



# A critical analysis of sources, pollution, and remediation of selenium, an emerging contaminant

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**Abstract** Selenium (Se) is an essential metalloid and is categorized as emerging anthropogenic contaminant released to the environment. The rise of Se release into the environment has raised concern about its bioaccumulation, toxicity, and potential to cause serious damages to aquatic and terrestrial ecosystem. Therefore, it is extremely important to monitor Se level in environment on a regular basis.

Understanding Se release, anthropogenic sources, and environmental behavior is critical for developing an effective Se containment strategy. The ongoing efforts of Se remediation have mostly emphasized monitoring and remediation as an independent topics of research. However, our paper has integrated both by explaining the attributes of monitoring on effective scale followed by a candid review of widespread

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technological options available with specific focus on Se removal from environmental media. Another novel approach demonstrated in the article is the presentation of an overwhelming evidence of limitations that various researchers are confronted with to overcome achieving effective remediation. Furthermore, we followed a holistic approach to discuss ways to remediate Se for cleaner environment especially related to introducing weak magnetic field for ZVI reactivity enhancement. We linked this phenomenal process to electrokinetics and presented convincing facts in support of Se remediation, which has led to emerge 'membrane technology', as another viable option for remediation. Hence, an interesting, innovative and future oriented review is presented, which will undoubtedly seek attention from global researchers.

**Keywords** Selenium · Contamination · Remediation technology · Bioremediation · Waste water

## Introduction

Selenium (Se) belongs to group VIA with atomic number 34, located just below sulfur on the periodic table. Environmental Se contamination is caused by both natural and anthropogenic sources (Sharma et al., 2018). In trace amounts, for all living organisms including humans, animals, plants, etc., it is a crucial and necessary nutrient; however, the gap between nutritional deficiencies and harmful thresholds is quite narrow (Huang et al., 2019a, b). At low concentrations, it is also beneficial to our health. In contrast, increased environmental Se level causes significant contamination in the soil, air, and water, as well as posing a serious health threat to humans (He et al., 2018a, b). In addition to its effects on humans, Se is a major threat to the water environment as well. Illegitimate discharge of Se-containing wastewater is a tragedy for marine environments, causing fish disfigurement and mortality in nearby lakes (Zou et al., 2020). Environmental Se is naturally found as metalloid that is released by natural weathering activities taking place at the crust part of the Earth (Zou & Mauter, 2021). Se contamination may also occur as a result of man-made actions like metal smelting, mining, coal-fired plants, oil refineries, and agricultural drainage (Gan et al., 2021).

Se(IV) has a higher toxicity than Se(VI). Se levels in soils are estimated to range between 0.01 and 2 mg kg<sup>-1</sup>, with global mean value of 0.4 mg kg<sup>-1</sup>. However, increased Se content (1200 mg kg<sup>-1</sup>) has been found in some seleniferous soils (Ullah et al., 2018a, b, c). Se-deficient soils contain <0.5 mg kg<sup>-1</sup> Se. Se deficiency is observed in humans when daily Se ingestion is <0.4 mg per day. Chronic toxicity develops at concentration of >0.4 mg/day (Zafeiriou et al., 2020). For a long time, the ideal dietary intake of Se has sparked heated disputes, which are still ongoing. In the literature, the values 0.04–0.05 mg Se per day are most usually reported as an ideal Se intake. The Institute of Medicine of the National Academy of Sciences of US established a tolerable upper consumption threshold of 0.4 mg/day for adults. European Food Safety Authority (EFSA) set adequate Se intake as 0.07 mg/day for adults and 0.085 mg/day for lactating women (Solovyev et al., 2021). The recommended dietary allowance (RDA) set by World Health Organization (WHO) for human diet is 0.05–0.055 mg Se/day, which one should take from food or any other supplements (Schiavon et al., 2020). In natural, water conditions its concentrations ranging from less than 0.0001 to more than 2 mg Se per liter. Se concentrations are higher in water affected by farm residue, wastewater from power plants, and industrial effluents. Because of its toxic nature and bioaccumulation via food chains in the adjacent biome, the high Se levels in water must be monitored and treated properly. The (United states environmental protection agency) USEPA lay down a maximum contaminant level (MCL) of 50 µg Se (total Se) per L in drinking water (Zhang et al., 2020a, b, c). Due to their high mobility and bioavailability, the two oxidized Se types, (Se(VI) and (Se(IV), are normally soluble and more harmful to biological systems (Zhou et al., 2019). At concentrations greater than 50 µg/L, Se(IV) and Se(VI) ions were classified as toxic elements. They were also discovered to be the dominant species in the marine world (Das et al., 2020). Furthermore, the Se(IV) and Se(VI) ions have detrimental health effects such as monstrous deformities, hair and nail loss, skin and eye irritation, gastrointestinal abnormalities, and neurological harm (He et al., 2020).

According to reports from various countries (USA, China, India, etc.), high levels of Se from polluted soils enter the food chain, causing major health

problems in animals and humans. Besides necessary nutrients, plants can absorb and accumulate potentially toxic metals like Se as well (Schiavon & Vecchia, 2017). To address this issue, contaminated areas are cleaned using a plant-based process known as "phyto-remediation." The key motive for introducing phyto-remediation is the potential for low-cost remediation. Phyto-remediation relies on a number of processes, which are efficient, environmentally friendly, and cost-effective (Muthusarayanan et al., 2018).

## Research method

The technique being applied in this review paper consists of two phases: (1) literature compilation and classification via searching information in databases according to a set of instructions, and (2) assessing and debating expertise by extracting knowledge based on technological efficiency on various toxic forms of Se.

### Literature compilation and classification

Literature information about the relevant topic was gathered by conducting a thorough search of Elsevier's, Web of Science's, Science Direct and Scopus' databases using relevant phrases and key words such as "Environmental Se contamination" or "bioremediation approaches" or "Se contaminated soil and water" and so on. Experimental methods, new derived innovations and technologies, and broad-spectrum developments in a variety of fields were the primary consideration used. Moreover, most related research works were assessed to see if they fit inside the scope of the research framework. To obtain available data, published reviews on Se were found and applied. The related articles identified were included when examining or evaluating other research works to guarantee the authenticity of all applicable published literature.

### Assessment and debating on the compiled literature

Assessment and debating on the compiled literature were done through expertise by extracting knowledge based on technological efficiency on various toxic forms of Se. It is critical to determine how the

articles will be used to do an appropriate analysis after conducting the literature review and selecting a final sample. After choosing a final sample, a consistent method for extracting relevant information from each article was applied. Data were abstracted in the form of descriptive information, such as authors, years of publication, topic, or study type, or impacts and findings. It could also take the shape of conceptualizations of a certain notion or theoretical viewpoint. This was done in accordance with the current review's goal and research question.

## Global sources of Se release

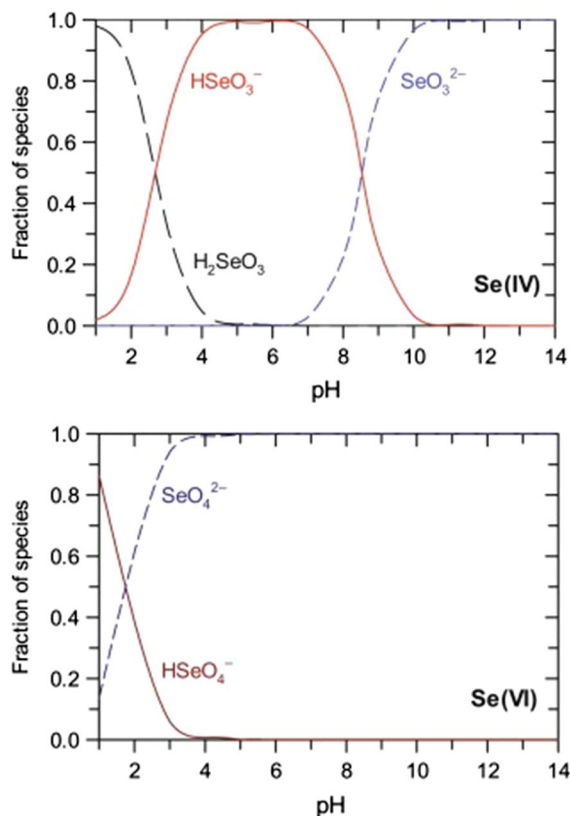
The release of selenium (environmental Se contamination) into the environment can be caused by both natural and man-made mechanisms. Volcanic eruptions, rock weathering, and other natural processes are examples of natural sources (Reich & Hondal, 2016), while industrial and agriculture production, coal combustion, oil refining, fossil fuel, insecticide production, mining, glass manufacture and photocells, and metallurgy are examples of non-natural sources (Ullah et al., 2017, 2018a, b, c; Zou et al., 2020). Se is among the most volatile trace elements in coal, and it is mainly emitted as vapor, primarily as  $\text{SeO}_2$  and  $\text{SeO}_3$  (Ullah et al., 2018a, b, c). One of the major cause of environmental Se is coal combustion. To address this problem, advanced safety technologies and appropriate discharge protocols are needed (Zou et al., 2020).

We don't have any mines that specifically provide Se on a worldwide platform. Se is most commonly derived from selenide in sulfide ores including copper, nickel, and lead. Electrolytic metal processing produces a lot of Se as a by-product, which comes from copper refineries' anode dust. Another source was mud from sulfuric acid plants' lead chambers, a method which is no more employed (El-Ramady et al., 2014). Se reserves are estimated using known copper deposits and average Se content. Se concentrations in coal range from 0.5 to 12 parts per million, or 80 to 90 times the average for copper deposits. Although practically viable, Se recovery from coal fly ash does not seem to be economically viable in the near future (U.S. Geological Survey, 2020).

## Selenium uses and its global production

Se's fundamental opto-electrical existence necessitates its commercial significance in nanotechnology. Se does have photovoltaic (light-to-electricity) and a photoconductive operation; as a result, it can be used in photocells, solar cells, and photocopiers. It is also commonly used in rectifiers because it can transform electric power to electricity (Macaskie et al., 2010). The most widespread application of Se is as an additive to glass. Glass is de-colored by some Se compounds, while others produce a deep red color. Architectural glass could also be tinted with Se to minimize sunlight transmission and giving it a bronze color. Se is used to make pigments for ceramics, paint, rubber, and plastics (Natasha et al., 2018). According to data from the United States Geological Survey (Anderson, 2017), 40% of Se is consumed for metallurgy, about 25% for glass production, 10% for agriculture, 10% for pigments and chemical industries, 10% for electronic products, and 5% for other uses. More than 80% of the commercially available Se is derived from anode slime, a by-product of Cu refining and electrolytic processing, as well as from the mining of metals such as Ni, Pb, Zn, and platinum group metals (Ullah et al., 2018a, b, c). Apart from its industrial and agricultural applications, Se is an important trace ingredient that is used as a supplement for human and animal diet.

The world's largest and leading countries for Se production are Japan, Belgium, Germany, and Canada as portrayed in Fig. 1. Se production is expected to be about 2500–2800 tonnes per year globally. Despite the fact that some countries, such as China, Russia, Finland, and Belgium, have Cu-refining industries, their Se output levels are still too low (Ullah et al., 2018a, b, c). China produced an estimated 920 tons of Se in 2016, a 13% increase from 2015 (Indian bureau of mines, 2020). As per the report of World Bureau of Metal Statistics, Se productivity in China was over 0.9 million metric tons in 2019, whereas it was around 2.2 million metric tons in Asia as a whole.



