Hu, C. Cai, Z. Yuan, J. Guo, Microbial selenate reduction driven by a denitrifying anaerobic methane oxidation biofilm, Environmental science & technology, 52 (2018) 4006-4012.

[19] Y. Zhang, M. Kuroda, S. Arai, F. Kato, D. Inoue, M. Ike, Biological treatment of selenate-containing saline wastewater by activated sludge under oxygen-limiting conditions, Water research, 154 (2019) 327-335.

[20] S. Xia, X. Xu, L. Zhou, Insights into selenate removal mechanism of hydrogen-based membrane biofilm reactor for nitrate-polluted groundwater treatment based on anaerobic biofilm analysis, Ecotoxicology and environmental safety, 178 (2019) 123-129.

[21] S.P. Hageman, R.D. van der Weijden, A.J. Stams, C.J. Buisman, Bio-production of selenium nanoparticles with diverse physical properties for recovery from water, International Journal of Mineral Processing, 169 (2017) 7-15.

[22] L.C. Tan, Y.V. Nancharaiah, E.D. van Hullebusch, P.N. Lens, Selenium: environmental significance, pollution, and biological treatment technologies, Biotechnology advances, 34 (2016) 886-907.

[23] Y.V. Nancharaiah, P.N. Lens, Selenium biomineralization for biotechnological applications, Trends in biotechnology, 33 (2015) 323-330.

[24] E.A. Pilon-Smits, D.L. LeDuc, Phytoremediation of selenium using transgenic plants, Current Opinion in Biotechnology, 20 (2009) 207-212.

[25] Y. He, Y. Xiang, Y. Zhou, Y. Yang, J. Zhang, H. Huang, C. Shang, L. Luo, J. Gao, L. Tang, Selenium contamination, consequences and remediation techniques in water and soils: a review, Environmental research, 164 (2018) 288-301.

[26] S.A. Wadhwani, U.U. Shedbalkar, R. Singh, B.A. Chopade, Biogenic selenium nanoparticles: current status and future prospects, Applied microbiology and biotechnology, 100 (2016) 2555-2566.

[27] A. Sinharoy, P.N.L. Lens, Biological Removal of Selenate and Selenite from Wastewater: Options for Selenium Recovery as Nanoparticles, Current Pollution

Reports, 6 (2020) 230-249.

[28] R.J.B. Reynolds, E.A. Pilon-Smits, Plant selenium hyperaccumulation-Ecological effects and potential implications for selenium cycling and community structure, Biochimica et Biophysica Acta (BBA)-General Subjects, 1862 (2018) 2372-2382.

[29] Z. Li, D. Liang, Q. Peng, Z. Cui, J. Huang, Z. Lin, Interaction between selenium and soil organic matter and its impact on soil selenium bioavailability: A review, Geoderma, 295 (2017) 69-79.

[30] F.M. Fordyce, Selenium deficiency and toxicity in the environment, in: Essentials of medical geology, Springer, 2013, pp. 375-416.

[31] S. Santos, G. Ungureanu, R. Boaventura, C. Botelho, Selenium contaminated waters: An overview of analytical methods, treatment options and recent advances in sorption methods, Science of the Total Environment, 521 (2015) 246-260.

[32] L.H.E. Winkel, B. Vriens, G.D. Jones, L.S. Schneider, E. Pilon-Smits, G.S. Banuelos, Selenium Cycling Across Soil-Plant-Atmosphere Interfaces: A Critical Review, Nutrients, 7 (2015) 4199-4239.

[33] F.E. Huggins, C.L. Senior, P. Chu, K. Ladwig, G.P. Huffman, Selenium and arsenic speciation in fly ash from full-scale coal-burning utility plants, Environmental science & technology, 41 (2007) 3284-3289.

[34] I. Pumure, J. Renton, R. Smart, The interstitial location of selenium and arsenic in rocks associated with coal mining using ultrasound extractions and principal component analysis (PCA), Journal of hazardous materials, 198 (2011) 151-158.

[35] A. Khamkhash, V. Srivastava, T. Ghosh, G. Akdogan, R. Ganguli, S. Aggarwal, Mining-related selenium contamination in Alaska, and the state of current knowledge, Minerals, 7 (2017) 46.

[36] A. Haug, R.D. Graham, O.A. Christophersen, G.H. Lyons, How to use the world's

scarce selenium resources efficiently to increase the selenium concentration in food, Microbial Ecology in Health and Disease, 19 (2007) 209-228.

[37] Z.J. Wang, Y.X. Gao, Biogeochemical cycling of selenium in Chinese environments, Applied Geochemistry, 16 (2001) 1345-1351.

[38] J. Bech, M. Suarez, F. Reverter, P. Tume, P. Sánchez, J. Bech, A. Lansac, Selenium and other trace elements in phosphate rock of Bayovar–Sechura (Peru), Journal of Geochemical Exploration, 107 (2010) 136-145.

[39] A. Fernández-Martínez, L. Charlet, Selenium environmental cycling and bioavailability: a structural chemist point of view, Reviews in Environmental Science and Bio/Technology, 8 (2009) 81-110.

[40] L.H. Winkel, B. Vriens, G.D. Jones, L.S. Schneider, E. Pilon-Smits, G.S. Bañuelos, Selenium cycling across soil-plant-atmosphere interfaces: a critical review, Nutrients, 7 (2015) 4199-4239.

[41] M. Ihnat, Occurrence and distribution of selenium, CRC press, 1989.

[42] J.D. Hem, Study and interpretation of the chemical characteristics of natural water, Department of the Interior, US Geological Survey, 1985.

[43] H. Tian, K. Liu, J. Zhou, L. Lu, J. Hao, P. Qiu, J. Gao, C. Zhu, K. Wang, S. Hua, Atmospheric Emission Inventory of Hazardous Trace Elements from China’s Coal-Fired Power Plants□ Temporal Trends and Spatial Variation Characteristics, Environmental science & technology, 48 (2014) 3575-3582.

[44] R.J. Cassella, O.D. de Sant'Ana, A.T. Rangel, B. Maria de Fátima, R.E. Santelli, Selenium determination by electrothermal atomic absorption spectrometry in petroleum refinery aqueous streams containing volatile organic compounds, Microchemical journal, 71 (2002) 21-28.

[45] K.L. Wasewar, B. Prasad, S. Gulipalli, Removal of selenium by adsorption onto

granular activated carbon (GAC) and powdered activated carbon (PAC), CLEAN–Soil, Air, Water, 37 (2009) 872-883.

[46] A.D. Lemly, Symptoms and implications of selenium toxicity in fish: the Belews Lake case example, Aquatic Toxicology, 57 (2002) 39-49.

[47] S.J. Hamilton, Review of selenium toxicity in the aquatic food chain, Science of the Total Environment, 326 (2004) 1-31.

[48] P. Cordoba, L.C. Staicu, Flue gas desulfurization effluents: An unexploited selenium resource, Fuel, 223 (2018) 268-276.

[49] X. Xia, L. Ling, W.-x. Zhang, Genesis of pure Se (0) nano-and micro-structures in wastewater with nanoscale zero-valent iron (nZVI), Environmental Science: Nano, 4 (2017) 52-59.

[50] Z. Xu, W. Xu, Y. Lv, S. Wang, J. Wang, Phase separation of molybdenum, cesium and selenium from the borosilicate glass containing simulated nuclear wastes under a CO2-rich heating atmosphere, Journal of Nuclear Materials, 523 (2019) 216-222.

[51] T. Watari, B.C. McLellan, S. Ogata, T. Tezuka, Analysis of potential for critical metal resource constraints in the international energy agency’s long-term low-carbon energy scenarios, Minerals, 8 (2018) 156.

[52] W. Berger, F.-G. Simon, K. Weimann, E.A. Alsema, A novel approach for the recycling of thin film photovoltaic modules, Resources, Conservation and Recycling, 54 (2010) 711-718.

[53] D. Wu, W. Ren, Y. NuLi, J. Yang, J. Wang, Recent progress on selenium-based cathode materials for rechargeable magnesium batteries: a mini review, Journal of Materials Science & Technology, (2021).

[54] H. Abbas, D. Abou Baker, Biological evaluation of selenium nanoparticles biosynthesized by Fusarium semitectum as antimicrobial and anticancer agents,

Egyptian Journal of Chemistry, 63 (2020) 1119-1133.

[55] D. Medina Cruz, G. Mi, T.J. Webster, Synthesis and characterization of biogenic selenium nanoparticles with antimicrobial properties made by Staphylococcus aureus, methicillin-resistant Staphylococcus aureus (MRSA), Escherichia coli, and Pseudomonas aeruginosa, Journal of Biomedical Materials Research Part A, 106 (2018) 1400-1412.

[56] X. Wang, X. Pan, G.M. Gadd, Immobilization of elemental mercury by biogenic Se nanoparticles in soils of varying salinity, Science of the total environment, 668 (2019) 303-309.

[57] J.R. Arthur, F. Nicol, G.J. Beckett, Selenium deficiency, thyroid hormone metabolism, and thyroid hormone deiodinases, The American journal of clinical nutrition, 57 (1993) 236S-239S.

[58] J.R. Arthur, R.C. McKenzie, G.J. Beckett, Selenium in the immune system, The Journal of nutrition, 133 (2003) 1457S-1459S.

[59] L.J. Machlin, A. Bendich, Free radical tissue damage: protective role of antioxidant nutrients, The FASEB journal, 1 (1987) 441-445.

[60] K.M. Kubachka, T. Hanley, M. Mantha, R.A. Wilson, T.M. Falconer, Z. Kassa, A. Oliveira, J. Landero, J. Caruso, Evaluation of selenium in dietary supplements using elemental speciation, Food chemistry, 218 (2017) 313-320.

[61] Y. Wu, P. Yang, J. Chen, J.F. Shao, R. Gui, Selenium Biofortification of Bamboo Shoots by Liquid Se Fertilization in the Culm Pith Cavity, ACS Food Science & Technology, (2020).

[62] F. Fordyce, Selenium geochemistry and health, Ambio, (2007) 94-97.

[63] A. Nesterov, The clinical course of Kashin-Beck disease, Arthritis & Rheumatism: Official Journal of the American College of Rheumatology, 7 (1964) 29-40.

[64] G.F. Combs, Selenium in global food systems, British journal of nutrition, 85 (2001) 517-547.

[65] G. Alfthan, M. Eurola, P. Ekholm, E.-R. Venäläinen, T. Root, K. Korkalainen, H. Hartikainen, P. Salminen, V. Hietaniemi, P. Aspila, Effects of nationwide addition of selenium to fertilizers on foods, and animal and human health in Finland: From deficiency to optimal selenium status of the population, Journal of Trace Elements in Medicine and Biology, 31 (2015) 142-147.

[66] U. Garg, L.D. Smith, Biomarkers in Inborn Errors of Metabolism: Clinical Aspects and Laboratory Determination, Elsevier, 2017.

