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Review

Recent Progress in Selenium Remediation from Aqueous Systems: State-of-the-Art Technologies, Challenges, and Prospects

Muhammad Ali Inam [1,2], Muhammad Usman [1], Rashid Iftikhar [2], Svetlozar Velizarov [3,*] and Mathias Ernst [1,*]

[1] Institute of Water Resources and Water Supply, Hamburg University of Technology (TUHH), Am Schwarzenberg-Campus 3, 21073 Hamburg, Germany; muhammad.ali.inam@tuhh.de (M.A.I.); usman@aqua-consult.de (M.U.)

[2] School of Civil and Environmental Engineering (SCEE), Institute of Environmental Sciences and Engineering (IESE), National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan; ainam@iese.nust.edu.pk (M.A.I.); rashid.iftikhar@iese.nust.edu.pk (R.I.)

[3] LAQV/REQUIMTE, Department of Chemistry, NOVA School of Science and Technology, NOVA FCT, Universidade NOVA de Lisboa, 2829-516 Caparica, Portugal

* Correspondence: s.velizarov@fct.unl.pt (S.V.); mathias.ernst@tuhh.de (M.E.); Tel.: +49-40-42878-3453 (M.E.)

Abstract

The contamination of drinking water sources with selenium (Se) oxyanions, including selenite (Se(IV)) and selenate (Se(VI)), contains serious health hazards with an oral intake exceeding 400 µg/day and therefore requires urgent attention. Various natural and anthropogenic sources are responsible for high Se concentrations in aquatic environments. In addition, the chemical behavior and speciation of selenium can vary noticeably depending on the origin of the source water. The Se(VI) oxyanion is more soluble and therefore more abundant in surface water. Se levels in contaminated waters often exceed 50 µg/L and may reach several hundred µg/L, well above drinking water limits set by the World Health Organization (40 µg/L) and Germany (10 µg/L), as well as typical industrial discharge limits (5–10 µg/L). Overall, Se is difficult to remove using conventionally available physical, chemical, and biological treatment technologies. The recent literature has therefore highlighted promising advancements in Se removal using emerging technologies. These include advanced physical separation methods such as membrane-based treatment systems and engineered nanomaterials for selective Se decontamination. Additionally, other integrated approaches incorporating photocatalysis coupled adsorption processes, and bioelectrochemical systems have also demonstrated high efficiency in redox transformation and capturing of Se from contaminated water bodies. These innovative strategies may offer enhanced selectivity, removal, and recovery potential for Se-containing species. Here, a current review outlines the sources, distribution, and chemical behavior of Se in natural waters, along with its toxicity and associated health risks. It also provides a broad and multi-perspective assessment of conventional as well as emerging physical, chemical, and biological approaches for Se removal and/or recovery with further prospects for integrated and sustainable strategies.

Keywords: selenium pollution; water and wastewater purification technologies; removal and recovery; redox transformation; integrated treatment

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1. Introduction

Selenium (Se) is a trace element that is crucial for the synthesis of selenoproteins and enzymes involved in antioxidant defense, thyroid hormone metabolism, and immune function [1]. It is found with a low average abundance in Earth's crust, estimated at approximately 0.13 mg/kg [2]. Despite its scarcity, Se has gained significant attention in the 21st century due to its uneven global distribution, variable abundance, and unique chemical properties. Its presence in the environment is mainly influenced by natural geological processes and anthropogenic activities. For instance, areas underlain by sedimentary rocks can contain a higher abundance of Se up to 12 mg/Kg, whereas igneous rocks typically contain much lower Se concentrations ranging from 0.05 to 0.09 mg/kg [3]. The Se concentration in soils typically lies in the range from 0.01 to 2 mg/Kg worldwide, with an average value of 0.4 mg/kg [4]. However, certain regions in China showed significantly higher soil Se levels, such as 87.3 mg/kg in Enshi Prefecture, Hubei Province, and 36.1 mg/kg in Ziyang County [5,6]. Conversely, very low Se content in the soils of Finland, Scotland, and Sweden has been found, often leading to deficiencies in local populations [7]. The recommended daily allowance (RDA) for Se is approximately 55 µg/day for adults, with the tolerable upper intake level around 400 µg/day [8,9]. This highlights selenium's dual health impact; while deficiency can impair biological functions, excess intake can cause toxicity leading to a condition known as selenosis, such as hair and nail brittleness or loss, gastrointestinal disturbances, skin rashes, and neurological abnormalities [10].