**Fig. 1** Speciation diagrams of selenite [ $\text{SeO}_3^{2-}$ , Se(IV)] and selenate [ $\text{SeO}_4^{2-}$ , Se(VI)] as a function of pH; conditions: zero ionic strength at 25 °C, and 1 bar pressure. Reproduced with the permission of Sharma et al., (2018)

## Physicochemical characteristics and toxicity/essentiality

### Se types and its chemical characteristics

Se is a nonmetal with an atomic number of 34 and an atomic mass of 78.96 in the group 16 of the periodic table (Ullah et al., 2018a, b, c), positioned between Sulfur and tellurium. This group is known as Oxoacids. Chemical features of group 16 change dramatically as the atomic mass of the elements increases (Kieliszek, 2019). Atoms with the same atomic number but a varying number of neutrons (different mass numbers) in their nuclei are called isotopes of an element. There are over 20 distinct isotopes of selenium, but only a few of them are stable (Chemistry of Selenium (Z=34), 2021). The six naturally found isotopes of Se are  $^{74}\text{Se}$  (0.89%),  $^{82}\text{Se}$  (8.73%),  $^{76}\text{Se}$  (9.32%),

<sup>77</sup>Se (9.63%), <sup>78</sup>Se (23.77%), and <sup>80</sup>Se (49.61%). Fission produces major isotopes like <sup>77</sup>Se, <sup>78</sup>Se, <sup>79</sup>Se, and <sup>80</sup>Se, which are stable in nature (Naga Jyothi et al., 2020). It is widely recognized that the chemical form of Se has a significant impact on its toxicity, especially the toxicity profiles of inorganic and organic Se compounds differ significantly, with the latter being far less harmful than the former (He et al., 2018a, b). Se is distinguished by the convenience with which it transforms between oxidation forms. Several factors affect these transformations; including pH, free oxygen concentration, redox potential, and humidity. The formation of Se compounds in lower oxidation states is favored by anaerobic and acidic environments. Higher oxidation states of this element are prevalent under aerobic environment and at alkaline pH (Kieliszek & Błazejak, 2016). Some selected Se's physicochemical features and natural isotope content are listed in Table 1.

Se, [Ar] 4s<sup>2</sup>3d<sup>10</sup>4p<sup>4</sup> as a member of group 16 (6A or chalcogens), discovered by J. J. Berzelius, is too much similar to sulfur from chemical perspective. The Se atom's preferred coordination is two, with a bond angle of 105°. In its condensed state, Se's bonding configuration is very flexible, and it can take on various allotropic forms (Saji & Lee, 2013). Some selected characteristics and appearance of Se are depicted in Fig. 2. Se occurs in five allotropic forms in its free state, two of which are amorphous and the other three are crystalline (Chemistry of Selenium (Z=34), 2021).

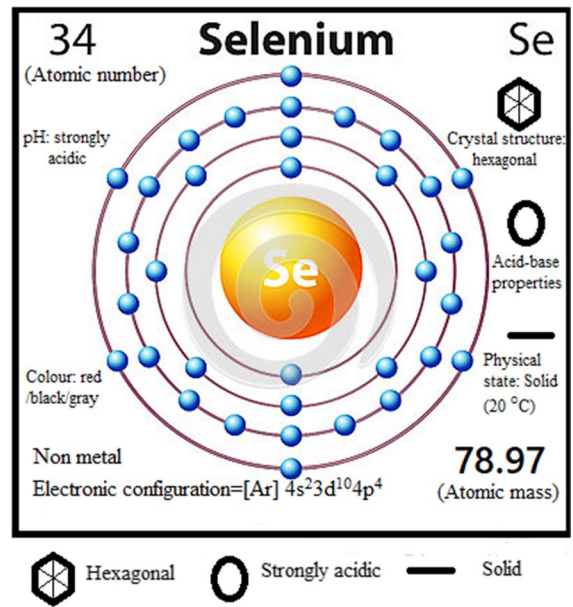


Fig. 2 Characteristics and appearance of selenium

Several reagents react with Se chemically, letting it to be infused into organic compounds. In addition, symmetric or non-symmetric diselenides are frequently used as raw material for more complicated chalcogen-containing derivatives (Gebreyessus & Zewge, 2019). Se forms hydrogen selenide (H<sub>2</sub>Se), in the same way as other chalcogens do. It's a noxious, colorless gas with a heavy odor. It has a higher acidity than H<sub>2</sub>S and ionizes into HSe<sup>-</sup> in solution

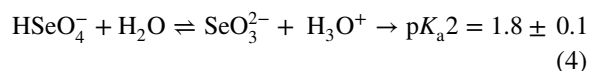
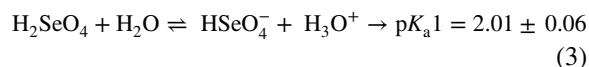
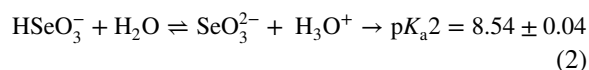
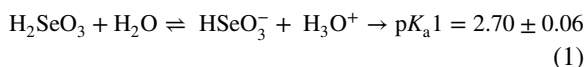
**Table 1** Selected physicochemical characteristics and natural isotopic abundance of Se; Source: Adapted from Pons et al. (2020); Kieliszek, (2019); Fordyce (2013) and Ullah et al., (2018a, b, c)

Name of element	Selenium	Natural isotopes of Se	Abundance (in %)
Chemical representation	Se	<sup>80</sup> Se	49.60
Position in the periodic table	VIA	<sup>78</sup> Se	23.77
Atomic number	34	<sup>76</sup> Se	9.36
Density	4.808 g cm <sup>-3</sup>	<sup>77</sup> Se	7.63
Atomic mass	78.97	<sup>74</sup> Se	0.88
Electronic configuration	[Ar] 3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>4</sup>	<sup>82</sup> Se	8.73
Boiling point	685 °C		
Melting point	220 °C		
Oxidation states	- II, 0, IV, VI		
Vapor pressure	1 mmHg @ 356 °C		
Electron affinity	- 4.3 Ev		
Ionization potential	9.75 Ev		

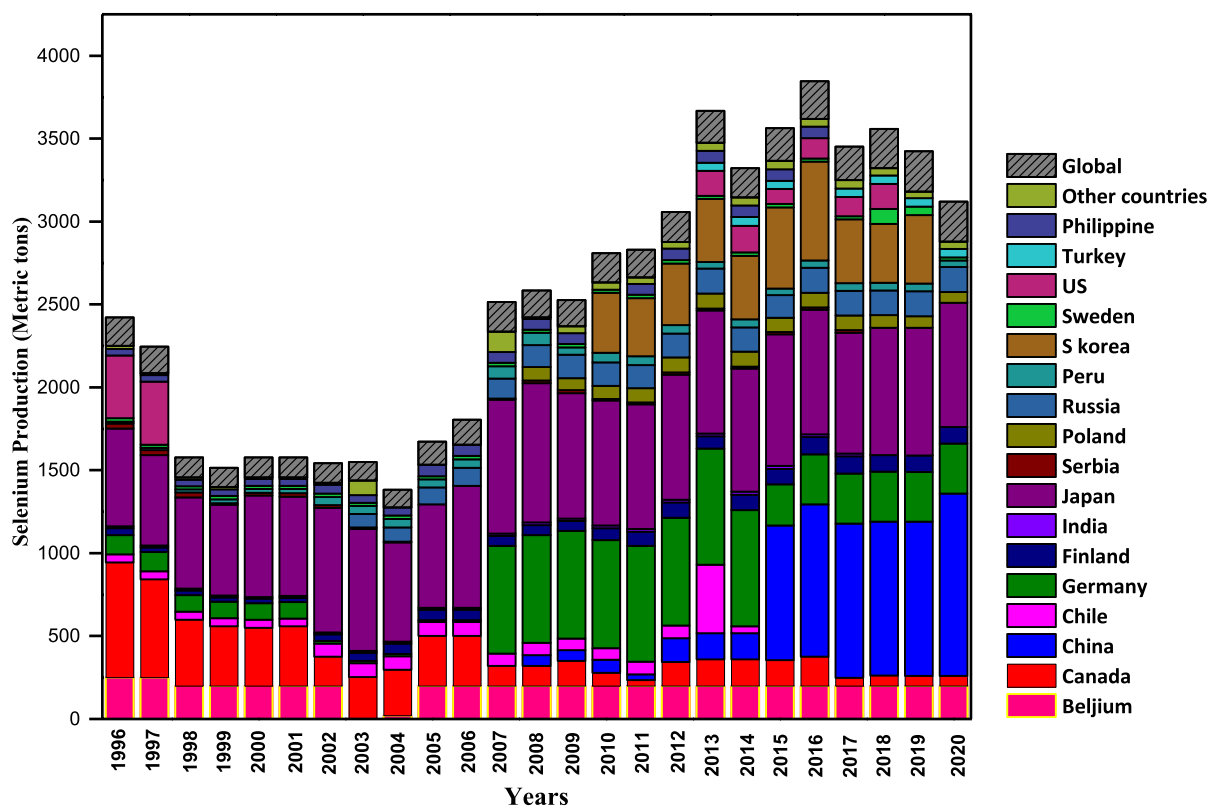


(Devi et al., 2017a). Despite the fact that Se alone is not that much poisonous, however, numerous of its compounds are highly toxic. As an instance  $\text{H}_2\text{Se}$  is a harmful colorless gas with a foul odor. For most metals, it produces selenides (e.g.,  $\text{AlSe}_3$ ,  $\text{CdSe}$  and  $\text{Na}_2\text{Se}$ ). Se is found in groundwater in soluble phases of Se (+VI), Se (+IV), and Se (-II). Because of its higher bioavailability, Se (+IV) is much more harmful (Gebreyessus & Zewge, 2019).

Se(IV) and Se(VI) have especially significant environmental consequences (Lin et al., 2020); the inorganic forms of Se (IV;  $\text{SeO}_3^{2-}$  and VI;  $\text{SeO}_4^{2-}$ ) exist as diprotic acid in the form of selenious acid ( $\text{H}_2\text{SeO}_3$ ) and selenic acid ( $\text{H}_2\text{SeO}_4$ ), respectively. The reactions of dissociation and their  $\text{p}K_a$  values are described in the following reactions (Sharma et al., 2018):



Based on  $\text{p}K_a$  values, speciation diagrams are depicted in Fig. 3. The pH of natural waters ranges from 5.0 to 9.0, indicating that both  $\text{HSeO}_3^-$  and  $\text{SeO}_3^{2-}$  Se(IV) species are present. In comparison, the dominating Se(VI) species in the same pH range would be  $\text{SeO}_4^{2-}$ . Se bioavailability is strongly influenced by pH, and it increases as pH rises (Sarwar et al., 2020).



**Fig. 3** Global annual selenium refinery production for different countries across the world (1996–2020). Adapted and Reproduced with permission from ‘(Ullah et al., 2018a, b, c)’

## Se toxicity and essentiality

Selenium toxicity in the human health was first established in the 1960s based on its harmful effects. Since it is a trace and essential constituent, only a trace amount is required to preserve its vital physiological functions. At high concentrations, it is said to cause toxicity and oxidative stress in humans which can lead to selenosis, a chronic disease. Excess Se intake, whether acute or chronic, can cause Se toxicity. Nail discoloration, fragility, and loss; hair loss; tiredness; touchiness; and stinking breath odor (often characterized as "garlic breath") are all symptoms of Se toxicity (MacFarquhar, 2011). Prolonged intake of Se from food or water may be consumed in organic or inorganic forms. A garlicky odor in breath and a metallic taste in the mouth are the first signs of chronic Se toxicity, also known as selenosis. In more than 70–75% of patients, this is often followed by gastrointestinal symptoms like nausea or diarrhea, as well as fatigue and irritation, as well as joint discomfort.