[67] R. Stoffaneller, N.L. Morse, A review of dietary selenium intake and selenium status in Europe and the Middle East, Nutrients, 7 (2015) 1494-1537.

[68] S. Zhu, Y. Liang, D. Gao, X. An, F. Kong, Spraying foliar selenium fertilizer on quality of table grape (Vitis vinifera L.) from different source varieties, Scientia Horticulturae, 218 (2017) 87-94.

[69] A. Gastélum-Estrada, S.O. Serna-Saldívar, D.A. Jacobo-Velázquez, Fighting the COVID-19 Pandemic through Biofortification: Innovative Approaches to Improve the Immunomodulating Capacity of Foods, ACS Food Science & Technology, (2021).

[70] K.J. Schulz, J.H. DeYoung, R.R. Seal, D.C. Bradley, Critical mineral resources of the United States: economic and environmental geology and prospects for future supply, Geological Survey, 2018.

[71] T. Kelly, G. Matos, D. Buckingham, C. DiFrancesco, K. Porter, C. Berry, M. Crane, T. Goonan, J. Sznopek, Historical statistics for mineral and material commodities in the United States: US Geological Survey, in, 2018.

[72] B. Buchs, M.W. Evangelou, L.H. Winkel, M. Lenz, Colloidal properties of nanoparticular biogenic selenium govern environmental fate and bioremediation

effectiveness, Environmental science & technology, 47 (2013) 2401-2407.

[73] Y. Kilic, G. Kartal, S. Timur, An investigation of copper and selenium recovery from copper anode slimes, International Journal of Mineral Processing, 124 (2013) 75-82.

[74] Y. Zhang, J.N. Moore, Interaction of selenate with a wetland sediment, Applied Geochemistry, 12 (1997) 685-691.

[75] S.O. Okonji, G. Achari, D. Pernitsky, Environmental Impacts of Selenium Contamination: A Review on Current-Issues and Remediation Strategies in an Aqueous System, Water, 13 (2021) 1473.

[76] P.N. Lens, K. Pakshirajan, Environmental Technologies to Treat Selenium Pollution: Principles and Engineering, in, IWA Publishing, 2021.

[77] Y.Y. Zhang, M. Kuroda, S. Arai, F. Kato, D. Inoue, M. Ike, Biological treatment of selenate-containing saline wastewater by activated sludge under oxygen-limiting conditions, Water Research, 154 (2019) 327-335.

[78] E. Piacenza, A. Presentato, E. Zonaro, S. Lampis, G. Vallini, R.J. Turner, Microbial-based bioremediation of selenium and tellurium compounds, Biosorption'.(Ed. J Derco) pp, (2018) 117-147.

[79] C.M. Hill, Review of available technologies for the removal of selenium from water, Final Report, prepared for North American Metals Council (NAMC), (2010) 48-60.

[80] X. Xia, Z. Zhou, S. Wu, D. Wang, S. Zheng, G. Wang, Adsorption removal of multiple dyes using biogenic selenium nanoparticles from an Escherichia coli strain overexpressed selenite reductase CsrF, Nanomaterials, 8 (2018) 234.

[81] K. Kalaitzidou, A. Zouboulis, M. Mitrakas, Cost evaluation for Se (IV) removal, by applying common drinking water treatment processes: Coagulation/precipitation or

adsorption, Journal of Environmental Chemical Engineering, 8 (2020) 104209.

[82] P. Dessì, R. Jain, S. Singh, M. Seder-Colomina, E.D. van Hullebusch, E.R. Rene, S.Z. Ahammad, A. Carucci, P.N. Lens, Effect of temperature on selenium removal from wastewater by UASB reactors, Water Research, 94 (2016) 146-154.

[83] T. Norgate, S. Jahanshahi, Low grade ores–smelt, leach or concentrate?, Minerals Engineering, 23 (2010) 65-73.

[84] Q. Dehaine, L. Filippov, R. Joussemet, Rare earths (La, Ce, Nd) and rare metals (Sn, Nb, W) as by-products of kaolin production–Part 2: Gravity processing of micaceous residues, Minerals Engineering, 100 (2017) 200-210.

[85] G.B. Abaka-Wood, M. Zanin, J. Addai-Mensah, W. Skinner, Recovery of rare earth elements minerals from iron oxide–silicate rich tailings–Part 1: Magnetic separation, Minerals Engineering, 136 (2019) 50-61.

[86] N.A. Oladoja, E.I. Unuabonah, O.S. Amuda, O.M. Kolawole, Operational principles and material requirements for coagulation/flocculation and adsorption-based water treatment operations, in: polysaccharides as a green and sustainable resources for water and wastewater treatment, Springer, 2017, pp. 1-11.

[87] T. Su, X. Guan, G. Gu, J. Wang, Adsorption characteristics of As (V), Se (IV), and V (V) onto activated alumina: effects of pH, surface loading, and ionic strength, Journal of Colloid and Interface Science, 326 (2008) 347-353.

[88] M.A. López-Antón, M. Díaz-Somoano, J. Fierro, M.R. Martínez-Tarazona, Retention of arsenic and selenium compounds present in coal combustion and gasification flue gases using activated carbons, Fuel processing technology, 88 (2007) 799-805.

[89] M. Matulová, M. Bujdoš, M.B. Miglierini, Z. Mitróová, M. Kubovčíková, M. Urík, The effects of selenate on goethite synthesis and selenate sorption kinetics onto a

goethite surface-A three-step process with an unexpected desorption phase, Chemical Geology, 556 (2020) 119852.

[90] H. Asiabi, Y. Yamini, M. Shamsayei, Highly selective and efficient removal of arsenic (V), chromium (VI) and selenium (VI) oxyanions by layered double hydroxide intercalated with zwitterionic glycine, Journal of hazardous materials, 339 (2017) 239-247.

[91] J.S. Yamani, A.W. Lounsbury, J.B. Zimmerman, Adsorption of selenite and selenate by nanocrystalline aluminum oxide, neat and impregnated in chitosan beads, Water research, 50 (2014) 373-381.

[92] A.W. Lounsbury, J.S. Yamani, C.P. Johnston, P. Larese-Casanova, J.B. Zimmerman, The role of counter ions in nano-hematite synthesis: implications for surface area and selenium adsorption capacity, Journal of hazardous materials, 310 (2016) 117-124.

[93] A.W. Lounsbury, R. Wang, D.L. Plata, N. Billmyer, C. Muhich, K. Kanie, T. Sugimoto, D. Peak, J.B. Zimmerman, Preferential adsorption of selenium oxyanions onto {1 1 0} and {0 1 2} nano-hematite facets, Journal of colloid and interface science, 537 (2019) 465-474.

[94] M.B. Shakoor, Z.-L. Ye, S. Chen, Engineered biochars for recovering phosphate and ammonium from wastewater: A review, Science of The Total Environment, (2021) 146240.

[95] P. Godlewska, A. Bogusz, J. Dobrzyńska, R. Dobrowolski, P. Oleszczuk, Engineered biochar modified with iron as a new adsorbent for treatment of water contaminated by selenium, Journal of Saudi Chemical Society, 24 (2020) 824-834.

[96] Y. Wang, F. Dang, X. Zheng, H. Zhong, Biochar amendment to further reduce methylmercury accumulation in rice grown in selenium-amended paddy soil, Journal of hazardous materials, 365 (2019) 590-596.

[97] S. Wang, K. Xiao, Y. Mo, B. Yang, T. Vincent, C. Faur, E. Guibal, Selenium (VI) and copper (II) adsorption using polyethyleneimine-based resins: Effect of glutaraldehyde crosslinking and storage condition, Journal of hazardous materials, 386 (2020) 121637.

[98] S.C. Tang, I.M. Lo, Magnetic nanoparticles: essential factors for sustainable environmental applications, Water research, 47 (2013) 2613-2632.

[99] Y. Fu, J. Wang, Q. Liu, H. Zeng, Water-dispersible magnetic nanoparticle–graphene oxide composites for selenium removal, Carbon, 77 (2014) 710-721.

[100] S. Das, M.J. Hendry, J. Essilfie-Dughan, Adsorption of selenate onto ferrihydrite, goethite, and lepidocrocite under neutral pH conditions, Applied Geochemistry, 28 (2013) 185-193.

[101] S. Mandal, S. Pu, X. Wang, H. Ma, Y. Bai, Hierarchical porous structured polysulfide supported nZVI/biochar and efficient immobilization of selenium in the soil, Science of the Total Environment, 708 (2020) 134831.

[102] S.-H. Hong, F.N. Lyonga, J.-K. Kang, E.-J. Seo, C.-G. Lee, S. Jeong, S.-G. Hong, S.-J. Park, Synthesis of Fe-impregnated biochar from food waste for Selenium (VI) removal from aqueous solution through adsorption: Process optimization and assessment, Chemosphere, (2020) 126475.

[103] S. Satyro, H. Li, A.M. Dehkhoda, R. McMillan, N. Ellis, S.A. Baldwin, Application of Fe-biochar composites for selenium (Se+ 6) removal from aqueous solution and effect of the presence of competing anions under environmentally relevant conditions, Journal of Environmental Management, 277 (2021) 111472.

[104] S. Jevtić, I. Arčon, A. Rečnik, B. Babić, M. Mazaj, J. Pavlović, D. Matijaševic, M. Nikšić, N. Rajić, The iron (III)-modified natural zeolitic tuff as an adsorbent and carrier for selenium oxyanions, Microporous and mesoporous materials, 197 (2014) 92-100.

[105] X. Zhang, X. Li, Z. Jin, S.H. Tumrani, X. Ji, Selenium in wastewater can be adsorbed by modified natural zeolite and reused in vegetable growth, Science Progress, 104 (2021) 00368504211019845.

[106] J. Hein, M. Stamatakis, J. Dowling, Trace metal-rich Quaternary hydrothermal manganese oxide and barite deposit, Milos Island, Greece, Applied Earth Science, 109 (2000) 67-76.

[107] K. Tokunaga, Y. Yokoyama, S. Kawagucci, A. Sakaguchi, Y. Terada, Y. Takahashi, Selenium coprecipitated with barite in marine sediments as a possible redox indicator, Chemistry Letters, 42 (2013) 1068-1069.

[108] N. Börsig, A.C. Scheinost, S. Shaw, D. Schild, T. Neumann, Uptake mechanisms of selenium oxyanions during the ferrihydrite-hematite recrystallization, Geochimica et Cosmochimica Acta, 206 (2017) 236-253.

[109] P.C.M. Francisco, T. Sato, T. Otake, T. Kasama, S. Suzuki, H. Shiwaku, T. Yaita, Mechanisms of Se (IV) co-precipitation with ferrihydrite at acidic and alkaline conditions and its behavior during aging, Environmental science & technology, 52 (2018) 4817-4826.

[110] N. Börsig, A.C. Scheinost, S. Shaw, D. Schild, T. Neumann, Retention and multiphase transformation of selenium oxyanions during the formation of magnetite via iron (II) hydroxide and green rust, Dalton Transactions, 47 (2018) 11002-11015.