Due to the potential health risks associated with elevated Se concentrations, particularly in raw drinking water sources, the scientific community has shown growing interest in understanding its abundance and distribution and in developing effective remediation strategies. Various natural and anthropogenic activities are major contributors to Se contamination in water reservoirs worldwide, often leading to concentrations that exceed guideline values set by environmental regulatory agencies. Stringent international regulations for Se in drinking water exist, for instance the World Health Organization (WHO), U.S. Environmental Protection Agency (US EPA), and European Union (EU) have set the Drinking Water Regulation Limit (DWRL) for Se as 40 µg/L, 50 µg/L, and 20 µg/L, respectively [11,12]. German drinking water ordinance has, in accordance with the EU DWRL, set an even lower permissible Se level of 10 µg/L in drinking water; the same is true for the Pakistan National Water Quality Standards (Pak-NWSQ) [13,14]. To meet stringent Se guidelines and ensure public health safety, an efficient and technoeconomic feasible treatment approach is needed.

This review briefly highlights the sources and distribution of Se in natural water bodies and outlines its key chemical properties, toxicity aspects, and the conventionally available technologies in removing Se oxyanions from water. Moreover, a multi-perspective assessment of emerging physiochemical and biological technologies for Se removal from water and the associated challenges are discussed in this review. Lastly, this review also highlights the prospects for integrative and sustainable treatment approaches with the aim of Se recovery and circular economy aspects from an aqueous environment.

1.1. Sources of Selenium in Natural Waters

Selenium occurs naturally and ranks 69th in elemental abundance in Earth's crust. It is a constituent of around 60 minerals, commonly found in coal, volcanic ash, and phosphate rocks, often in association with metal sulfide ores. In the human body, Se is present in trace amounts (13–20 mg) and plays a vital role in biological processes [15]. Most environmental Se problems are caused from mobilization under natural conditions, including geological formations, weathering reactions, volcanic activity, biogenic emissions, wildfires, and sea spray [15,16]. In accordance, China holds the largest Se reserves worldwide, primarily linked to copper and coal deposits, especially in provinces such as Hubei, Shaanxi, and

Guizhou, leading to significant selenium mobilization and contamination of natural waters in these regions [17]. Various anthropogenic activities, including fossil fuel combustion, mining and smelting of metal sulfide ores, irrigation activities, industrial processes, and municipal wastewater discharge, are additional pathways, resulting in higher Se levels in the surrounding environment [15,16,18]. The pictorial overview indicating anthropogenic sources of Se is presented in Figure 1. Overall, elevated Se levels in groundwater and surface water are primarily due to leaching from selenium-rich geologic formations and the enhanced mobilization of selenate (SeO_4^{2-}) by agricultural irrigation in seleniferous soils, especially in regions with high evaporation and limited rainfall, such as California's San Joaquin Valley [19]. Such activities can enhance the bioavailability of Se in aquatic environments, thereby posing risks to humans and ecosystems, particularly in Se-sensitive regions.