Ever since revelation of Se's importance for mankind in 1974, there has been a steady increase in interest in this trace element. Modern Se investigations are characterized by examinations of Se in food chain of living organisms (Golubkina et al., 2014), biogeochemical cycling (Natasha et al., 2018), Se toxicity and deficiency (Schiavon & Vecchia, 2017). Moreover, the phenomenon of selenium protection against viral disorders has been extensively described in the light of the corona-virus pandemic (Zhang et al., 2020a, b, c), implying that selenium supplementation could open up new avenues in COVID treatment, given that scientific evidence in China found that regions with high selenium levels had much reduced COVID morbidity and mortality.

It is worth noting that, when it comes to Se, the importance of the multifaceted Se/ natural antioxidants' influences on human beings is underappreciated. Selenium, as a natural antioxidant, plays an important role in antioxidant resistance in both humans and plants. In practice, this implies that stuffs containing high amounts of selenium and other natural antioxidants may be more beneficial to human health than those containing only high quantities of this microelement. This could be crucial in the fight against viral infections in humans, as recent research suggests that medicinal plant polyphenols have a high chance of protecting against COVID (Chausali et al.,

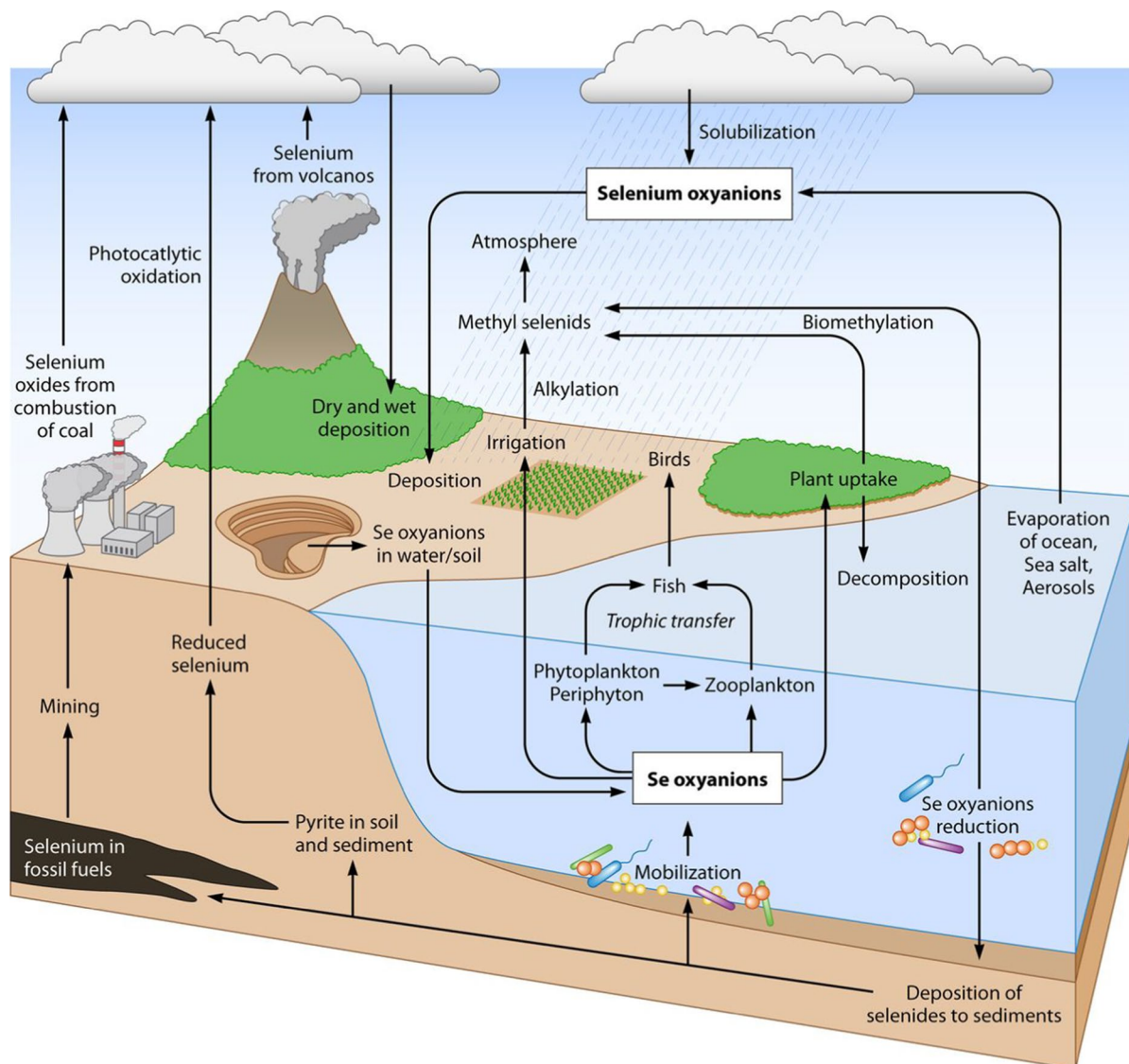
2021). Furthermore, the synergistic action of natural antioxidants, the variety of physiologically active chemicals and deficient of side effects frequently associated with food supplements, plants rich in selenium and other antioxidants may provide significant benefits in comparison with dietary supplements.

Se is key part of the glutathione peroxidase (GSH-Px), an enzyme that can decrease lipoperoxides and hydrogen peroxide by accelerating the conversion of reduced glutathione (GSH) to oxidized glutathione (GSSG), protecting the body from oxidative damage. Animals also require Se as a trace element. Excessive Se consumption, on the other hand, can result in Se poisoning. According to the dosage and time of ingestion, Se toxicity can be separated into acute and chronic Se poisoning. Respiratory distress, dyskinnesia, diarrhea, and even death were common symptoms of acute poisoning. The symptoms of chronic toxicity are loss of appetite, growth retardation, wool loss, and lameness (Li et al., 2021).

## Se in the environment

Se is a critical trace element in biological systems, but its presence in the Earth's crust is irregular. In terms of essentiality, some of the elements such as hydrogen, oxygen, carbon, nitrogen, phosphorus, sulfur, and selenium are dominant components of all life forms, and Se is next to S. Both man-made and natural sources are responsible for environmental Se, resulting in its cycle (Fig. 4). Se can be present in a variety of natural settings, including rocks, soils, waterways, and the atmosphere. Complex biogeochemical cycling processes release it from Se-rich sources such as phosphatic rocks, organic-rich black shales, and coals (Nancharaiah & Lens, 2015a, b).

Weathering of seleniferous soils and rocks can cause natural Se pollution. Se concentrations in most soils are quite minimal. Mining, metal refinement, flue gases, and other manufacturing practices all contribute to anthropogenic Se emissions. In Canada, the Kesterson National Wildlife Reservoir has seen a high incidence of embryonic illnesses and deaths of waterfowl and certain other wildlife due to Se pollution. Anthropogenic activities such as coal mining and the use of Se-rich fossil fuels in industries account for up to 40% of Se in air, as well as aquatic systems, which have a wastewater discharge capacity of 5 g Se/L. In



**Fig. 4** Global selenium cycle in nature. Reproduced with the permission of ‘(Nancharaiah & Lens, 2015a, b)

this regard, Se contamination in groundwater and surface water has recently become a serious problem in many river basins around the world (Gebreeyessus & Zewge, 2019).

#### Environmental considerations (nutrient or toxicant)

Selenium is a crucial nutrient as well as a possible threat to Earth’s ecosystems. It has two faces, just like

the moon: it is poisonous for every single organism while still being important for the survival of many bacteria and animal life (Reich & Hondal, 2016). Environmental considerations are integral to decisions regarding its essentiality (as nutrient) and toxicity (Stillings, 2017). Se is a multifarious metalloid that occurs naturally in minor amounts all through earth’s crust, water, and air. Because of its existence above acceptable limit in water assets, it has recently piqued solid attention of environmental and water quality scientists. With regard to its consumption, Se



has the narrowest spectrum between nutritional deficiency (Devi et al., 2017b), as mentioned above. In 1957, it was confirmed that food Se has a major role in protecting vitamin E-deficient rats and chicks from liver necrosis and exudative diathesis, respectively. During 1958, a connection was discovered among extremely limited soil Se contents and a disease named ‘white muscle disease’. First ever biochemical function of Se was identified in 1973, by determining Se as an integral part of erythrocyte GPx (glutathione peroxidase), a Se-dependent antioxidant enzyme. Se in the GPx enzyme was discovered as selenocysteine (SeCys) after five years (Zwolak, 2020). Humans receive Se’s dietary roles by 25 selenoproteins, each of which has selenocysteine as its energetic core. The UGA codon in mRNA defines the selenocysteine inclusion for the production of a selenoprotein under suitable circumstances, but many intertwining aspects are also essential (Ullah et al., 2018a, b, c). Se and other potential toxic elements may compete with body organ function, endocrine system dysfunction, and nervous system disturbance, or they may serve as a secondary concern in a number of diseases (Ali et al., 2017). The first ever reported mankind disorder related to lack of Se was Keshan disease; hence, it has been proposed to be necessary in trace amount for humans. Cirrhosis, carcinoma, Kashin Beck disease, and other clinical disorders are also caused by Se deficiency in humans (Zwolak, 2020). Plant development, yield, quality, antioxidative ability, and modulation of multiple stress-responsive genes can all be improved with a small amount of Se (Gupta & Gupta, 2017). However, at high concentrations, it is said to cause toxicity and oxidative stress in humans which can lead to selenosis, a chronic disease. Chronic selenosis is thought to be caused by intake of Se-contaminated water for a long period of time. Symptoms of selenosis include hair loss, fingernail changes and brittleness, pulmonary edema, skin rash, garlic breath, and nervous system irregularities (Fairweather-Tait et al., 2011).

The nutrient and toxic aspects of Se are distinct in a sense that the amount necessary to maintain health or causes toxicity is very narrow. The recommended dietary allowance (RDA) for an adult person is 55  $\mu\text{g}\cdot\text{day}^{-1}$ , set by US Department of Agriculture, while the WHO has set a toxic limit of 800  $\mu\text{g}$  per day for adults. That’s why Jukes refers to Se as an “essential poison” (Jukes, 1983).

## Current developments on Se remediation research

The Se helpful impacts on people well-being are emphatically reliant on its content and chemical state, separation, precise classification and evaluation of Se species, is yet debatable (Pedrero & Madrid, 2009). It becomes harmful when the intake level exceeds its optimum level (Zhang et al., 2014a, b) causing health consequences like hepatic cancer, prostate carcinoma, disruption of DNA (genotoxicity), and cytotoxicity (lethal to cells) (Santos et al., 2015). Selenosis may occur when Se content surpasses the upper limit level. Selenosis may bring about different sicknesses in people identified with dermal or nervous disorders, defective skin and nails, hair loss, an irregular movement and occasionally cause paralysis.

Besides the normally happening Se in seleniferous soils, its contamination may likewise result from anthropogenic actions as well, for example, coal-fired plants, metal purifying, mining, petroleum treatment facilities, and agriculture drainage (Eurola et al., 2004). Based on toxicity, Se is considered as an emerging pollutant, which is generally identified with inorganic Se structures ((Se(VI) and Se(IV)) in soil. These inorganic forms of Se rapidly get into food cycle after ingestion by different life forms (plants and animal), menacing lives of the higher nutrition category, coupled with humans (Longchamp et al., 2015).