[111] A.C. Scheinost, L. Charlet, Selenite reduction by mackinawite, magnetite and siderite: XAS characterization of nanosized redox products, Environmental science & technology, 42 (2008) 1984-1989.

[112] R. Singh, Membrane technology and engineering for water purification: application, systems design and operation, Butterworth-Heinemann, 2014.

[113] C. Hu, Q. Chen, G. Chen, H. Liu, J. Qu, Removal of Se (IV) and Se (VI) from

drinking water by coagulation, Separation and Purification Technology, 142 (2015) 65-70.

[114] H.K. Hansen, S.F. Pena, C. Gutierrez, A. Lazo, P. Lazo, L.M. Ottosen, Selenium removal from petroleum refinery wastewater using an electrocoagulation technique, Journal of Hazardous Materials, 364 (2019) 78-81.

[115] H.K. Hansen, P. Nunez, C. Jil, Removal of arsenic from wastewaters by airlift electrocoagulation. Part 1: Batch reactor experiments, Separation science and technology, 43 (2008) 212-224.

[116] H.K. Hansen, L.M. Ottosen, Removal of arsenic from wastewaters by airlift electrocoagulation: Part 3: Copper smelter wastewater treatment, Separation Science and Technology, 45 (2010) 1326-1330.

[117] K. Baek, N. Kasem, A. Ciblak, D. Vesper, I. Padilla, A.N. Alshawabkeh, Electrochemical removal of selenate from aqueous solutions, Chemical engineering journal, 215 (2013) 678-684.

[118] D. Merrill, M. Manzione, J. Peterson, D. Parker, W. Chow, A. Hobbs, Field Evaluation of arsenic and selnium removal by iron coprecipitation, Journal (Water Pollution Control Federation), (1986) 18-26.

[119] M.Y.A. Mollah, P. Morkovsky, J.A.G. Gomes, M. Kesmez, J. Parga, D.L. Cocke, Fundamentals, present and future perspectives of electrocoagulation, Journal of Hazardous Materials, 114 (2004) 199-210.

[120] M. Lv, Z. Zhang, J. Zeng, J. Liu, M. Sun, R.S. Yadav, Y. Feng, Roles of magnetic particles in magnetic seeding coagulation-flocculation process for surface water treatment, Separation and Purification Technology, 212 (2019) 337-343.

[121] T. Ohara, H. Kumakura, H. Wada, Magnetic separation using superconducting magnets, Physica C: Superconductivity, 357 (2001) 1272-1280.

[122] D. Feng, C. Aldrich, H. Tan, Removal of heavy metal ions by carrier magnetic separation of adsorptive particulates, Hydrometallurgy, 56 (2000) 359-368.

[123] S. Sun, H. Zeng, Size-controlled synthesis of magnetite nanoparticles, Journal of the American Chemical Society, 124 (2002) 8204-8205.

[124] C. Tsouris, D. DePaoli, J. Shor, M.-C. Hu, T.-Y. Ying, Electrocoagulation for magnetic seeding of colloidal particles, Colloids and Surfaces A: Physicochemical and Engineering Aspects, 177 (2001) 223-233.

[125] C. Du, Y. Hu, H. Han, W. Sun, P. Hou, R. Liu, L. Wang, Y. Yang, R. Liu, L. Sun, Magnetic separation of phosphate contaminants from starch wastewater using magnetic seeding, Science of the Total Environment, 695 (2019) 133723.

[126] Y. Li, J. Wang, Y. Zhao, Z. Luan, Research on magnetic seeding flocculation for arsenic removal by superconducting magnetic separation, Separation and Purification Technology, 73 (2010) 264-270.

[127] S.O. Okonji, J.A. Dominic, D. Pernitsky, G. Achari, Removal and recovery of selenium species from wastewater: Adsorption kinetics and co-precipitation mechanisms, Journal of Water Process Engineering, 38 (2020) 101666.

[128] N. Geoffroy, G. Demopoulos, The elimination of selenium (IV) from aqueous solution by precipitation with sodium sulfide, Journal of hazardous materials, 185 (2011) 148-154.

[129] T.T.Y. Tan, C.K. Yip, D. Beydoun, R. Amal, Effects of nano-Ag particles loading on TiO2 photocatalytic reduction of selenate ions, Chemical Engineering Journal, 95 (2003) 179-186.

[130] S. Sanuki, T. Kojima, K. Arai, S. Nagaoka, H. Majima, Photocatalytic reduction of selenate and selenite solutions using TiO(2) powders, Metallurgical and Materials Transactions B-Process Metallurgy and Materials Processing Science, 30 (1999) 15-20.

[131] S. Sanuki, K. Arai, T. Kojima, S. Nagaoka, H. Majima, Photocatalytic reduction

of selenate and selenite solutions using TiO 2 powders, Metallurgical and Materials Transactions B, 30 (1999) 15-20.

[132] X. Zhao, G. Zhang, Z. Zhang, TiO2-based catalysts for photocatalytic reduction of aqueous oxyanions: State-of-the-art and future prospects, Environment international, 136 (2020) 105453.

[133] V.N.H. Nguyen, R. Amal, D. Beydoun, Photocatalytic reduction of selenium ions using different TiO2 photocatalysts, Chemical engineering science, 60 (2005) 5759-5769.

[134] C.-H. Wu, S.-L. Lo, C.-F. Lin, C.-Y. Kuo, Modeling competitive adsorption of molybdate, sulfate, and selenate on γ-Al2O3 by the triple-layer model, Journal of colloid and interface science, 233 (2001) 259-264.

[135] R.P. Rietra, T. Hiemstra, W.H. van Riemsdijk, Comparison of selenate and sulfate adsorption on goethite, Journal of colloid and interface science, 240 (2001) 384-390.

[136] C.-H. Wu, S.-L. Lo, C.-F. Lin, Competitive adsorption of molybdate, chromate, sulfate, selenate, and selenite on γ-Al2O3, Colloids and Surfaces A: Physicochemical and Engineering Aspects, 166 (2000) 251-259.

[137] A.B. Holmes, D. Khan, D. de Oliveira Livera, F. Gu, Enhanced photocatalytic selectivity of noble metallized TiO 2 nanoparticles for the reduction of selenate in water: tunable Se reduction product H 2 Se (g) vs. Se (s), Environmental Science: Nano, (2020).

[138] T. Tan, D. Beydoun, R. Amal, Effects of organic hole scavengers on the photocatalytic reduction of selenium anions, Journal of Photochemistry and Photobiology A: Chemistry, 159 (2003) 273-280.

[139] T.T. Tan, D. Beydoun, R. Amal, Photocatalytic reduction of Se (VI) in aqueous solutions in UV/TiO2 system: importance of optimum ratio of reactants on TiO2 surface, Journal of Molecular Catalysis A: Chemical, 202 (2003) 73-85.

[140] H. Yamashita, M. Harada, J. Misaka, M. Takeuchi, K. Ikeue, M. Anpo, Degradation of propanol diluted in water under visible light irradiation using metal ion-implanted titanium dioxide photocatalysts, Journal of Photochemistry and

Photobiology A: Chemistry, 148 (2002) 257-261.

[141] L. Zhu, X. Kong, C. Yang, B. Ren, Q. Tang, Fabrication and characterization of the magnetic separation photocatalyst C-TiO2@ Fe3O4/AC with enhanced photocatalytic performance under visible light irradiation, Journal of hazardous materials, 381 (2020) 120910.

[142] I.H. Yoon, K.W. Kim, S. Bang, M.G. Kim, Reduction and adsorption mechanisms of selenate by zero-valent iron and related iron corrosion, Applied Catalysis B-Environmental, 104 (2011) 185-192.

[143] A. Faisal, A. Sulaymon, Q. Khaliefa, A review of permeable reactive barrier as passive sustainable technology for groundwater remediation, International Journal of Environmental Science and Technology, 15 (2018) 1123-1138.

[144] S.J. Morrison, D.R. Metzler, B.P. Dwyer, Removal of As, Mn, Mo, Se, U, V and Zn from groundwater by zero-valent iron in a passive treatment cell: reaction progress modeling, Journal of Contaminant Hydrology, 56 (2002) 99-116.

[145] T.M. Statham, L.R. Mason, K.A. Mumford, G.W. Stevens, The specific reactive surface area of granular zero-valent iron in metal contaminant removal: Column experiments and modelling, Water research, 77 (2015) 24-34.

[146] T. Zeng, E.R. Rene, S. Zhang, P.N. Lens, Removal of selenate and cadmium by anaerobic granular sludge: EPS characterization and microbial community analysis, Process Safety and Environmental Protection, 126 (2019) 150-159.

[147] W.X. Zhang, Nanoscale iron particles for environmental remediation: An overview, Journal of Nanoparticle Research, 5 (2003) 323-332.

[148] Y. Furukawa, J.-w. Kim, J. Watkins, R.T. Wilkin, Formation of ferrihydrite and associated iron corrosion products in permeable reactive barriers of zero-valent iron, Environmental Science & Technology, 36 (2002) 5469-5475.

[149] J.-M.R. Génin, G. Bourrié, F. Trolard, M. Abdelmoula, A. Jaffrezic, P. Refait, V. Maitre, B. Humbert, A. Herbillon, Thermodynamic equilibria in aqueous suspensions of synthetic and natural Fe (II)− Fe (III) green rusts: Occurrences of the mineral in hydromorphic soils, Environmental Science & Technology, 32 (1998) 1058-1068.

[150] D.H. Phillips, B. Gu, D.B. Watson, Y. Roh, Impact of sample preparation on

mineralogical analysis of zero-valent iron reactive barrier materials, Journal of environmental quality, 32 (2003) 1299-1305.

[151] S. Bae, W. Lee, Inhibition of nZVI reactivity by magnetite during the reductive degradation of 1, 1, 1-TCA in nZVI/magnetite suspension, Applied Catalysis B: Environmental, 96 (2010) 10-17.

[152] Y.H. Huang, T.C. Zhang, Effects of dissolved oxygen on formation of corrosion products and concomitant oxygen and nitrate reduction in zero-valent iron systems with or without aqueous Fe2+, Water research, 39 (2005) 1751-1760.

[153] Y. Mu, F. Jia, Z. Ai, L. Zhang, Iron oxide shell mediated environmental remediation properties of nano zero-valent iron, Environmental Science: Nano, 4 (2017) 27-45.

[154] C. Shan, J. Chen, Z. Yang, H. Jia, X. Guan, W. Zhang, B. Pan, Enhanced removal of Se (VI) from water via pre-corrosion of zero-valent iron using H2O2/HCl: Effect of solution chemistry and mechanism investigation, Water research, 133 (2018) 173-181.

[155] A. Agrawal, P.G. Tratnyek, Reduction of nitro aromatic compounds by zero-valent iron metal, Environmental Science & Technology, 30 (1995) 153-160.

[156] C. Geiger, N. Ruiz, C. Clausen, D. Reinhart, J. Quinn, Ultrasound pretreatment of elemental iron: kinetic studies of dehalogenation reaction enhancement and surface effects, Water Research, 36 (2002) 1342-1350.

[157] Y.H. Liou, S.-L. Lo, C.-J. Lin, W.H. Kuan, S.C. Weng, Effects of iron surface pretreatment on kinetics of aqueous nitrate reduction, Journal of hazardous materials, 126 (2005) 189-194.

[158] S. Comba, A. Di Molfetta, R. Sethi, A comparison between field applications of nano-, micro-, and millimetric zero-valent iron for the remediation of contaminated aquifers, Water, Air, & Soil Pollution, 215 (2011) 595-607.

[159] N. Remya, J.-G. Lin, Current status of microwave application in wastewater treatment—a review, Chemical Engineering Journal, 166 (2011) 797-813.

[160] L.P. Liang, X.H. Guan, Y.Y. Huang, J.Y. Ma, X.P. Sun, J.L. Qiao, G.M. Zhou, Efficient selenate removal by zero-valent iron in the presence of weak magnetic field, Separation and Purification Technology, 156 (2015) 1064-1072.

[161] N. Feng, H. Ghoveisi, G. Bitton, J.-C.J. Bonzongo, Removal of phyto-accessible copper from contaminated soils using zero valent iron amendment and magnetic separation methods: Assessment of residual toxicity using plant and MetPLATE™ studies, Environmental Pollution, 219 (2016) 9-18.

[162] H. Ghoveisi, N. Feng, A. Boularbah, G. Bitton, J.-C.J. Bonzongo, Effect of aging and wet-dry cycles on the elimination of the bioavailable fractions of Cu and Zn in contaminated soils by zero valent iron and magnetic separation technique, Journal of Environmental Engineering, 144 (2018) 04018068.

[163] X. Guan, H. Yang, Y. Sun, J. Qiao, Enhanced immobilization of chromium (VI) in soil using sulfidated zero-valent iron, Chemosphere, 228 (2019) 370-376.

[164] M. Sillanpää, M. Shestakova, Chapter 2 - Electrochemical Water Treatment Methods, in: M. Sillanpää, M. Shestakova (Eds.) Electrochemical Water Treatment Methods, Butterworth-Heinemann, 2017, pp. 47-130.

[165] S. Vasudevan, M.A. Oturan, Electrochemistry: as cause and cure in water pollution—an overview, Environmental chemistry letters, 12 (2014) 97-108.

[166] A. Ciblak, X. Mao, I. Padilla, D. Vesper, I. Alshawabkeh, A.N. Alshawabkeh, Electrode effects on temporal changes in electrolyte pH and redox potential for water treatment, Journal of Environmental Science and Health, Part A, 47 (2012) 718-726.

[167] Y. Wang, Y. Xue, J. Su, S. Zheng, H. Lei, W. Cai, W. Jin, Efficient electrochemical recovery of dilute selenium by cyclone electrowinning, Hydrometallurgy, 179 (2018) 232-237.

[168] Y. Wang, Y. Xue, C. Zhang, S. Mo, Y. Xue, Microstructural Refinement towards the Electrochemical Co–Deposition Recovery of Copper and Selenium, ChemistrySelect, 3 (2018) 11127-11133.

[169] A.S. Koparal, Ü.B. Öğütveren, Removal of nitrate from water by electroreduction and electrocoagulation, Journal of hazardous materials, 89 (2002) 83-94.

[170] K. Baek, A. Ciblak, X. Mao, E.-J. Kim, A. Alshawabkeh, Iron anode mediated transformation of selenate in sand columns, Water research, 47 (2013) 6538-6545.

[171] A. Alekperov, Electrochemistry of selenium and tellurium, Russian Chemical Reviews, 43 (1974) 235.

[172] B. Maranowski, M. Strawski, W. Osowiecki, M. Szklarczyk, Study of selenium electrodeposition at gold electrode by voltammetric and rotating disc electrode techniques, Journal of Electroanalytical Chemistry, 752 (2015) 54-59.

[173] S.-Y. Zhang, J. Zhang, Y. Liu, X. Ma, H.-Y. Chen, Electrochemical synthesis of selenium nanotubes by using CTAB soft-template, Electrochimica acta, 50 (2005) 4365-4370.

[174] S. Chaudhary, A. Umar, S. Mehta, Selenium nanomaterials: an overview of recent developments in synthesis, properties and potential applications, Progress in Materials Science, 83 (2016) 270-329.

[175] S. Zou, M.S. Mauter, Direct Electrochemical Pathways for Selenium Reduction in Aqueous Solutions, ACS Sustainable Chemistry & Engineering, 9 (2021) 2027-2036.

[176] S. Zou, M.S. Mauter, Competing Ion Behavior in Direct Electrochemical Selenite Reduction, ACS ES&T Engineering, (2021).

[177] Y.V. Nancharaiah, P. Lens, Ecology and biotechnology of selenium-respiring bacteria, Microbiology and Molecular Biology Reviews, 79 (2015) 61-80.

[178] A.V. Tugarova, A.A. Kamnev, Proteins in microbial synthesis of selenium nanoparticles, Talanta, 174 (2017) 539-547.

[179] A. Shrift, A selenium cycle in nature?, Nature, 201 (1964) 1304-1305.

[180] R. McCready, J. Campbell, J. Payne, Selenite reduction by Salmonella heidelberg, Canadian journal of microbiology, 12 (1966) 703-714.

[181] J.F. Stolz, P. Basu, J.M. Santini, R.S. Oremland, Arsenic and selenium in microbial metabolism, Annu. Rev. Microbiol., 60 (2006) 107-130.

[182] Y.V. Nancharaiah, P. Lens, Ecology and biotechnology of selenium-respiring bacteria, Microbiol. Mol. Biol. Rev., 79 (2015) 61-80.

[183] M. Fujita, M. Ike, S. Nishimoto, K. Takahashi, M. Kashiwa, Isolation and characterization of a novel selenate-reducing bacterium, Bacillus sp. SF-1, Journal of Fermentation and Bioengineering, 83 (1997) 517-522.

[184] I. Schroder, S. Rech, T. Krafft, J.M. Macy, Purification and characterization of the selenate reductase from Thauera selenatis, Journal of Biological Chemistry, 272 (1997) 23765-23768.

[185] K.H. Williams, M.J. Wilkins, A.L. N'Guessan, B. Arey, E. Dodova, A. Dohnalkova, D. Holmes, D.R. Lovley, P.E. Long, Field evidence of selenium bioreduction in a uranium-contaminated aquifer, Environmental microbiology reports, 5 (2013) 444-452.

[186] R.S. Oremland, J.T. Hollibaugh, A.S. Maest, T.S. Presser, L.G. Miller, C.W. Culbertson, Selenate reduction to elemental selenium by anaerobic bacteria in sediments and culture: biogeochemical significance of a novel, sulfate-independent respiration, Appl. Environ. Microbiol., 55 (1989) 2333-2343.

[187] Y.Q. Tan, Y.T. Wang, Y. Wang, D. Xu, Y.T. Huang, D. Wang, G.J. Wang, C. Rensing, S.X. Zheng, Novel mechanisms of selenate and selenite reduction in the obligate aerobic bacterium Comamonas testosteroni S44, Journal of Hazardous Materials, 359 (2018) 129-138.

[188] M. Lenz, E.D. Van Hullebusch, G. Hommes, P.F.X. Corvini, P.N.L. Lens, Selenate removal in methanogenic and sulfate-reducing upflow anaerobic sludge bed reactors, Water Research, 42 (2008) 2184-2194.

[189] N.A. Steinberg, J.S. Blum, L. Hochstein, R.S. Oremland, Nitrate is a preferred electron acceptor for growth of freshwater selenate-respiring bacteria, Appl. Environ. Microbiol., 58 (1992) 426-428.

[190] L.C. Tan, Y.V. Nancharaiah, S. Lu, E. van Hullebusch, G. Gerlach, P.N. Lens, Biological treatment of selenium-laden wastewater containing nitrate and sulfate in an upflow anaerobic sludge bed reactor at pH 5.0, in: Anaerobic Treatment of Mine Wastewater for the Removal of Selenate and its Co-Contaminants, CRC Press, 2018, pp. 127-152.

[191] S. Rech, J. Macy, The terminal reductases for selenate and nitrate respiration in Thauera selenatis are two distinct enzymes, Journal of bacteriology, 174 (1992) 7316-7320.

[192] S. Soda, A. Hasegawa, M. Kuroda, A. Hanada, M. Yamashita, M. Ike, Selenium recovery from kiln powder of cement manufacturing by chemical leaching and bioreduction, Water Science and Technology, 72 (2015) 1294-1300.

[193] M. Kuroda, E. Notaguchi, A. Sato, M. Yoshioka, A. Hasegawa, T. Kagami, T.

Narita, M. Yamashita, K. Sei, S. Soda, Characterization of Pseudomonas stutzeri NT-I capable of removing soluble selenium from the aqueous phase under aerobic conditions, Journal of bioscience and bioengineering, 112 (2011) 259-264.

[194] A. Sinharoy, P.N. Lens, Biological removal of selenate and selenite from wastewater: options for selenium recovery as nanoparticles, Current Pollution Reports, 6 (2020) 230-249.

[195] S.S. Veeravalli, S.R. Chaganti, J.A. Lalman, D.D. Heath, Fermentative H2 production using a switchgrass steam exploded liquor fed to mixed anaerobic cultures: Effect of hydraulic retention time, linoleic acid and nitrogen sparging, International journal of hydrogen energy, 39 (2014) 9994-10002.

[196] Z. Wang, B. Zhang, Y. Jiang, Y. Li, C. He, Spontaneous thallium (I) oxidation with electricity generation in single-chamber microbial fuel cells, Applied Energy, 209 (2018) 33-42.

[197] J. Liu, J.C. Taylor, S.A. Baldwin, Removal of selenate from brine using anaerobic bacteria and zero valent iron, Journal of environmental management, 222 (2018) 348-358.

[198] F.M. Mosallam, G.S. El-Sayyad, R.M. Fathy, A.I. El-Batal, Biomolecules-mediated synthesis of selenium nanoparticles using Aspergillus oryzae fermented Lupin extract and gamma radiation for hindering the growth of some multidrug-resistant bacteria and pathogenic fungi, Microbial pathogenesis, 122 (2018) 108-116.

[199] R. Jain, N. Jordan, S. Tsushima, R. Hübner, S. Weiss, P.N. Lens, Shape change of biogenic elemental selenium nanomaterials from nanospheres to nanorods decreases their colloidal stability, Environmental Science: Nano, 4 (2017) 1054-1063.

[200] B.P. Rosen, Z. Liu, Transport pathways for arsenic and selenium: a minireview, Environment international, 35 (2009) 512-515.