Soil and groundwater remediation are usually divided into two categories: ex situ and in situ. Ex situ remediation approach is removing contaminated soils or groundwater from the subsoil and treating it on-site or transferring it for cleaning to another area. In situ procedures, on the other hand, are processes that remove polluted soil or groundwater from the soil directly. Since in situ treatment is less expensive than ex situ treatment, so it is frequently chosen. (Hussain et al., 2022; Smarzewska & Guziejewski, 2021). Se remediation technologies available to date will be discussed as under.

## Se remediation technologies

### Bioremediation approach

Bioremediation is an approach of applying live organisms (fungi, bacteria, yeast) for eradicating different

contaminants to prevent the environment from deterioration. Bioremediation is mostly executed for removal of toxic petroleum impurities (Smarzewska & Guziejewski, 2021). Moreover, this technique is also suggested in regions polluted after being exposed to toxic elements as found in sewage treatment works, factories, landfills, steelworks, as well as in soils where nuclear tests have been tried. Contaminants of this sort turns less destructive under the control of microorganisms (Azubuike et al., 2016). In bioremediation, micro-organisms and macro-fauna are engaged through biological treatment to eliminate, transform, or disintegrate the targeted contaminants. This technique is considered economical and less destructive to the environment for Se removal compared to traditional physicochemical techniques (Gan et al., 2021).

Owing to its physical properties, elemental Se is insoluble in water as opposed to Se(VI) and Se(IV), having low toxicity in both aquatic and terrestrial settings. As a result, it has been determined that reducing both species of Se ((Se(VI) and Se(IV))

to elemental Se is an optimal remediation technique for depolluting Seas well as the retrieval of this metalloid from polluted sites (soil, waste water) (Nancharaiah & Lens, 2015a, b). As a result, microorganisms play an important part in the alteration of Se(IV) and Se(VI) through metabolic reactions (Paul & Shah, 2019) as illustrated in Table 2. Contamination of soil and water poses a serious danger to the ecosystem. Sulfate and nitrate are the two main components of water contamination, and they cause harm to the marine environment. Se is found in industrial effluent in the form of Se(VI) ( $\text{SeO}_4^{2-}$ ) and Se(IV) ( $\text{SeO}_3^{2-}$ ) oxyanions, which are the main toxic contaminants (Johansson et al., 2015). Se in trace amounts is essential for a safe terrestrial and aquatic life; however, increased level of Se in the form of  $\text{SeO}_3^{2-}$ ,  $\text{SeO}_4^{2-}$  and nano-Se is harmful to all living things (Kumar & Prasad, 2021). It's quite important to chemically reduce these toxic compounds during wastewater treatment while keeping in view the environmental penalties of its by-product. The bio-reduction of elemental Se as well

**Table 2** Techniques used for bioremediating selenium from the environment using different microbes

Microbe spp.	Region/Isolation place	Bioremediation function	Resistance mechanism	References
<i>Ascomycete</i>	coal mine drainage impacted wetland (Central Pennsylvania)	Selenite and selenate reduction	Aerobic reduction of selenite and selenate	(Sabuda et al., 2020)
<i>Duganella sp.</i>	Punjab, India	Selenite reduction	Selenite reduction under aerobic conditions producing elemental Se	(Bajaj et al., 2012)
<i>Agrobacterium sp.</i>	Punjab, India	Selenite reduction	Selenite reduction under aerobic conditions producing elemental Se	–
<i>Enterobacter cloacae</i>	California, USA	Selenite reduction	Se(VI) reduction to precipitate insoluble $\text{Se}^0$ particles	(Yee et al., 2007)
<i>Bacillus cereus</i>	Coal mines in Asansol, India	Detoxification of selenite	Synthesis of stable $\text{Se}^0$ nanoparticles	(Dhanjal & Cameotra, 2010)
<i>Pseudomonas putida</i>	Costa Rica, USA	Reduction of selenite	Selenite reduction to nano-Se	(Avenidaño et al., 2016)
<i>Vibrio natriegens</i>	Spain	Reduction of selenite	Selenite reduction, eco-friendly synthesis of Se nanoparticles	(Fernández-Llamosas et al., 2017)
<i>Bacillus mycoides</i>	Se-polluted soil, Italy	Reduction of selenite	Reduction of selenite	(Lampis et al., 2014)
<i>Alcaligenes faecalis Se03</i>	Herbivorous insect ( <i>Monochamus alternatus</i> ) larvae's gut/ Anhui, China	Reduction of selenite	Tolerance and reduction of selenite	(Wang et al., 2018)
<i>Alishewanella sp</i>	China	Reduction of selenite	Reduction of selenite	(Xia et al., 2018)

as Se(VI) and Se(IV) oxyanions is harmless and environmental-friendly approach for remediation of water and soil Se (Tan et al., 2016). In bioremediation approach, plant crude extracts and microorganisms are applied for bio-reducing the oxy-anions of Se and other oxidized contaminants (Eswayah et al., 2016). For monitoring environmental pollution (soil, water, air), small monitoring tools coupled with Se nano-biosensors are integrated. These Se nano-particle-making methods (bio-reduction and biosynthesis) may be applied to bio-remediate Se contamination (Gunti et al., 2019; Visha et al., 2015). Based on its ability to reduce Se(IV) into Se<sup>0</sup> (elemental Se) nanoparticles and resilience in soil, *Streptomyces sp. ES2-5* may be used for Se-contaminated water and soil (Tan et al., 2016). As per a prior study's results, *Pseudomonas aeruginosa* may be a viable green option in bio-remediating toxic SeO<sub>3</sub><sup>2-</sup>-contaminated water (Kora & Rastogi, 2016). To handle soil Se-contamination, a different approach was applied. Se coupled with *24-Epi-brassinolide* has improved the antioxidant enzymatic function and proline in a Cu-tolerant plant (*Brassica juncea*), allowing the plant to accumulate copper in to the upper portion of plant. Using these plants, this method may be practiced to detoxify soil Cu (Yusuf et al., 2016). Since it has the potential to adsorb several toxic elements (Cd, Hg, Cu, Zn), biosynthesized Se nanoparticles can be used to get rid of soil and water contaminated with these metals (Yang et al., 2019).

*Alishewanella spp. WH16-1* is type of facultative, motile, Gram-negative, rod-shaped and anaerobic bacterium, set apart from mining soil, which proficiently removes Se(IV) under aerobic circumstances. CsrF is a flavoprotein that shares 37% of its amino acid sequence with the *E. coli* ChrR (chromate reductase). ChrR discovered from genome is known as CsrF. CsrF's ability to curtail Se(IV) in vivo was discovered through gene mutation and complementation, as well as heterologous expression. The filtered CsrF was yellow, coupled with an absorption range close to that of FMN. In vitro, CsrF catalyzes the reduction of Se(IV) using NAD(P)H as co-factors under ideal conditions of 30–37 °C and pH 7.0. The Km for the Se(IV) reduction using Nicotinamide Adenine Dinucleotide Phosphate (NADPH) as the electron donor was 204.1 ± 27.91 μmol/L (Xia et al., 2018). Site-directed mutagenesis showed that Arg13 and Gly113

were essential for the reduction of Se(IV) to Se(0). CsrF is considered a novel and well-characterized bacterial aerobic Se(IV) reductase (Xia et al., 2018).

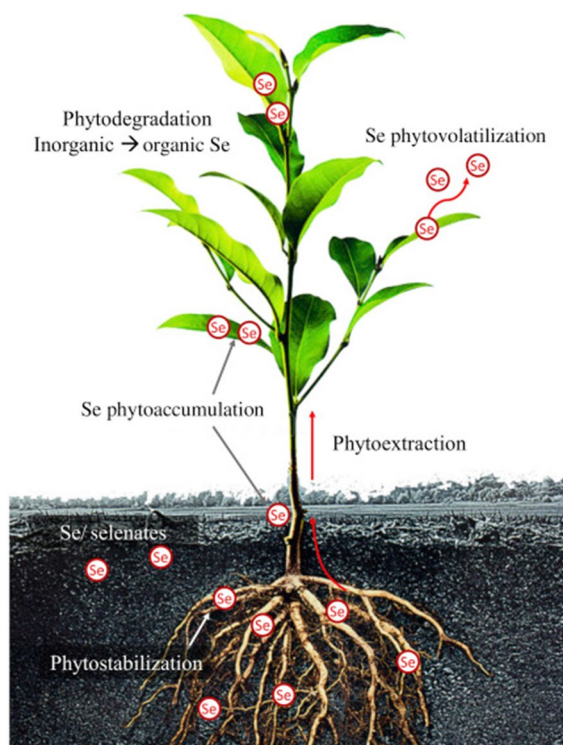
Some species of bacteria have been discovered so far which are capable to reduce Se(IV) to Se(0), through detoxification process. The reduction of Se(IV) by bacteria can happen both with and without application of enzymes. Siderophore, H<sub>2</sub>S, and glutathione are examples of chemical compounds, which are reduced non-enzymatically (Nancharaiyah & Lens, 2015a, b). Se(IV) reduction through enzymes in anaerobic bacteria normally manifests as a reduction in the interim of respiration. Some previous conducted studies are currently known to reduce Se(IV) through hydrogenase I (Yanke et al., 1995), ArsC (arsenate reductase), NR (nitrite reductase) (He et al., 2018a, b), and fumarate reductase (Li et al., 2014). Under aerobic situations, flavin oxidoreductase (Hunter, 2014a, b), thioredoxin reductase (Hunter, 2014a, b), and glutathione reductase have been documented to act as aerobic Se(IV) reductases; nevertheless, they have yet to be thoroughly investigated in vivo, and there are insufficient proofs in vitro. Furthermore, in some bacteria, Se(IV) reduction products may form Se nanoparticles (Tan et al., 2016; Zhang et al., 2014a, b).

### Phytoremediation

Phytoremediation, a form of environmental remediation also known as green biotechnology, is an approach applied to deal with toxic environmental contaminants using various plant species (Huang et al., 2019a, b). This technique entirely depends on plants which can thrive in a polluted environment, which later can easily extract/remove toxic elements by harvesting plants or volatilizing them into their least detrimental forms (Hasanuzzaman et al., 2020). This process, which primarily involves phytoextraction and phytovolatilization, is effective in removing Se from polluted environments (Wu et al., 2015). Phytoremediation technology based on the mechanism, by which plants remove or reduce the harmful effects of pollutants from the soil, is broadly categorized into: phyto-extraction, phyto-transformation, phyto-stimulation, phyto-stabilization, rhizo-filtration and phyto-volatilization (Chowdhury et al., 2016). Se(VI) is the most common type of Se in soils. Plants can absorb Se(VI) after it has been taken up by plants,

accumulating it in the root and then translocating it to the shoot. Selenocysteine (organic Se) is formed during the assimilation of inorganic Se(VI). Se can be released in volatile forms by plants (Fig. 5).

Environmental Se pollution due to various industrial operations has recently become an attractive field for researchers. Phytoremediation has been identified as a viable and efficient method of removing Se from a Se-contaminated area. Some plant species have developed tolerance to Se and commonly accumulate tissue Se concentration  $> 100 \text{ mg Se kg}^{-1}$  dry weight. These plants are named as Se accumulators. Plants have a different tendency to accumulate Se in tissues. Plants that grow in seleniferous areas and are capable of accumulating a large amount of Se ( $1000\text{--}15,000 \text{ mg Se kg}^{-1}$  dry weight) are known as Se hyperaccumulators, such as *Astragalus*, *Conopsis*, *Morinda*, *Stanleya*, *Xylorhiza*, and *Nepturia* (Ullah et al., 2018a, b, c). The phenomena of readily absorbing Se by nearly all plant spp. may be



**Fig. 5** Various types of phytoremediation of selenium occurring in plants. Passage and probable fates of selenium in plants. Adapted with the permission of Usmani et al. (2018)

applied to remove Se from polluted areas as well as for plant biofortification. Selected plant spp. (crops and non-crops) that have been used in Se phytoremediation are listed in Table 3.

Phytoremediation approach is less expensive and safer technology than traditional methods, resulting in least totals of harmful substances (Favas et al., 2018). As a result of this argumentation, this "green technology" is a highly fascinating approach with many forms such as, phytoextraction, phytovolatilization, and phytostabilization. All phytoremediation approaches have benefits as well as drawbacks (Usmani et al., 2018).

Lot of research work has been done so far to better understand the application of this green technology approach for seleniferous soil treatment under various environments. Study conducted by Esringü and Turan (2012) found that adding ethylenediamine disuccinate and diethylenetriamine pentaacetate (synthetic chelating agents) with Se-contaminated soil helped soil particles to free Se by making it more readily available for roots uptake. As a result, Brussels sprouts increase Se elimination by 12- to 20 times.

Plant Se uptake suppression in seleniferous conditions is also a promising strategy for eliminating harmful effects of Se. According to Mackowiak and Amacher (2008), adding sulfur to Se-rich soil reduced Se absorption by Alfalfa and Western Wheatgrass by more than 60%. Since sulfate is a compositional correspondent of  $\text{SeO}_4^{2-}$ , serving as a competitive anion for plant uptake, so from economic perspective this is a feasible choice for dealing with Se-impacted and revegetated domains.

In a greenhouse-based study, Lindblom et al. (2014) looked at how the Se hyperaccumulator *Stanleya pinnata* (also known as desert prince plume) and the non-accumulator *Stanleya elata* (known by the common name Panamint prince plume) removed Se from seleniferous soil. In comparison with uninoculated *Stanleya pinnata*, Se absorption was increased twofold to threefold in *Stanleya pinnata* inoculated with *A. seleniiphila*, with a 30% increase in Se uptake in roots. Se accumulation in soil inoculated with *A. leprosis* was 1.5 times lower than in uninoculated *Stanleya pinnata*, though inoculation with fungi shows no influence on Se accumulation in *Stanleya elata*; nonetheless, it did have a negative impact on plant development. These phenomena conclude that depending on the host plant spp., accumulation of Se

**Table 3** The following list indicates different plants that have been applied for Se phytoremediation

Name of plant spp.	Family	Reference
<i>Puccinellia distans</i> (weeping alkali grass)	Poaceae	(Kök et al., 2020)
<i>Lemna minor</i>	Araceae	(Ohlbaum et al., 2018)
<i>Egeria densa</i>	Hydrocharitaceae	(Ohlbaum et al., 2018)
<i>Arundo donax</i> , <i>Oryza sativa</i> , <i>Triticum aestivum</i>	Poaceae	(Yasin et al., 2014)
<i>Eichhornia crassipes</i>	Pontederiaceae	(Pal & Rai, 2010)
<i>Astragalus bisulcatus</i>	Fabaceae	(Dixit et al., 2015)
<i>Brassica juncea</i>	Brassicaceae	(Dhankher et al., 2012)
<i>Brassica juncea</i>	Brassicaceae	(Yasin et al., 2014)
<i>Allium cepa</i>	Liliaceae	(Yadav, 2007)
<i>Stanleya pinnata</i> , <i>Stanleya elata</i>	Brassicaceae	(Lindblom et al., 2014)
<i>Gaillardia aristata</i> and <i>Calendula officinalis</i>	Asteraceae	(Liu et al., 2018)
<i>Populus</i> spp.	Salicaceae	(Winkel et al., 2012)
<i>Hippuris vulgaris</i> L	Plantaginaceae	(Hasanuzzaman et al., 2020)
<i>Lemnoideae</i> spp.	Lemnaceae	–
<i>Corchorus capsularis</i>	Malvaceae	–
<i>Eucalyptus globulus</i>	Myrtaceae	–
<i>Chara</i> spp.	Characeae	(Hasanuzzaman et al., 2020)
<i>Bolboschoenus maritimus</i>	Cyperaceae	(Pilon-Smits et al., 1999)
<i>Pteris vittata</i>	Pteridaceae	(Feng & Wei, 2012)
<i>Juncus xiphioides</i>	Juncaceae	(Hasanuzzaman et al., 2020)
<i>Azolla caroliniana</i>	Salviniaceae	(Pilon-Smits et al., 1999)
<i>Ipomoea purpurea</i>	Convolvulaceae	(Sabogal & Borkowski, 2007)
<i>Typha latifolia</i>	Typhaceae	(Jeke et al., 2015)

and plant development may be affected by injecting rhizospheric fungi.

Soil Se remediation through hyperaccumulator plants has been commonly practiced approach. Yadav (2007) explored the possibility of *Allium cepa* (also known as onion) growing in soil spiked with Se, with an objective of introducing this *Allium cepa* in seleniferous soils. It was concluded that this species can be used to accumulate Se in proportion to available soil Se(VI) levels and may transport Se from seleniferous parts to Se-deficient soils. Yasin et al. (2014) conducted similar kind of research in which Se accumulator spp. Mustard was applied to extract Se from naturally seleniferous soils. The effects of two Se-tolerant bacterial consortia (G1 and G2) on Se accumulation and plant growth were investigated. Eventually, *B. juncea* could be used for seleniferous soil remediation to produce Se-enriched plant content. Moreover, its inoculation with the bacterial consortium G1 improves the performance of this method by promoting plant development. Under hydroponic

conditions, the Chinese Brake fern can integrate a considerable amount of Se, which can be used for Se-contaminated water remediation (Feng & Wei, 2012). Further investigation is necessary to evaluate the efficacy of its remediation and the factors that influence Se elimination.

#### Reduction and in situ bio-reduction approach for Se remediation

Nanotechnology and nanomaterials have shown considerable capacity in addressing water and soil contamination issues in the recent pasts. The application of nanoscale zero-valent iron (nZVI) technology for clean-up of contaminated environment has gotten a lot of coverage, which is one of the most commonly used nanomaterial for soil, groundwater, and hazardous waste management and remediation (Chen et al., 2020). Based on its versatile particle size, high specific surface area, quick reaction pace, good reduction efficiency, and appropriate expense, nZVI is an



attractive in situ remediation nanomaterial (Chekli et al., 2013). This material is used to detoxify a variety of contaminants, including halogenated HCs, azo dyes, nitroaromatic composites, antibiotics, hexavalent chromium (Cr(VI)), metal ions (Liu et al., 2017). Increased number of findings suggests that nZVI could successfully diagnose and remediate Se from contaminated media.

According to Zhou et al., (2016a, b), reduction of Se(VI) and Se(IV) to elemental Se(0) is the primary Se(IV)-nZVI mechanism process. Se(VI) is chemically reduced to selenide and elemental Se, separated from water using nZVI. The fast removal of Se(VI) and large potential for encapsulation of Se can be thoroughly explained by the reduction and sequestration processes. There is an option that the irregularities present on the nZVI particle shell may accelerate Se distribution and maximize nZVI's potential for Se adsorption (Zhou et al., 2016a, 2016b). Furthermore, the scanning transmission electron microscopy (STEM) and X-ray energy-dispersive spectroscopy (XEDS) techniques appear to be a useful way to visualize solid-phase processes, especially for plotting inorganic elements in solitary nanoparticle at atomic scale (Tang et al., 2016).

To minimize Se content in pit lakes of Gilt-Edge Superfund Site and Sweetwater uranium mine (USA), economical biological reduction with water modification sources coupled by nutrients, such as that of carbon source, which was successfully implemented for Se remediation (Köppel et al., 2012). An emerging chemisorption technique was developed for Se(VI) processing. In situ solidification approach was applied via incorporating a shapeless absorbent with active surface species for Se(IV) chemisorption and to treat polluted water in order to extract more than 99% of total Se from waste water (Wadgaonkar et al., 2018). In Rifle (Colorado, USA), Williams et al. (2013) investigated Se remediation from groundwater by injecting  $C_2H_3O_2^-$  into a uranium-contaminated reservoir. In the microbial biofilm, Se oxyanions were biologically reduced to elemental Se. A study of microbial communities revealed a correlation between acetate oxidation and oxalate reduction. The two commanding members of Se-reducing biofilm were species of *Thauera* and *Dechloromonas*.

In situ remediation of Se-rich soil has many drawbacks, including lower remediation efficiency, re-oxidation of non-soluble elemental Se to soluble

oxy-anions, with deterioration of aquifer system. Se is re-processed in same soil–water system where farming lands are irrigated with groundwater.

### Electro-coagulation (EC)

Electro-coagulation (EC) is an electrochemical approach that produces coagulant substances in situ by electro-dissolving sacrificial anodes, which are typically made of iron or aluminum. An electric current is used to disrupt suspended or emulsified contaminants. When compared to other traditional approaches, EC has benefits like lower energy usage and least operating charges (Shahedi et al., 2020). EC is a well-known method for treating a variety of metals and metalloids found in wastewaters, particularly As (Hansen & Ottosen, 2010). Because Se is closely allied in chemical properties with As in several cases, so the method applied by Hansen and Ottosen (2010) can be practiced for Se remediation as well.

In earlier research studies, electro-coagulation approach was practiced to treat wastewater contaminated with copper industry, resulting in a 90% decline in Se concentration. Hydrous ferric oxides (HFOs) were the chemical compounds that immobilized Se, and their effectiveness differed depending on the pH value. In pH range of 4 to 6, HFOs are just slightly soluble. However, HFOs are soluble at low pH (less than 3), so the reduction phenomena of  $Fe^{+3}$  to  $Fe^{+2}$  may happen, reducing the number of appropriate HFO (Hansen et al., 2019). The elemental Se(0) in colloidal form has a negative impact on membrane separation technology and water bodies. In order to overcome this concern, issue, EC technique was applied for the first time by Staicu et al. (2015), to investigate Se(0) remediation capability. A form of *Pseudomonas fluorescens* developed colloidal Se(0), which suggested restricted gravitational setting. Getting rid of maximum Se(0) turbidity (97%) was attained by applying iron electrodes on 200 mA, whereas perhaps at high power (300 mA) did aluminum electrodes strip 96% of colloidal Se(0). EC with Fe electrodes remediated 93% of Se content at highest Se(0) removal rate, as compared to Al electrodes which was about 54%.

In a pilot scale study, pH values in slightly acidic condition (4.5–6.5) were found to be optimal for the reduction of Se(IV) and selenocyanate. At pH 4, nZVI was used to accelerate the amount of Se(IV)

and Se(VI) removal. Despite this, least removal efficiency of less than 10% for Se(VI) at moderately acidic condition was observed when processed iron salts (Yoon et al., 2011). During iron hydroxides' production through reduction process or iron nanoparticles, no Se adsorption at basic pH of 7.8–10 was detected (Sharrad et al., 2012). HFOs are required for wastewater treatment applying electro-coagulation method. Table 4 lists the proposed reaction mechanisms for remediation of Se. Since Se(IV) will adsorb onto metal oxy-hydroxides and Se(VI) has poor adsorption and limited precipitation features, it is assumed that mostly Se in the form of Se(IV) would be extracted from wastewater (Baek et al., 2013a, b).