[201] J.-B. Vincourt, D. Jullien, F. Amalric, J.-P. Girard, Molecular and functional characterization of SLC26A11, a sodium-independent sulfate transporter from high endothelial venules, The FASEB journal, 17 (2003) 1-21.

[202] T. Wang, X. Lou, G. Zhang, Y. Dang, Improvement of selenium enrichment in Rhodotorula glutinis X-20 through combining process optimization and selenium

transport, Bioengineered, 10 (2019) 335-344.

[203] R.J. Turner, J.H. Weiner, D.E. Taylor, Selenium metabolism in Escherichia coli, Biometals, 11 (1998) 223-227.

[204] R.A. LaRossa, Mutant selections linking physiology, inhibitors, and genotypes, Escherichia coli and Salmonella: cellular and molecular biology, 2nd ed. American Society for Microbiology, Washington, DC, (1996) 2527-2587.

[205] J.J. Ojeda, M.L. Merroun, A.V. Tugarova, S. Lampis, A.A. Kamnev, P.H. Gardiner, Developments in the study and applications of bacterial transformations of selenium species, Critical Reviews in Biotechnology, 40 (2020) 1250-1264.

[206] D. Wang, C. Rensing, S. Zheng, Microbial reduction and resistance to selenium: mechanisms, applications and prospects, Journal of Hazardous Materials, (2021) 126684.

[207] A. Abdelouas, W. Gong, W. Lutze, J. Shelnutt, R. Franco, I. Moura, Using cytochrome c 3 to make selenium nanowires, Chemistry of materials, 12 (2000) 1510-1512.

[208] X. Gao, T. Gao, L. Zhang, Solution–solid growth of α-monoclinic selenium nanowires at room temperature, Journal of Materials Chemistry, 13 (2003) 6-8.

[209] B. Zhang, X. Ye, W. Dai, W. Hou, F. Zuo, Y. Xie, Biomolecule-assisted synthesis of single-crystalline selenium nanowires and nanoribbons via a novel flake-cracking mechanism, Nanotechnology, 17 (2005) 385.

[210] C.M. Debieux, E.J. Dridge, C.M. Mueller, P. Splatt, K. Paszkiewicz, I. Knight, H. Florance, J. Love, R.W. Titball, R.J. Lewis, A bacterial process for selenium nanosphere assembly, Proceedings of the National Academy of Sciences, 108 (2011) 13480-13485.

[211] S. Lampis, E. Zonaro, C. Bertolini, D. Cecconi, F. Monti, M. Micaroni, R.J. Turner, C.S. Butler, G. Vallini, Selenite biotransformation and detoxification by Stenotrophomonas maltophilia SeITE02: novel clues on the route to bacterial biogenesis of selenium nanoparticles, Journal of hazardous materials, 324 (2017) 3-14.

[212] S. Lampis, E. Zonaro, C. Bertolini, P. Bernardi, C.S. Butler, G. Vallini, Delayed formation of zero-valent selenium nanoparticles by Bacillus mycoides SeITE01 as a

consequence of selenite reduction under aerobic conditions, Microbial cell factories, 13 (2014) 1-14.

[213] J. Dobias, E.I. Suvorova, R. Bernier-Latmani, Role of proteins in controlling selenium nanoparticle size, Nanotechnology, 22 (2011) 195605.

[214] A.V. Tugarova, P.V. Mamchenkova, V.A. Khanadeev, A.A. Kamnev, Selenite reduction by the rhizobacterium Azospirillum brasilense, synthesis of extracellular selenium nanoparticles and their characterisation, New biotechnology, 58 (2020) 17-24.

[215] S. Yan, K.Y. Cheng, M.P. Ginige, G. Zheng, L. Zhou, A.H. Kaksonen, High-rate microbial selenate reduction in an up-flow anaerobic fluidized bed reactor (FBR), Science of The Total Environment, 749 (2020) 142359.

[216] L. Li, B. Zhang, C. He, H. Zhang, Hydrodynamics-and hydrochemistry-affected microbial selenate reduction in aquifer: Performance and mechanisms, Science of The Total Environment, 768 (2021) 145331.

[217] B. Song, Z. Tian, R. van der Weijden, C. Buisman, J. Weijma, High-rate biological selenate reduction in a sequencing batch reactor for recovery of hexagonal selenium, Water Research, 193 (2021) 116855.

[218] Z. Zhang, Y. Xiong, H. Chen, Y. Tang, Understanding the composition and spatial distribution of biological selenate reduction products for potential selenium recovery, Environmental Science: Water Research & Technology, 6 (2020) 2153-2163.

[219] O. Otsuka, Y. Yanaba, T. Yoshikawa, M. Yamashita, Fundamental Studies on Oxidizing Roasting of the “Bioselenium”, Materials Transactions, 57 (2016) 1183-1191.

[220] Z.M. Zhang, G. Chen, Y.N. Tang, Towards selenium recovery: Biocathode induced selenate reduction to extracellular elemental selenium nanoparticles, Chemical Engineering Journal, 351 (2018) 1095-1103.

[221] P. Sonkusre, R. Nanduri, P. Gupta, S.S. Cameotra, Improved extraction of intracellular biogenic selenium nanoparticles and their specificity for cancer chemoprevention, Journal of Nanomedicine & Nanotechnology, 5 (2014) 1.

[222] T. Kagami, T. Narita, M. Kuroda, E. Notaguchi, M. Yamashita, K. Sei, S. Soda,

M. Ike, Effective selenium volatilization under aerobic conditions and recovery from the aqueous phase by Pseudomonas stutzeri NT-I, Water research, 47 (2013) 1361-1368.

[223] W. Zhang, Z. Chen, H. Liu, L. Zhang, P. Gao, D. Li, Biosynthesis and structural characteristics of selenium nanoparticles by Pseudomonas alcaliphila, Colloids and Surfaces B: Biointerfaces, 88 (2011) 196-201.

[224] S. Fischer, T. Krause, F. Lederer, M.L. Merroun, A. Shevchenko, R. Hübner, T. Firkala, T. Stumpf, N. Jordan, R. Jain, Bacillus safensis JG-B5T affects the fate of selenium by extracellular production of colloidally less stable selenium nanoparticles, Journal of hazardous materials, 384 (2020) 121146.

[225] B. Zare, S. Babaie, N. Setayesh, A.R. Shahverdi, Isolation and characterization of a fungus for extracellular synthesis of small selenium nanoparticles, Nanomedicine Journal, 1 (2013) 13-19.

[226] L.C. Staicu, E.D. Van Hullebusch, P.N. Lens, E.A. Pilon-Smits, M.A. Oturan, Electrocoagulation of colloidal biogenic selenium, Environmental Science and Pollution Research, 22 (2015) 3127-3137.

[227] L.C. Staicu, E.D. van Hullebusch, M.A. Oturan, C.J. Ackerson, P.N. Lens, Removal of colloidal biogenic selenium from wastewater, Chemosphere, 125 (2015) 130-138.

[228] C.T. Ho, J.W. Kim, W.B. Kim, K. Song, R.A. Kanaly, M.J. Sadowsky, H.-G. Hur, Shewanella-mediated synthesis of selenium nanowires and nanoribbons, Journal of Materials Chemistry, 20 (2010) 5899-5905.

[229] A. Sinharoy, S. Saikia, K. Pakshirajan, Biological removal of selenite from wastewater and recovery as selenium nanoparticles using inverse fluidized bed bioreactor, Journal of Water Process Engineering, 32 (2019) 100988.

[230] Z.M. Zhang, I. Adedeji, G. Chen, Y.N. Tang, Chemical-Free Recovery of Elemental Selenium from Selenate-Contaminated Water by a System Combining a Biological Reactor, a Bacterium-Nanoparticle Separator, and a Tangential Flow Filter, Environmental Science & Technology, 52 (2018) 13231-13238.

[231] G. Zha, B. Yang, H. Luo, D. Huang, W. Jiang, B. Xu, D. Liu, Innovative green approach for the selective extraction of high-purity selenium from hazardous selenium

sludge, Separation and Purification Technology, 266 (2021) 118536.

[232] J. Hait, R. Jana, V. Kumar, S. Sanyal, Some studies on sulfuric acid leaching of anode slime with additives, Industrial & engineering chemistry research, 41 (2002) 6593-6599.

[233] O. Hyvärinen, L. Lindroos, E. Yllö, Recovering selenium from copper refinery slimes, JOM, 41 (1989) 42-43.

[234] D.-k. Lu, Y.-f. Chang, H.-y. Yang, X. Feng, Sequential removal of selenium and tellurium from copper anode slime with high nickel content, Transactions of Nonferrous Metals Society of China, 25 (2015) 1307-1314.

[235] M. Khanlarian, F. Rashchi, M. Saba, A modified sulfation-roasting-leaching process for recovering Se, Cu, and Ag from copper anode slimes at a lower temperature, Journal of environmental management, 235 (2019) 303-309.

[236] P.M. Haygarth, Global importance and global cycling of selenium, Selenium in the Environment, 1 (1994) 1-27.

[237] M. Al Kuisi, A. Abdel-Fattah, Groundwater vulnerability to selenium in semi-arid environments: Amman Zarqa Basin, Jordan, Environmental geochemistry and health, 32 (2010) 107-128.

[238] M. Bajaj, E. Eiche, T. Neumann, J. Winter, C. Gallert, Hazardous concentrations of selenium in soil and groundwater in North-West India, Journal of Hazardous Materials, 189 (2011) 640-646.

[239] G. Zelmanov, R. Semiat, Selenium removal from water and its recovery using iron (Fe3+) oxide/hydroxide-based nanoparticles sol (NanoFe) as an adsorbent, Separation and Purification Technology, 103 (2013) 167-172.

[240] L.E. McDonald, M.M. Strosher, Selenium mobilization from surface coal mining in the Elk River Basin, British Columbia: a survey of water, sediment and biota, (1998).

[241] A.R. Kumar, P. Riyazuddin, Speciation of selenium in groundwater: Seasonal variations and redox transformations, Journal of hazardous materials, 192 (2011) 263-269.

[242] H. Zhang, C. Guo, H. Feng, Y. Shen, Y. Wang, T. Zeng, S. Song, Total mercury, methylmercury, and selenium in aquatic products from coastal cities of China:

Distribution characteristics and risk assessment, Science of The Total Environment, (2020) 140034.

[243] S. Soda, M. Kashiwa, T. Kagami, M. Kuroda, M. Yamashita, M. Ike, Laboratory-scale bioreactors for soluble selenium removal from selenium refinery wastewater using anaerobic sludge, Desalination, 279 (2011) 433-438.

[244] S. Lawson, J. Macy, Bioremediation of selenite in oil refinery wastewater, Applied Microbiology and Biotechnology, 43 (1995) 762-765.

[245] S. Contreras-B, M.L. Lozano-V, Water, endangered fishes, and development perspectives in arid lands of Mexico, Conservation Biology, 8 (1994) 379-387.

[246] A. Lemly, Hazard of selenium to fish and migratory birds at Ouray National Wildlife Refuge, Utah, Blacksburg, VA. US Forest Service, Southern, (1995).