Adsorption

In the industrial field, the adsorption method is a powerful platform for Se remediation (Okonji et al., 2020). The adsorption approach compared to other Se-removing techniques such as anion exchange, coagulation/filtration, reverse osmosis, sorption, and lime softening has the rewards of cost-effective remediation, ease to implement, and performance. Heavy metal cations and metalloid anions have been found to be extracted using the adsorption process (Zhou et al., 2016a, b). Removal of Se(IV) and Se(VI) through adsorption into solid surfaces such as activated alumina, powdered activated carbon (PAC), granular activated carbon (GAC), activated double hydroxides, nano-TiO<sub>2</sub>, chitosan-clay composites and oxides has been studied in several studies (Sharma et al., 2018; Tokunaga & Takahashi, 2017). Examples regarding adsorption, biosorption and reduction methods for Se removal from water are reported in Table 5. Several researchers have identified the impact of pH on adsorption process such as Se(IV) adsorption onto powdered activated carbon and granular activated

carbon, which was found to be maximum under lower pH value and declined with initial pH rises (Wasewar et al., 2009). Both pH and surface loading also influenced the adsorption of Se(IV) onto activated alumina (Su et al., 2008).

Wu et al. (2020) investigated that Se equilibrium adsorption via Cu-Al<sub>2</sub>O<sub>3</sub>/ceramic particles can be achieved in 60 min, with a maximum Se adsorption performance of 95.36%, as per the adsorption findings. The adsorption of Se onto Cu-Al<sub>2</sub>O<sub>3</sub>/ceramic particles is pH dependent, and the reasonable Se adsorption capability is relatively consistent at pH spectrum 2–8. In another study, the ability of four adsorbent agents to extract inorganic and organic Se specie from polluted water, namely n-ZVI, Fe<sub>3</sub>O<sub>4</sub>, FeCl<sub>3</sub> and granular activated carbon, was tested. The effectiveness of a modified co-precipitation process that used a mixture of FeCl<sub>3</sub> and FeCl<sub>2</sub> had also been studied. The ferric oxyhydroxide colloids produced through FeCl<sub>3</sub> precipitation were observed to be the utmost effective of the adsorbents examined, removing more than 95% of Se(VI) with a single dose of 1 g/L ferric chloride. The ideal pH range discovered lies between 4.0–5.5 for removing Se(VI), regardless of the adsorbent. The removal proportion of Se(IV) was quick with least doses of adsorbents (Okonji et al., 2020). Adsorption of Se(IV) and Se(VI) onto soil minerals may result in reduced Se eco-toxicity via removing from water resources. For example, the study conducted by Yue et al. (2020) gained the perceptions on the Fe–O–Se bonding process on goethite and hematite. With the rise in pH (from 3 to 7), the adsorption extents of Se oxyanions on goethite and hematite decreased, as did the positive zeta potential, which provides less electrostatic attraction.

In another study, batch experiments were used by Ma et al. (2018) to explore trace Se(IV) mitigation from water using hematite-coated magnetic

**Table 4** Reaction pathways for remediation of Se applying HOFs

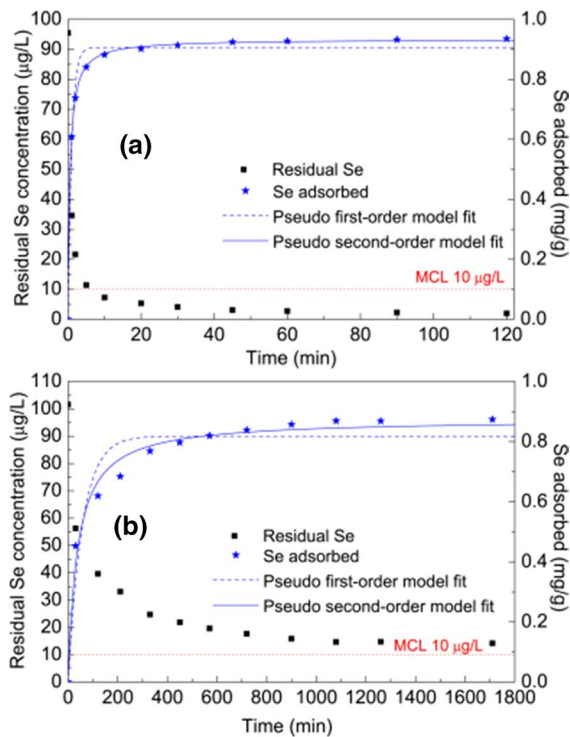
Products	Reaction	Reference
Ferrous ions formation	Fe <sup>0</sup> → 2e + Fe <sup>+2</sup> (Anodic reaction) 2H <sub>2</sub> O + 2e → H <sub>2</sub> + 2OH <sup>-</sup> (Cathodic reaction)	(Arienzo et al., 2002)
Ferric ions formation	4Fe <sup>+2</sup> + O <sub>2</sub> + 4H <sub>3</sub> O <sup>+</sup> → 4Fe <sup>+3</sup> + 6H <sub>2</sub> O	(Hansen et al., 2019)
HFOs formation	Fe <sup>+3</sup> + 3H <sub>2</sub> O → Fe(OH) <sub>3</sub> + 3H <sup>+</sup> Fe <sup>+2</sup> + 2H <sub>2</sub> O → Fe(OH) <sub>2</sub> + 2H <sup>+</sup>	(Arienzo et al., 2002)
Selenium adsorption	Fe(OH) <sub>3</sub> + SeO <sub>3</sub> <sup>-2</sup> + H <sup>+</sup> → Fe(OH) <sub>2</sub> + CSeO <sub>3</sub> <sup>-</sup> + H <sub>2</sub> O	(Gutiérrez et al., 2015)

**Table 5** Examples of adsorption, biosorption and reduction processes to remove excess water Se

Approach applied	Agent used	Reference
Adsorption	Cu-Al <sub>2</sub> O <sub>3</sub> /ceramic particles	Wu et al., (2020)
	Nano-zero-valent iron (nZVI), magnetite (Fe <sub>3</sub> O <sub>4</sub> ), ferric chloride (FeCl <sub>3</sub> ) and granular activated carbon (GAC)	Okonji et al., (2020)
	Goethite ( $\alpha$ -FeOOH) and hematite ( $\alpha$ -Fe <sub>2</sub> O <sub>3</sub> )	Yue et al., ((2020)
	Hydrogen-terminated diamond [H-Ter-D] (0 0 1) surface	Liu et al., (2019)
	Hematite-coated magnetic nanoparticle (MNP@hematite)	Ma et al., (2018)
	Polymer–clay composites	Bleiman & Mishael, (2010)
	Lepidocrocite ( $\gamma$ -FeOOH) nanoflakes and lepidocrocite decorated on multi-layered graphene ( $\gamma$ -FeOOH-MLG)	Jadhav et al., (2020)
	Biochar produced from wheat straw impregnated by Fe(NO <sub>3</sub> ) <sub>3</sub> (0.8, 4 and 10% w/v) and pyrolyzed at 200 °C	Godlewska et al., (2020)
	Composites and oxides activated alumina	
	Granular-activated carbon	Wasewar et al., (2009)
	Intercalated layered soluble hydroxides	Ma et al., (2017)
	Tire-derived-carbon supported with magnetic iron oxide nanoparticle adsorbents	Ying et al., (2020)
	Biofilm model developed in a H <sub>2</sub> -based membrane biofilm reactor (MBfR)	Chen et al., (2019)
	Naturally occurring metal oxides (hematite, manganese dioxide ( $\beta$ -MnO <sub>2</sub> ) $\alpha$ and $\gamma$ -alumina oxides)	Xu et al., (2020)
Biosorption	Dried biomass of baker's yeast, <i>Saccharomyces cerevisiae</i> ,	Khakpour et al., (2014)
	Fe-biochar from two algal sources; " <i>Gracilaria</i> waste and the freshwater macroalgae <i>Oedogonium</i>	Johansson et al., (2016)
	<i>Eucalyptus camaldulensis</i> bark	Rajamohan & Rajasimman, (2015)
	<i>Cyperus laevigatus</i> biomass and green-synthesized nanosilver (AgNPs)	Badr et al., (2020)
	citrus peels (bare), Ca-alginate gel beads, and Ca-alginate-citrus peels composite beads (Ca-alginate@citrus)	Dev et al., (2020)
Reduction	Extracellular polymeric substances (EPS), (a high-molecular-weight biopolymer)	Zhang et al., (2020a, b, c)
	<i>Brassica oleracea</i> with the previously isolated heterotrophic aerobic Se(IV)-reducing <i>Pseudomonas</i> sp. T5-6-I strain	Lusa et al., (2019)
	Ni-Fe Bimetallic nanoparticle	Jegadeesan & Arumugam, (2017)
	Fe (nanocomposite of nZVI@D201)	Shan et al., (2017)
	Zero-valent iron (ZVI), coupled with weak magnetic field (WMF)	Liang et al., (2015)

nanoparticles (MNP@Fe<sub>2</sub>O<sub>3</sub>) at various solution scenarios, and the results portrayed in Fig. 6 reveal that MNP@Fe<sub>2</sub>O<sub>3</sub> had a Se(IV) adsorption potential of 25.0 mg-g<sup>-1</sup>. In 10 min, 0.1 g-L<sup>-1</sup> of MNP@Fe<sub>2</sub>O<sub>3</sub> could reduce 100 mg-L<sup>-1</sup> of Se(IV) to below 10 mg-L<sup>-1</sup>. In a pH range of 4 to 9, MNP@Fe<sub>2</sub>O<sub>3</sub> can efficiently remediate Se(IV). In order to adsorb Se from water, polymer–clay blends were developed by Bleiman and Mishael (2010). Chitosan–montmorillonite blend had the highest adsorption efficiency. The Langmuir model agreed well with the adsorption isotherms of Se(VI) on the composite, Al-oxide, and Fe-oxide, giving a slightly higher potential for

the composite, 18.4, 17.2, and 8.2 mg-g<sup>-1</sup>, respectively. Furthermore, the blend's adsorption was independent of pH, whereas the adsorption of the oxides declined at higher pH.  $\gamma$ -FeOOH nanoflakes with higher Se adsorption potential were applied in situ to multilayered graphene to create an innovative and multi-purpose adsorbent with exceptional adsorption capacity by Jadhav et al. (2020), to see whether they could be used to remove Se(VI) ions from groundwater. Their work examines the adsorption mechanism and the benefits of incorporating graphene to improve the adsorbent's ability to remove Se from contaminated water. Langmuir adsorption isotherms assessed



**Fig. 6** Adsorption kinetics of Se(IV) by MNP@hematite (a) and MNP core (b) at 25 °C. Initial solution pH 7.0, adsorbent dosage 0.1 g/L. Reproduced with the permission of Ma et al. (2018)

the highest adsorption capability of  $\gamma$ -FeOOH and  $\gamma$ -FeOOH-MLG samples to be 40.09 and 83.44  $\text{mg g}^{-1}$ , respectively, whereas the highest adsorption potential of  $\gamma$ -FeOOH was observed to be at pH near to the PZC (point of zero charge) 5.97 ( $\pm 1$ ), which is useful for large aquifer scenarios. Fe-modified engineered biochar has been used as a novel adsorbent for Se removal, applied by Godlewska et al. (2020).  $\text{Fe}(\text{NO}_3)_3$  was impregnated into commercially available wheat straw biochar (0.8, 4, and 10% w/v) and heat-treated at 200 °C. For the biochars investigated, the optimal pH, adsorption kinetics, and Se(VI) adsorption spectra were investigated. The alteration greatly improved biochar’s ability to adsorb Se(VI). The best adsorption performance was obtained in biochar that had been updated with 10%  $\text{Fe}(\text{NO}_3)_3$ .

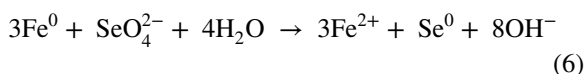
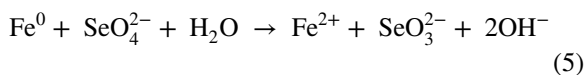
In complex solutions, the removal of oxoanions Se(VI)/Se(IV) is somehow tough process (Ma et al., 2017). The MoS4-LDH material exhibits great results for synchronized removal of hazardous Se oxoanions in a rapid and highly efficient manner.