[247] A. Lemly, Preliminary assessment of selenium hazards on Caribou National Forest, Idaho. Blacksburg, VA. US Forest Service, Southern Research Station, Coldwater Fisheries Research Unit, Department of Fisheries and Wildlife Sciences, Virginia Tech University, in, Technical Report, 1999.

[248] A. Tugarova, E. Vetchinkina, E. Loshchinina, A. Shchelochkov, V. Nikitina, A. Kamnev, The ability of the rhizobacterium Azospirillum brasilense to reduce selenium (IV) to selenium (0), Microbiology, 82 (2013) 352-355.

[249] M. Ikram, M. Faisal, Comparative assessment of selenite (SeIV) detoxification to elemental selenium (Se0) by Bacillus sp, Biotechnol. Lett., 32 (2010) 1255-1259.

[250] Y. Yuan, J. Zhu, C. Liu, S. Yu, L. Lei, Biomineralization of Se nanoshpere by Bacillus licheniformis, Journal of Earth Science, 26 (2015) 246-250.

[251] N.S. Khoei, S. Lampis, E. Zonaro, K. Yrjälä, P. Bernardi, G. Vallini, Insights into selenite reduction and biogenesis of elemental selenium nanoparticles by two environmental isolates of Burkholderia fungorum, New biotechnology, 34 (2017) 1-11.

[252] J. Theisen, N. Yee, The molecular basis for selenate reduction in Citrobacter freundii, Geomicrobiology Journal, 31 (2014) 875-883.

[253] F.A. Tomei, L.L. Barton, C.L. Lemanski, T.G. Zocco, N.H. Fink, L.O. Sillerud, Transformation of selenate and selenite to elemental selenium byDesulfovibrio desulfuricans, Journal of Industrial Microbiology, 14 (1995) 329-336.

[254] C.A. Watts, H. Ridley, K.L. Condie, J.T. Leaver, D.J. Richardson, C.S. Butler, Selenate reduction by Enterobacter cloacae SLD1a-1 is catalysed by a molybdenum-dependent membrane-bound enzyme that is distinct from the membrane-bound nitrate reductase, FEMS microbiology letters, 228 (2003) 273-279.

[255] J. Fellowes, Reductive biosynthesis of elemental selenium and tellurium nanoparticles by Geobacter sulfurreducens, The Bacterial Biogenic Synthesis of Magnetic, Catalytic and Semiconducting Nanomaterials, (2018) 174.

[256] X. Xu, W. Cheng, X. Liu, H. You, G. Wu, K. Ding, X. Tu, L. Yang, Y. Wang, Y. Li, Selenate reduction and selenium enrichment of tea by the endophytic Herbaspirillum sp. strain WT00C, Current microbiology, (2019) 1-14.

[257] J. Macy, S. Lawson, Cell yield (Y M) of Thauera selenatis grown anaerobically with acetate plus selenate or nitrate, Archives of microbiology, 160 (1993) 295-298.

[258] J. Zhang, Y. Wang, Z. Shao, J. Li, S. Zan, S. Zhou, R. Yang, Two selenium tolerant Lysinibacillus sp. strains are capable of reducing selenite to elemental Se efficiently under aerobic conditions, Journal of Environmental Sciences, 77 (2019) 238-249.

[259] G. Subedi, J. Taylor, I. Hatam, S.A. Baldwin, Simultaneous selenate reduction and denitrification by a consortium of enriched mine site bacteria, Chemosphere, 183 (2017) 536-545.

[260] M. Ike, K. Takahashi, T. Fujita, M. Kashiwa, M. Fujita, Selenate reduction by bacteria isolated from aquatic environment free from selenium contamination, Water Research, 34 (2000) 3019-3025.

[261] R. Huber, M. Sacher, A. Vollmann, H. Huber, D. Rose, Respiration of arsenate and selenate by hyperthermophilic archaea, Systematic and applied microbiology, 23 (2000) 305-314.

[262] M. Roux, G. Sarret, I. Pignot-Paintrand, M. Fontecave, J. Coves, Mobilization of selenite by Ralstonia metallidurans CH34, Appl. Environ. Microbiol., 67 (2001) 769-773.

[263] W.J. Hunter, L.D. Kuykendall, Reduction of selenite to elemental red selenium by Rhizobium sp. strain B1, Current microbiology, 55 (2007) 344-349.

[264] R.S. Dungan, S.R. Yates, W.T. Frankenberger Jr, Transformations of selenate and selenite by Stenotrophomonas maltophilia isolated from a seleniferous agricultural drainage pond sediment, Environmental Microbiology, 5 (2003) 287-295.

[265] S. Dhanjal, S.S. Cameotra, Aerobic biogenesis of selenium nanospheres by Bacillus cereus isolated from coalmine soil, Microbial cell factories, 9 (2010) 52.

[266] P. Narasingarao, M.M. Häggblom, Sedimenticola selenatireducens, gen. nov., sp. nov., an anaerobic selenate-respiring bacterium isolated from estuarine sediment, Systematic and applied microbiology, 29 (2006) 382-388.

[267] W.J. Hunter, D.K. Manter, Bio-reduction of selenite to elemental red selenium by Tetrathiobacter kashmirensis, Current microbiology, 57 (2008) 83-88.

[268] Y. Zhang, M. Kuroda, S. Arai, F. Kato, D. Inoue, M. Ike, Biological removal of selenate in saline wastewater by activated sludge under alternating anoxic/oxic conditions, Frontiers of Environmental Science & Engineering, 13 (2019) 68.

[269] C.-Y. Lai, X. Yang, Y. Tang, B.E. Rittmann, H.-P. Zhao, Nitrate shaped the selenate-reducing microbial community in a hydrogen-based biofilm reactor, Environmental science & technology, 48 (2014) 3395-3402.

[270] T. Eregowda, E.R. Rene, P.N. Lens, Bioreduction of selenate in an anaerobic biotrickling filter using methanol as electron donor, Chemosphere, 225 (2019) 406-413.

[271] Z. Zhang, G. Chen, Y. Tang, Towards selenium recovery: Biocathode induced selenate reduction to extracellular elemental selenium nanoparticles, Chemical Engineering Journal, 351 (2018) 1095-1103.

[272] N. Srivastava, M. Mukhopadhyay, Biosynthesis and structural characterization of selenium nanoparticles using Gliocladium roseum, Journal of Cluster Science, 26 (2015) 1473-1482.

[273] E. Vetchinkina, E. Loshchinina, V. Kursky, V. Nikitina, Reduction of organic and inorganic selenium compounds by the edible medicinal basidiomycete Lentinula edodes and the accumulation of elemental selenium nanoparticles in its mycelium, Journal of Microbiology, 51 (2013) 829-835.

[274] H. Zhang, H. Zhou, J. Bai, Y. Li, J. Yang, Q. Ma, Y. Qu, Biosynthesis of selenium nanoparticles mediated by fungus Mariannaea sp. HJ and their characterization,

Colloids and Surfaces A: Physicochemical and Engineering Aspects, 571 (2019) 9-16.

[275] T. Wang, L. Yang, B. Zhang, J. Liu, Extracellular biosynthesis and transformation of selenium nanoparticles and application in H2O2 biosensor, Colloids and Surfaces B: Biointerfaces, 80 (2010) 94-102.

[276] Y. Cheng, X. Xiao, X. Li, D. Song, Z. Lu, F. Wang, Y. Wang, Characterization, antioxidant property and cytoprotection of exopolysaccharide-capped elemental selenium particles synthesized by Bacillus paralicheniformis SR14, Carbohydrate polymers, 178 (2017) 18-26.

[277] S. Shoeibi, M. Mashreghi, Biosynthesis of selenium nanoparticles using Enterococcus faecalis and evaluation of their antibacterial activities, Journal of Trace Elements in Medicine and Biology, 39 (2017) 135-139.

[278] A. Presentato, E. Piacenza, M. Anikovskiy, M. Cappelletti, D. Zannoni, R.J. Turner, Biosynthesis of selenium-nanoparticles and-nanorods as a product of selenite bioconversion by the aerobic bacterium Rhodococcus aetherivorans BCP1, New biotechnology, 41 (2018) 1-8.

[279] M.A. Ruiz-Fresneda, A.S. Eswayah, M. Romero-González, P.H. Gardiner, P.L. Solari, M.L. Merroun, Chemical and structural characterization of Se IV biotransformations by Stenotrophomonas bentonitica into Se 0 nanostructures and volatiles Se species, Environmental Science: Nano, 7 (2020) 2140-2155.

[280] Y.-H. Cui, L.-L. Li, N.-Q. Zhou, J.-H. Liu, Q. Huang, H.-J. Wang, J. Tian, H.-Q. Yu, In vivo synthesis of nano-selenium by Tetrahymena thermophila SB210, Enzyme and Microbial Technology, 95 (2016) 185-191.

[281] N. Srivastava, M. Mukhopadhyay, Biosynthesis and structural characterization of selenium nanoparticles mediated by Zooglea ramigera, Powder technology, 244 (2013) 26-29.

[282] M. Rovira, J. Giménez, M. Martínez, X. Martínez-Lladó, J. de Pablo, V. Marti, L. Duro, Sorption of selenium (IV) and selenium (VI) onto natural iron oxides: goethite and hematite, Journal of hazardous materials, 150 (2008) 279-284.

[283] Z. Ma, C. Shan, J. Liang, M. Tong, Efficient adsorption of Selenium (IV) from water by hematite modified magnetic nanoparticles, Chemosphere, 193 (2018) 134-141.

[284] M. Martinez, J. Giménez, J. De Pablo, M. Rovira, L. Duro, Sorption of selenium (IV) and selenium (VI) onto magnetite, Applied Surface Science, 252 (2006) 3767-3773.

[285] Z. Lu, J. Yu, H. Zeng, Q. Liu, Polyamine-modified magnetic graphene oxide nanocomposite for enhanced selenium removal, Separation and Purification Technology, 183 (2017) 249-257.

[286] W. Cui, P. Li, Z. Wang, S. Zheng, Y. Zhang, Adsorption study of selenium ions from aqueous solutions using MgO nanosheets synthesized by ultrasonic method, Journal of Hazardous Materials, 341 (2018) 268-276.

[287] Y.N. Larimi, M.H. Mallah, M.A. Moosavian, J. Safdari, Fabrication of a magmolecule using nanoparticle and evaluation of its adsorption capacity for selenium ions from nuclear wastewater, Journal of Radioanalytical and Nuclear Chemistry, 298 (2013) 1511-1518.