Se biosorption from aqueous media in two stages using dried baker’s yeast biomass *Saccharomyces cerevisiae* (type of yeast) was achieved by Khakpour et al. (2014). Variations in pH, initial ion content, and biomass dosage were used to optimize Se biosorption. It was determined that the dry residue of *S. cerevisiae* is an appropriate sorbent for remediation of Se ions from water, based on the outcome of the removal % in the two-stage bioremediation method. Se oxyanions are abundant in ash disposal waters from coal-fired power plants; they offer a difficult water treatment situation to be removed via conventional approaches. Fe-biochar was made from two algal sources: "Gracilaria residue" (organic remainder when agar is removed from grown *Gracilaria*) and aquatic macro algae *Oedogonium*, in an innovative procedure (Johansson et al., 2016). Fe-biochar made from *Oedogonium* waste possesses greater potential capacity for Se than Fe-biochar made from *Gracilaria* residue. However, the best Fe-biochars obtained from these residues were able to treat Se in a power plant’s ash disposal effluent. Fe-biochar produced from macroalgae is a useful approach for treating complex effluent comprising Se oxyanions.

Citrus peels have currently been used as a non-traditional biosorbent to eliminate a variety of inorganic aquatic pollutants. Dev et al. (2020) used Citrus peels (bare), Ca-alginate gel beads, and Ca-alginate-citrus peels blend beads (Ca-alginate@citrus) to biosorb Se(IV) from a liquid solution. Citrus peels were entrapped in Ca-alginate, which provided a structural frame for citrus peel units while also preserving the property of maximum removal proficiency of Se(IV) for Citrus peel. It was concluded that the maximum Se(IV) biosorption capacities for citrus peels, Ca-alginate, and Ca-alginate@citrus were measured to be 116.2, 72.1, and 111.9  $\text{mg g}^{-1}$ , respectively, with citrus peels (immobilized) exhibiting between maximum described Se(IV) adsorption values in previous studies. Recently, biosorption has emerged as a biologically safe alternative to traditional techniques. Biosorption has a number of advantages over traditional methods, including being less expensive, more efficient, having a high potency of metal(loid) removal, quick and safe process, and having no negative environmental effects. Biomass recycling is also possible to some extent. Biomass from bacteria, algae, fungi, and waste materials are all potential biosorbents (Paul & Bhakta, 2021).

The reduction of Se(IV) by various EPS (extracellular polymeric substances) sources was studied by Zhang et al., (2020a, b, c). EPS was found to reduce Se(IV) and partially convert it to elemental Se. Transmission electron microscopy and energy-dispersive spectroscopy confirmed that the formed elemental Se was mostly Se nanoparticles. Study on the reduction of Se(IV) through boreal *Pseudomonas* sp. strain T5-6-I was conducted by Lusa et al. (2019) under oxic conditions. *Pseudomonas* sp. T5-6-I successfully reduced Se(IV) to elemental Se(0). Furthermore, this *Pseudomonas* sp. strain increased the accumulation of Se ( $^{75}\text{Se(IV)}$ ) in *B. oleracea*. Table 5 provides the examples of the evaluation of reduction methods for the removal of Se(IV) and Se(VI).

The reduction of Se(VI) anion to Se(IV) and Se(0) has been discovered using zero-valent iron (Shan et al., 2017). From Se(VI) and Se(IV), ferrous hydroxides, aluminum, and zinc can make Se(0) and metal selenides.

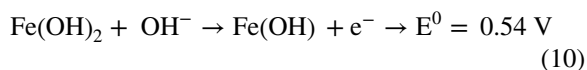
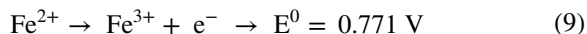
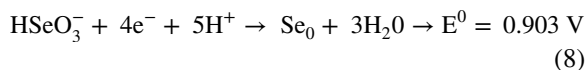
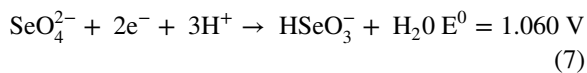


Se(VI) is quickly reduced from aqueous solution by nanosized Fe and NiFe nanoparticles. Se(VI) was completely removed in 5 h; however, NiFe was much more effective than Fe or Ni alone in removing Se(VI).

### Electrochemical technique

Electrochemical techniques have recently been executed to transform pollutants and overcome ZVI's uncontrollable reactivity. The oxidation of the iron anode in an electrochemical system with an iron anode prevents the formation of oxygen and the oxidation of water. In a mixed cell, it contains ferric ions and ferrous, producing ferric hydroxides and ferrous (Ciblak et al., 2012). Sand-packed column experiments were executed to explore the mediation and removal of aqueous Se(VI) by iron electrolysis. An iron anode produces ferrous ions, while the cathode produces OH, resulting in  $\text{Fe(OH)}_2$ , which can reduce Se(VI) to Se(0). Furthermore, siderite has the ability to convert Se(IV) or Se(VI) or to Se(0). The electrochemical reduction of Se(VI)

to Se(IV) or Se(0) and oxidation of ferrous or  $\text{Fe(OH)}_2$  can take place in the following ways (Baek et al., 2013a, 2013b);



The rate of Se(VI) removal is attributed to contact time and  $\text{Fe(OH)}_2$  or  $\text{FeCO}_3$  yield. In a 48-h operation at 0.2 mM initial concentration, 1.8 m/day seepage velocity, and 1.26 mA/cm<sup>2</sup> current density, electrolysis converts 82.2% of Se(VI). The findings suggest that the electrochemical operation may be capable of removing Se(VI) from a solitary well.  $\text{Fe(OH)}_2$  may have reduced Se(IV) from Se(VI) to Se(II) or Se(0), non-extractable precipitates. When the applied current is increased and the initial concentration of Se(VI) is reduced, the amount of Se(VI) reduction increases. The amount of reducing agent  $\text{Fe(OH)}_2$  is proportional to the applied current (Yang et al., 2015). Different background electrolytes have different redox potentials and pH, but the removal proportion for Se(VI) from solution was different. Due to the presence of dissolved oxygen, ferrous irons will be oxidized to ferric forms. Incomplete ferrous oxidation may result in a slight reduction in  $\text{Fe(OH)}_2$ , a Se(IV) reducing agent (Zhang et al., 2014a, b).

The use of direct electrochemical reduction to remove Se from complex wastewaters is a novel approach. Electrochemical reduction of Se(IV) is thermodynamically advantageous, anion structure reorganization impedes process kinetics, and the stage of reduced Se(0) defines operational efficiency. Via a four- or six-electron route, Se(IV) can be electrochemically separated from the aqueous solution, with the former producing elemental Se firmly connected to surface of electrode while the latter providing Se(-II) which is then transformed to Se(0) (Zou & Mauter, 2021). They observed Se(IV) removal levels by up to 89 mg/h/m<sup>2</sup> of electrode surface area, 10% Faradaic performance, and up to 95% removal in a simple batch design system, although, based on the electron



pathway and the adsorbent dose of Se(IV), moderate exchange between these metrics was witnessed.

Weak magnetic field (WMF) coupled with ZVI for remediation of Se

WMF has recently emerged as a new technology to increase the reactivity of ZVI, which can improve pollutants removal effectiveness, due to its low cost, ease of handling, and lack of secondary emissions (Liang et al., 2020). Weak magnetic field (WMF) supports ZVI corrosion and Fe(II) release, resulting in greater Se(VI) sequestration. The magnetic field has a significant impact on ZVI-based chemical reactions that involve a variety of approaches (Ullah et al., 2020). The effectiveness of the WMF-ZVI mechanism for sequestration of Se(IV) and Se(VI) has been investigated.

Liang et al., (2014a, b) investigated that the removal of Se(IV) by ZVI is greatly accelerated by a WMF. As a function of pH and initial Se(IV) concentrations, Se(IV) removal was investigated under WMF-ZVI system. The addition of WMF expedited Se(IV) elimination and increased ZVI's operating pH range from 4.0–6.0 to 4.0–7.2. At lower initial Se(IV) concentrations, the WMF generated a larger boost in Se(IV) elimination by ZVI. The Lorentz force and magnetic field gradient force may be primarily responsible for the WMF-induced improvement in Se(IV) elimination by zero-valent iron. WMF does not require additional energy or expensive reagents. Using WMF to improve Se(IV) elimination by ZVI is a promising and environmentally friendly approach. Similarly, another study was conducted by Liang et al. (2015), in the presence of WMF for efficient Se(VI) removal by ZVI. Under WMF at pH 6.0, they discovered that Se(VI) could be successfully removed by ZVI. In 90 min, 10.0 mg/L Se(VI) could be entirely removed by 1.0 g/L ZVI and 2.5 g/L ZVI could completely remove 40.0 mg/L Se(VI) in 4 h under oxidizing condition with the use of WMF. Under WMF-ZVI system, removal rate of Se(VI) was higher at oxic conditions compared to anoxic circumstances. Liang et al., (2014a, b) proved that the WMF-ZVI system and aging have a significant impact on the sequestration of Se(IV). With WMF, ZVI aged at pH 6.0 for 6 to 60 h, it yielded nearly constant rates of Se(IV) removal. However, the rate of Se(IV) sequestration in the WMF-ZVI system increased by tenfold

to 100-fold when compared to the alone ZVI system. Furthermore, WMF shifts the mechanism of Se(IV) removal by ZVI aged for 6–60 h from adsorption to direct reduction.

The ability and resulting outcomes of ZVI in water treatment can be influenced by aging matrices. Zhang et al. (2018) fabricated eight aging zero-valent iron (AZVI) samples in various coexisting solutes and studied their reactivity toward Se(IV) removal. It was discovered that ZVI's characteristics and reactivity differed greatly depending on the aging matrices. Furthermore, the application of a WMF increased AZVI's Se(IV) sequestration rates by 4.3–39.6 folds. In a study, (Xu et al., 2016) explored the possibility to de-passivate AZVI and removal of Se(IV) using a WMF. According to their results, the application of WMF depassivated the manufactured AZVI samples with corrosion products of wise variety and constituents. The reaction of the AZVI samples with Fe<sub>3</sub>O<sub>4</sub> as the primary component of the passive film or a thin layer of α-Fe<sub>2</sub>O<sub>3</sub> and -γ-FeOOH in the exterior passive film was restored by a magnetic field of 1 mT.

Briefly, WMF appears to be a viable option for depassivating aged ZVI and enhancing Se(IV) and Se(VI) removal from groundwater and wastewater.