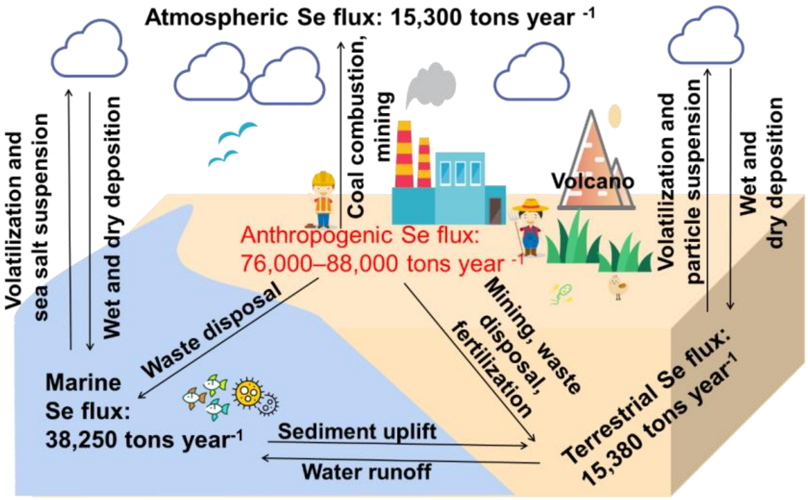


Fig. 1. Global Se flux and cycling in the ecosystem (data from [30, 236]).

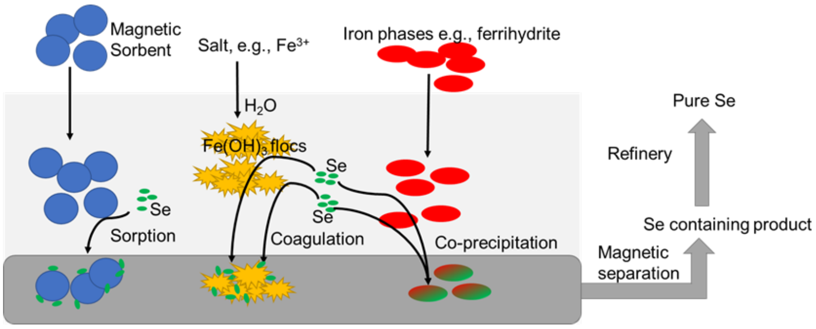


Fig. 2. Se removal and recovery by sorption, coagulation and co-precipitation followed by magnetic separation and product refining (mechanisms are from [86, 111, 113]).

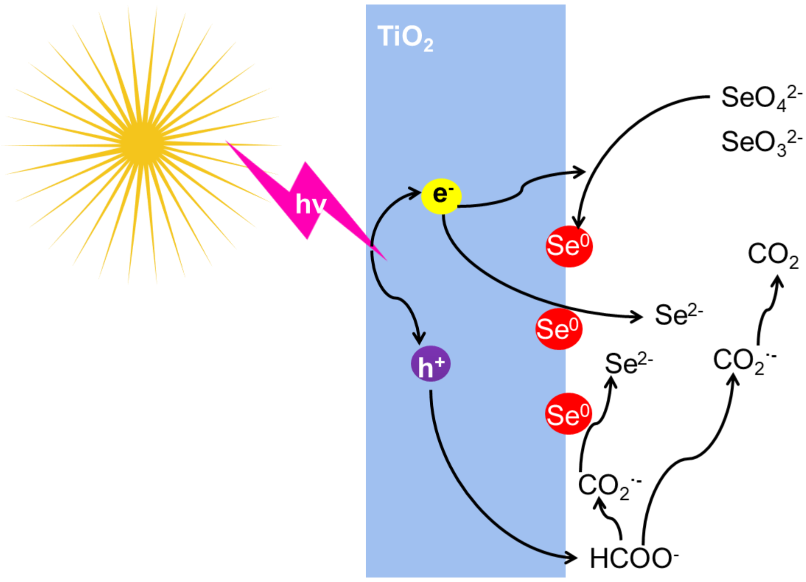


Fig. 3. Photocatalytic reduction process of SeO_4^{2-} and SeO_3^{2-} to solid Se(0) and gaseous Se(-II) by TiO_2 in the presence of formic acid (mechanism is from [136]).

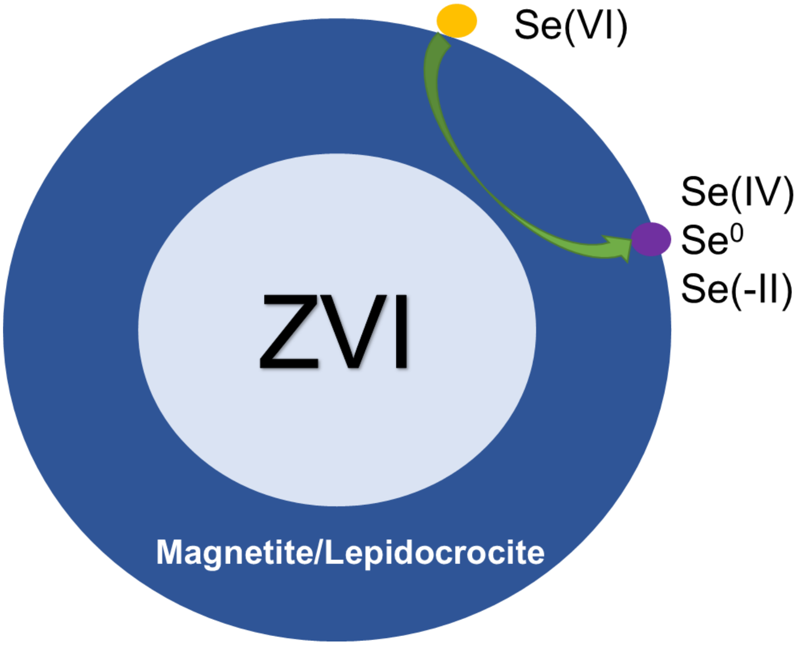
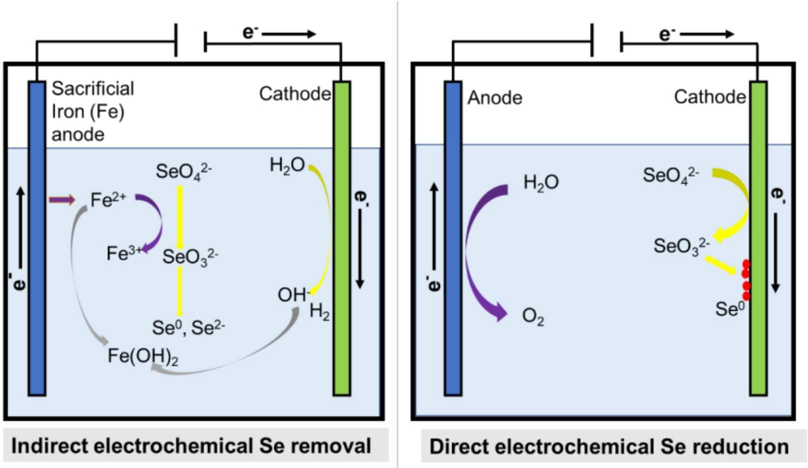


Fig. 4. Reduction and adsorption of selenate by zero-valent iron (ZVI) (mechanisms are from [142]).



Indirect electrochemical Se removal

Direct electrochemical Se reduction

Fig. 5. Comparison of indirect and direct electrochemical Se removal (mechanisms are from [117] and [175]).

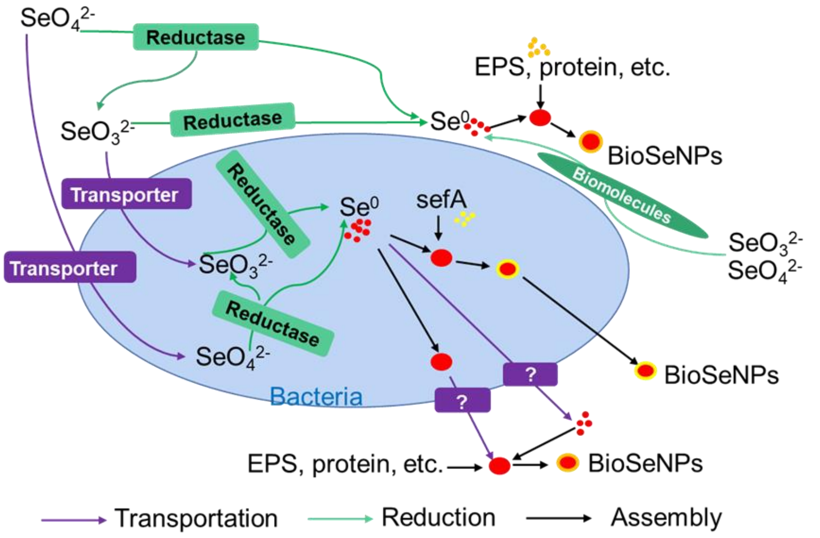


Fig. 6. Schematic model for representative SeO_4^{2-} and SeO_3^{2-} reduction by bacteria (summarized and adapted from [182, 205, 206].

Table 1. Se concentration in contaminated location and cases for contaminated wildlife (adapted and updated from [25])

Contamination	**Se source**	**Se concentration**	**Major aquatic life contaminated**	**Ref.**
Amman Zarqa Basin (AZB), Jordan	Lower aquifer	1.6–30 µg L^{-1}		[237]
	Middle aquifer	1.5–742 µg L^{-1}		
	Upper aquifer	0.4–246 µg L^{-1}		
Barwa, Jainpur	Groundwater	341 µg L^{-1}		[238]
California's San Joaquin Vally	Drainage water of soils	75–1400 µg L^{-1}		[239]
Canada	Coal mining waste		Stream fish	[240]
Chandigarh, India	Groundwater	0.9 µg L^{-1}		[238]
	Groundwater	0.15–0.43 µg L^{-1} [Se(IV)]		[241]
		0.16–4.73 µg L^{-1} [Se(IV)]		
China	Seleniferous soils	up to 59 mg kg^{-1}		[238]
			Shellfish, muscles, etc.	[242]
Hisar	Groundwater	3.2 µg L^{-1}		[238]

Ireland	Seleniferous soils	up to 1200 mg kg^{-1}		[238]
Japan	Industrial wastewater	$\leq$ 0.1 mg L^{-1}		[243]
	Kiln powder leachate from a cement-manufacturing plant	2–42 mg L^{-1}		[192]
	Se refinery wastewater	13.2–74.0 mg L^{-1}		[244]
Mexico	Irrigation drainage		Stream and river fish	[245]
	Discharge mine and process waters of the uranium mine	1.6 mg L^{-1}		[224]
India	Groundwater	669.5 mg L^{-1}		[238]
	Plants	3–670 mg kg^{-1}		[238]
	Soil	6.5 mg kg^{-1}		[238]
USA	Coal combustion waste	-	Reservoir fish	[46]
	Irrigation drainage	-	Fish, aquatic birds	[246]
	Phosphate mining waste	-	Fish, aquatic birds	[247]
	Seleniferous soils	up to 28 mg kg^{-1}		[238]

Table 2. Identified microorganisms with the ability of Se oxyanion reduction.