## Membrane technology

Membrane technology has become a viable trend for reclaiming water from various wastewater streams. A membrane, in its most basic form, is a barrier that separates two stages by selectively limiting component movement through it (Ezugbe & Rathilal, 2020). Se has become an emerging health threat because of its presence in drinking water. The management of Se polluted ground water for drinkable water use is a costly endeavor (Zeeshan et al., 2020). Membrane technology is one of the most efficient approach for large-scale Se separation, which has the rewards of high efficacy, convenient implementation, and low power consumption (Qiu et al., 2020). For example, He et al., (2018a, b) used Na ion modified carbon quantum dot (Na-CQD) during interfacial polymerization to fabricate thin nanocomposite membranes. Because of their greater surface hydrophilicity and smaller pore sizes than the original thin-film composites (TFC) membrane, the new Na-CQD-modified thin-film nanocomposite membranes have improved pure water permeability and harmful ion resistance

level. This research may help with the development of nanoparticle-modified polymeric membranes for waste water treatment (He et al., 2018a, b). Because of the increased surface interaction, the inclusion of functional nanomaterial has a major impact on Se isolation. As a result, it's critical to figure out how to build functional membranes that have high retention efficacy while also being environmentally friendly (Qiu et al., 2020). To obtain both high water permeation and rejection at the same time, dissolution casting technique was used to produce a novel nano-filtration polyamide core shell biofunctionalized (PA-CSBF) matrix membrane for Se decontamination (Zeeshan et al., 2020). Five different PA-CSBFs were mixed with varying amounts of core shell biofunctionalized (C-SB) nanoparticles. Because of their increased hydrophilicity, the novel modified PA-CSBF membranes exhibited improved pure water permeation and rejections for Se ion. At a permeate flux of 444L/m<sup>2</sup>h, the PA-CSBF4 membrane exhibited excellent regeneration function, with 98% rejection of Se ions. In another study, an effective and low-cost system for Se removing from drinking water has been developed by Malhotra et al., 2020, which consist of a flat sheet crossflow module of composite polyamide nanofiltration membrane operated under response surface optimized environment. Under optimized environment, this novel process yields a sustainable pure water flux of around 140 L/(m<sup>2</sup>h) at only 14 bar pressure while removing over 98% of Se from polluted water. The suggested system is easily scalable and has the ability to address Se-contaminated water for potable use at a minimal price.

In the reductive and oxidative degradation of organic pollutants, low-cost nanomaterials (Fe and FeO nanoparticles) have been extensively adopted. Redox transformations of metal species and/or adsorption of *spp.* on FeO surfaces can both be done using similar processes. Gui et al. produced iron-functionalized membranes for Se reduction and adsorption from coal-fired power plant scrubber water (Gui et al., 2015). Coating polyvinylidene fluoride (PVDF) membranes with polyacrylic acid (PAA), accompanied by ion exchange of ferrous ions and reduction to ZVI nanoparticles, was used to make both laboratory-based and large-scale membranes. The PAA system also improved Se removal from scrubber water by eliminating particle agglomeration and disappearance. Since high sulfate and chloride

content in scrubber water slowed the Se reduction reaction rate, this phenomenon was resolved by combining nanofiltration (NF) and iron-functionalized membranes, resulting in Se concentration of less than 10 mg/L.

### Electrokinetics

Electrokinetics (EK), which is widely thought of as a complementary approach, can be used in association with wide range of other techniques to address inorganic or organically contaminated soil. EK works particularly well on fine-grained sites with poor hydraulic conductivities (Huang et al., 2019a, 2019b). Providing power for electric fields, installing electrodes to produce electric fields, and incorporating electrolytes and other potential materials as active medium are all critical components of an electrokinetic system (Wang et al., 2021). EK and a permeable reactive barrier (PRB) were used by Huang et al., (2019a, 2019b) to study the synergistic impacts on the reductive absorption of Se(IV)oxyanions from spiked soils. PRB media were developed in the form of nZVI coupled with activated charcoal to be used in an electrolyzer. A mild rise in the amount of PRBs and a decline in the PRB thickness in the electrolyzer improved the separation and catalytic rescue of Se(IV) from spiked soil samples for the coupled systems. In the optimized electrolytic cell, maximum Se(VI) removal of nearly 95% and Se(VI) reduction rate of 90% were reported. Instead of the pH distribution, the AC-supported nZVI reduced the Se(IV) species to Se<sup>0</sup> and FeSe.

Summary on the benefits and drawbacks of different remediation techniques for selenium is presented in Table 6.

### Future outlook

The substantial release of Se into the environment has sparked fears about its bioaccumulation, toxicity, and potential to harm aquatic and terrestrial ecosystems. Consequently, Se monitoring in environment is perceived crucial for ecosystem health. The ongoing efforts for Se remediation employs a variety of technologies; however, their prime focus is on lowering its levels to less harmful state. Complete removal from environment and transformation into a Se-free

**Table 6** Summary on the benefits and drawbacks of different remediation techniques for selenium

Remediation approach	Se species	Benefits	Drawbacks	Mechanism	Comments
Physical	Inorganic Se	Employability on a large scale	Being expensive	Both lab-scale and full-scale membranes were made by covering PVDF membranes with PAA, followed by ion exchange of ferrous ions, and finally reduction to zero-valent iron nanoparticles	The use of nano-filtration (NF) and iron-functionalized membranes results in a selenium content of less than 10 g/L
Phytoremediation	Total Se	Green technology	Implementation constraints	Phyto-extraction and phyto-volatilization	Phytoremediation is an effective and feasible approach to get rid of Se from Se-contaminated environment
Biological	Inorganic Se	High removal efficiency	Slow process and requiring acidic condition	–	Widely implemented in industries
Bioremediation	Inorganic Se	Environment friendly; Biofilms can both detoxify and sequester selenium	Requires longer remediation time	Based on the transformation of poisonous, water-soluble Se oxyanions into elemental, water-insoluble Se oxyanions	Biofilms, or microbe communities, play an important role in biotransformation of elements into less harmful chemical forms

Table 6 (continued)

Remediation approach	Se species	Benefits	Drawbacks	Mechanism	Comments
Chemical Coagulation/Flocculation	Inorganic Se	Removal of other toxic metals besides selenium	Less effective in simultaneous removal of both selenium	High coagulant dosages and a weakly acidic pH can promote the production of hydroxide flocs with more positive adsorption sites and a higher zeta potential, making them more desirable for the removal of Se	It is possible to attain a Se(IV) removal effectiveness of over 98 percent....In the removal of Se, Fe-based coagulants were far more effective than Al-based coagulants
Chemical precipitation	Inorganic Se	High removal efficiency	Slow process and requiring acidic condition	Using sulfide ions to precipitate selenium	Sodium sulfide can be used to successfully precipitate precursors ions from weak acidic solutions
Co-precipitation	Inorganic Se	Economical and fast paced	Poor efficiency	During crystal development, the trace element became immobilized in the material	–
Reduction techniques	Inorganic Se	Defects in the nZVI particle shell greatly boost selenium diffusion and increase nZVI's ability for selenium sequestration		Chemical reduction of Se(IV) to Se(0)	Increasing evidence suggests that nZVI can successfully treat and eliminate selenium
Electrocoagulation (EC)	Inorganic Se	Wide range applicability	Power consumption	Iron (Fe) and aluminum (Al) sacrificial electrodes were used in a batch reactor under galvanostatic conditions	The use of Fe electrodes as soluble anode in electrocoagulation constitutes a better option than Al electrodes for the electrochemical sedimentation of colloidal Se(0)
Adsorption	Total Se	Economic and simple to employ	Finding a proper adsorbent	–	Different process variables, such as pH, temperature, contact time, starting concentration, adsorbent dose, and so on, all play a role in determining adsorbent capacity

zone is yet to be achieved. At the same time, there are few drawbacks associated with these remedial strategies as the available knowledge is continuously discovering concepts related to fate and types of Se in both terrestrial and aquatic environments such as selenomethionine, selenocysteine and other inorganic and organic forms. This has paved the way to emergence of new hybrid technologies focused on better control of Se environmental pollution. Considering the fact that researchers must always probe beneath the knowledge gaps, it is worth mentioning that future studies should focus on sources of Se contamination, which appears a function of anthropogenic activities verses natural sources.

A key goal of environmental management is to protect ecological and human health within the context of ecosystem sustainability (Burger et al., 2012). Perhaps no chemical pollutant has more contradictory information concerning ecological consequences in aquatic environments than selenium. Huge disparities in legislation pertaining to Se release and threshold values occur that demonstrate the inability of existing jurisdictions and policy impact on environmental safety. Owing to these differences, selenium is not considered a danger to the environment in Europe. It is not included in the European Commission's Dangerous Substance Directive's list of substances of concern. Moreover, among 41 chemicals that are subject to Environmental Quality Standards in Europe, Se is not included (Okonji et al., 2021). The US Se guidelines for marine waters allow a maximum concentration of 300 g/L and a continuous concentration of 71 g/L, despite planned revisions. The EPA's freshwater threshold is 5 g/L, but Canada's marine and freshwater standards are 2 g/L (Luoma & Presser, 2009). It is critical to reduce such inequalities and harmonize management of selenium's ecological concerns on a global scale. Where restrictions are not founded on convincing scientific evidence, the costs of addressing selenium concerns may rise (Li et al., 2010). With the extraction of coal and related fossil fuels, phosphate ore mining, and irrigation in semi-arid regions, the selenium problem may worsen in the coming years.

A comparative account reveals that bio-sorption and natural adsorbents have recently been shown as potentially most effective methods of removal of selenium species in wastewaters. Low raw material costs, superior adsorption performance, and

environmental friendliness are only a few of the advantages. As a result, it is referred to as a viable strategy for removing selenium. The majority of selenium bio-sorption research, on the other hand, has been concentrated on laboratory batch equilibrium investigations. There are two reasons for this: (a) the lack of bulk biomass for full-scale applications and (b) batch operations on a laboratory scale can be simple to perform but challenging in the field. As a result, finding low-cost bio-sorbents with excellent adsorption ability for selenium treatment is surely a field worth exploring further. According to the literature review, the bulk of modern research is focused on the removal of Se(IV) and Se(VI), but the key concern is the elimination of the organic form of Se. It has a higher bioavailability than other Se compounds and bio-accumulates faster. This is an untouched area yet and could be an important direction for researchers.

Since the species and biodiversity of Se and the associated microorganisms in soil have an impact on earthworm remediation of Se-contaminated soils, long-term research under in situ conditions, especially in the presence of crops, is needed to verify all of the findings.

Designing novel photo-catalysts that function under visible light excitation would aid in the production of solar excitation for effectively reducing Se(IV) and Se(VI), and preliminary research is highly promising. Future research is required to improve the development of Fe-composites, enhance the Fe durability on the surface of composite and also to validate the availability of both Se and Fe forms after the process of adsorption. More research is needed on the intrusion of additional anions prevalent in mine-influenced water until Fe composites may be utilized to treat industrial effluents with Se. Moreover, laboratory environments are not representative of the real-world situation. As a result, larger-scale field remediation studies are desperately required to investigate ZVI's commercial potential under weak magnetic field environments.

Furthermore, it is difficult to build and introduce a magnetic field at larger scale for Se remediation. As a result, it is important to further study and develop effective technique in order to make sure that magnetic field equipment operates reliably.



## Conclusion

The literature on physicochemical properties, sources, global production, uses of Se, environmental Se contamination and different treatment technologies applied for its remediation has been thoroughly collected, summarized, and analyzed in this review. Experimental methods, new derived innovations and technologies, and broad-spectrum developments in a variety of fields were the primary consideration used. Se's occurrence, geochemistry, environmental consideration, i.e., nutrient, and toxicity effects have all been a source of concern around the world. Innovations in analytical techniques and instrumentation, as well as Se identification and speciation, have both contributed to a better understanding of its mechanism in the environment. Se's natural distribution is unequal around the world; for some, it can prevail in low amount, while for others, it must be removed from an environmental medium. Since animals ingest Se from water and foodstuff, so toxicity threat must take both factors into account. To remove Se from all environmental compartments to adhere to the guidelines set forth by numerous government entities around the world, a variety of treatment technologies are available. The scale at which various physico-chemical and biological techniques are employed demands comprehensive review which is presented here in order to identify prevailing strengths and constraints in remediation of Se-contaminated environments.

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## Declarations

**Conflict of interest** The authors declare no conflict of interest and no significant financial assistance for this work that could have influenced its outcome.

**Consent to participate and Ethics approval** The study does not involve human subjects and/or animals, and the manuscript does not include case reports/case series.

**Consent for publication** All of the authors listed in the manuscript have agreed to be authors, have read and accepted the work, and have given their approval to the manuscript's submission and future publication.

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