Organism	**Origin**	**Growing condition**	**Se(0) formation location**	**Electron acceptor**	**Ref.**
Azospirillum brasilense	Culture collection of the Institute of Biochemistry and Physiology of Plants and Microorganisms	Aerobic	Intracellular	SeO_3^{2-}	[248]
Bacillus cereus	Inverse fluidised bed bioreactor	Anaerobic	Extracellular and intracellular	SeO_3^{2}	[229]
Bacillus licheniformis	Contaminated soil and water	Anaerobic	Extracellular and intracellular	SeO_3^{2}-	[249, 250]
Burkholderia fungorum	Oil refinery drainage	Anaerobic	Intracellular	SeO_3^{2-}	[251]
Citrobacter freundii	Marine and freshwater settings	Anaerobic	Intracellular	SeO_4^{2-}	[252]
Desulfovibrio desulfuricans	German Culture Collection in Braunschweig,		Intracellular	SeO_4^{2-}, SeO_3^{2-}	[253]
Enterobacter Cloacae		Aerobic and Anaerobic	Extracellular	SeO_4^{2-}, SeO_3^{2-}	[254]
Geobacter sulfurreducens			Extracellular	SeO_3^{2-}	[255]
Herbaspirillum	Ornamental tea plant	Aerobic	Extracellular	SeO_4^{2-}, SeO_3^{2-}	[256]
Thauera selenatis			Extracellular	SeO_4^{2-}, SeO_3^{2-}	[257]
Lysinibacillus macrolides,	Naturally occurred Se-rich soil	Aerobic	Extracellular and intracellular	SeO_3^{2-}	[258]
Lysinibacillus xylanilyticus	Naturally occurred Se-rich soil	Aerobic	Extracellular and intracellular	SeO_3^{2-}	[258]
Pseudomonas	Mine impacted natural marsh sediment			SeO_4^{2-}	[259]
Pseudomonas stutzeri		Aerobic		SeO_4^{2-}, SeO_3^{2-}	[260]
Pseudomonas fluorescens		Aerobic		SeO_3^{2-}	[260]

Formatted: Font: Times New Roman, Bold

Pyrobaculum arsenaticum	Hot spring at Pisciarelli Solfatara, Naples, Italy	Anaerobic		SeO_4^{2-}, SeO_3^{2-}	[261]
Ralstonia metallidurans	Metal-contaminated biotopes	Aerobic	Extracellular and intracellular	SeO_3^{2-}	[262]
Rhizobium	A laboratory bioreactor	Aerobic		SeO_3^{2-}	[263]
Salmonella Heidelberg	Alberta Provincial Laboratory of Public Healt		Intracellular	SeO_3^{2-}	[180]
Stenotrophomonas maltophilia	Seleniferous agricultural drainage pond sediment	Aerobic	Extracellular	SeO_4^{2-}, SeO_3^{2-}	[264]
Shewanella oneidensis	Uranium mining waste pile	Aerobic	Extracellular	SeO_3^{2-}	[224]
Shewanella putrefaciens	Coalmine soil	Aerobic	Extracellular	SeO_3^{2-}	[265]
Sedimenticola selenatireducens	Estuarine sediment	Anaerobic		SeO_4^{2-}	[266]
Stenotrophomonas maltophilia	*Astragalus bisulcatus* grown in a seleniferous soil (Se hyperaccumulator plant)		Extracellular	SeO_4^{2-}, SeO_3^{2-}	[211]
Tetrathiobacter kashmirensis	Soil	Aerobic		SeO_3^{2-}	[267]
Thauera selenatis		Anaerobic	Extracellular	SeO_4^{2-}	[191]

Table 3. Se oxyanion reduction in various bioreactors.

Bioreactor	**Inoculum**	**Se containing water**	**Electron donor**	**Dissolved oxygen**	**Initial pH**	**Temperature (℃)**	**HRT**	**Electron acceptor**	**Dominant bacteria**	**Reduction efficiency**	**Ref.**
Sequencing batch reactor	Activated sludge	Synthetic wastewater with 3% salinity	44 mM sodium lactate	Alternating anoxic/oxic conditions	7.0–7.1	-	3.75 d	395 mg L^{-1} Se(VI)	*Alcaligenes aquatilis; Peptoclostridium; Soehngenia Saccharolytica; Marinobacterium halophilum*	97%	[268]
Batch bottle	Anaerobic granular sludge	Synthetic wastewater	20 mM Sodium lactate	Anaerobic conditions	7.5	30	7 d	10 mg L^{-1} Se(VI)	*Methanobacterium; Bacteroidetes; Methanosaeta; Anaerolinea; Syntrophobacter*	98%	[146]
Biofilm reactor	Activated sludge	Synthetic mineral medium	2.5 psig (gauge pressure or 1.17 atm) H_2	7.7 -8.0 mg L^{-1} O_2	7.0 ± 0.2	-	130 mins	1 mg L^{-1} Se(VI); NO_3^-	*Hydrogenophaga; Dechloromonas; Methyloversatilis;*	60%	[269]

Biorickling filter	Activated sludge	Synthetic mineral medium	Methanol	Anaerobic conditions	7.5 ±0.1	Room temperature	18.4 mins	29 mg L^{-1} Se(VI)	-	90%	[270]
Two-chamber bioelectrochemical reactors	Activated sludge	Synthetic mineral medium	10 mg C L^{-1} of sodium acetate	Anaerobic conditions	7.0 ± 0.1	-	1.45 days	5 mg L^{-1} Se(VI)	-	99.6%	[271]

Table 4. Cases for microorganisms successfully applied in nano-Se synthesis.

Microorganisms	Se Source	Operating condition	Medium	Reaction time	Observed BioSeNPs deposit location	BioSeNPs morphology description	Ref.
Fungi							
Aspergillus terreus	80 mg L^{-1} Se(IV)	Aerobic and anaerobic; 30 ℃;	Culture supernatant	1 h	Extracellular	Spherical particles with average size of 47 nm.	[225]
Gliocladium roseum	118.5 mg L^{-1} Se(VI)	Aerobic；30 ℃；	Sterilized potato dextrose broth	24 h	Extracellular	Around 20–80 nm with some large particles of more than 100 nm and below 130 nm	[272]
Lentinula edodes	24 mg L^{-1} Se(VI) or Se(IV)	26 ℃	Beer wort	14 d	Intracellular	180.51 ± 16.82 nm Se(0) particles.	[273]
Mariannaea sp. HJ	79 mg L^{-1} Se(IV)	Aerobic; 30 ℃; pH at 10	Martin medium	4 d	Extracellular and Intracellular	The average size of intracellular BioSeNPs and extracellular BioSeNPs were calculated to be 45.19 and 212.65 nm, respectively.	[274]
Bacteria							

Azospirillum brasilense	Se(IV)	Aerobic; pH at 6.8–7.0.	Malate salt medium	18 h	Extracellular and Intracellular	Increasing the initial SeO_3^{2-} concentration resulted in smaller BioSeNPs. Their predominant size was 78−84 nm for 790 mg L^{-1} SeO_3^{2-}, 40-50 nm for 25 mM SeO_3^{2-}, and 25-28 nm for 50 mM SeO_3^{2-}.	[214]
Bacillus cereus	158 mg L^{-1} Se(IV)	pH at 7	Tryptic Soya Broth		Extracellular and Intracellular	150-200 nm.	[265]
Bacillus subtilis	316 mg L^{-1} Se(IV)$^-$	35 °C; pH at 7	Lysogeny broth	48 h	Extracellular	Spherical shaped with diameters ranging from 50 to 400 nm.	[275]
Bacillus paralicheniformis SR14	Se(IV)	37 °C; pH at 7	Synthetic medium	72 h	Extracellular and Intracellular	Particles ranged from 160 nm to 450 nm, with an average of 293.73 ± 4.03 nm.	[276]
Enterococcus faecalis	235 mg L^{-1} Se(IV)	Aerobic; 37 °C; pH at 7;	Broth medium	24 h	Extracellular	Spherical in shape with a size range of 29–195 nm.	[277]
Pseudomonas alcaliphila	790 mg L^{-1} Se(IV)	Aerobic 28 °C	Synthetic medium	48 h	-	During incubation: spherical particles with diameters from 50-500 nm. After incubation: nanorods.	[223]
Pseudomonas stutzeri NT-I	40 mg L^{-1} SeO_4^{2-}	Aerobic 40 °C	Synthetic medium	24 h	Extracellular and Intracellular	-	[12]

Rhodococcus aetherivorans	SeO_3^{2-}	Aerobic	Extracellular	Nanoparticles and Nanorods.	[278]
Stenotrophomonas bentonitica	SeO_3^{2-}	Aerobic	Extracellular and Intracellular		[279]
Tetrahymena thermophila SB210	SeO_3^{2-}	-	Intracellular	Red spherical selenium nanoparticles with diameters of 50 – 500 nm.	[280]
Zooglea ramigera	SeO_3^{2-}	Aerobic	Extracellular and Intracellular	Spherical in shape with the size range of 30 nm to 150 nm	[281]

Table 5. Sorption of Se(VI) and Se(IV) by magnetic sorbents.

Sorbent	**Sorbent dosage (g L^{-1})**	**Temperature (℃)**	**Specific surface area (m^{2} g^{-1})**	**pH**	**Sorbate**	**Isotherm**	**Kinetics**	**Maximum sorption capacity (mg g^{-1})**	**Ref.**
Goethite	5	Room temperature	2.01	7.5	1.6 mg L^{-1} Se(IV)	Langmuir	2nd	0.67	[282]
					1.6 mg L^{-1} Se(VI)	Langmuir	2nd	0.22	
Hematite modified magnetic nanoparticles	0.1	25	79.0	7	0-120 mg L^{-1} Se(IV)	Langmuir; Freundlich	2nd	25	[283]
Magnetite	0.1	Room temperature	0.89	4	0.05-39.5 mg L^{-1} Se(IV)	Langmuir		0.25	[284]
					0.05-39.5 mg L^{-1} Se(VI)	Langmuir		0.22	
Graphene oxide composites	1	25	NA	NA	0-100 mg L^{-1} Se(IV)	Langmuir; Freundlich		27.5	[99]
					0-100 mg L^{-1} Se(VI)	Langmuir; Freundlich		15	
Polyamine-modified magnetic graphene oxide nanocomposite	15.2×10^{-6}	Room temperature	NA	5.8	0-10 mg L^{-1} Se(IV)	Freundlich	2nd	120.1	[285]
					0-10 mg L^{-1} Se(VI)	Freundlich	2nd	83.7	
MgO nanosheets	0.03	25	166.44	10.5	1-100 mg L^{-1} Se(IV)	Langmuir	2nd	103.2	[286]

					1-100 mg L^{-1} Se(VI)	Langmuir	2nd	10.28	
Amino-functionalized magnetite nanoparticles	1	25	95.39	2.4	22.8 mg L^{-1} Se(IV)	NA	NA	38	[287]
Fe-impregnated biochar from food waste	2	25	NA	3	10-1000 mg L^{-1} Se(VI)$^{-}$	Freundlich	1st	11.7	[102]