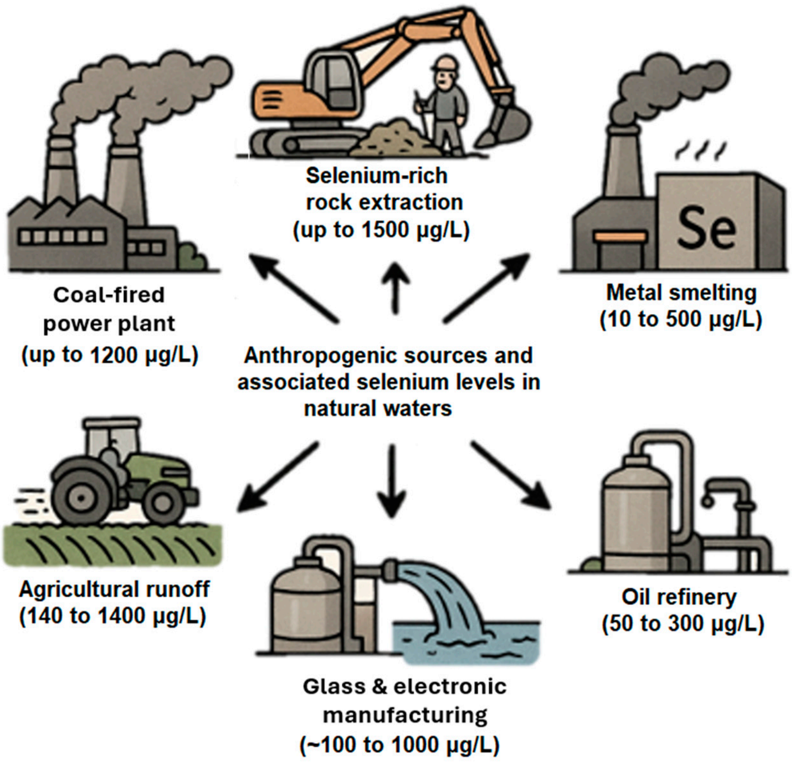

Figure 1. Anthropogenic sources and associated Se levels in natural waters [20–24].

1.2. Distribution of Selenium in Natural Waters

1.2.1. Groundwater

According to the United Nations World Water Development Report 2022, groundwater serves as a drinking water source for half of the global population [19]. Therefore, provision of groundwater with a minimum Se threshold is essential for ensuring public health. The greater risk of Se exposure is probably predominant in regions with seleniferous geological formations. In addition, hydrologic and anthropogenic factors are also responsible for typical Se contamination up to 1000 µg/L in groundwater reservoirs [4,25]. A high variation in Se concentrations in groundwater within arid and semi-arid regions has also been reported owing to geology, redox conditions, and agricultural activities. For instance, Se levels ranging from 0.09 to 742 µg/L in Amman Zarqa Basin, Jordon, have been reported, with 114 out of 250 groundwater samples exceeding the permissible drinking water limit [26]. Se contamination up to about 50 to 1000 µg/L in San Joaquin Valley, California, USA is well documented, where extensive irrigation has increased Se mobilization and accumulation in shallow groundwater [19]. Moreover, several other countries also reported elevated Se levels in groundwater, primarily due to geogenic sources, with concentrations reaching up to 2103 μg/L (Soan Sakesar Valley, Pakistan), 800 μg/L (Atacama Desert, Chile), and 4475 μg/L (Sirmaur district, Himachal Pradesh, India) [27–29]. Such high reported Se concentrations in groundwater underscore the combined influence of natural geological conditions and anthropogenic activities on its spatial distribution worldwide.

1.2.2. Surface Waters

The Se concentration in surface waters such as rivers and lakes typically remains below 10 μg/L under natural conditions; however, activities like mining, irrigation, and industrial discharges can significantly exceed its safe environmental and health thresholds [30,31]. For instance, an Se concentration reaching up to 300 μg/L has reportedly been found in Kesterson Reservoir of San Joaquin Valley, California, USA, owing to irrigation of selenium-rich soils [19]. Remarkably high Se levels up to 2700 μg/L in Martin Creek Reservoir, Texas, USA, have been observed due to coal-fired powerplant effluent discharge [30]. Moreover, elevated Se levels ranging from 2 to 519.3 μg/L in the rivers and lakes of Hubei Province (Enshi Prefecture), China, have been recorded because of natural weathering and mining activities [5,12]. Such high Se contamination and variability pose serious ecotoxicological risks, including bioaccumulation and impaired reproductive development in aquatic organisms as well as potential human health impacts including selenosis through the food chain.

1.2.3. Seawater

Selenium is relatively stable in marine environments, with an average concentration ranging from 0.1 to 0.4 μg/L. In estuarine environments, Se levels may vary due to biological activity, redox gradients, and riverine inputs; however, it remains below 1 μg/L under natural conditions with an estimated median concentration of 0.2 μg/L in global marine waters [32].

1.3. Selenium Chemistry and Toxicity

1.3.1. Selenium Chemistry and Speciation

Selenium, a Group VIA element in the periodic table, exhibits properties typical of metalloids but leans toward non-metallic behavior. Various forms of Se exist in the natural environment, including both inorganic and organic. Organic forms of Se, including selenomethionine, selenocysteine, and their methylated derivatives, may be present in water bodies near agricultural areas due to plant uptake and subsequent biotransformation of inorganic Se into organic compounds [33]. Predominantly, coastal waters can also contain considerably higher organic Se owing to intense biological activities and anthropogenic pollution [4]. In contrast, inorganic Se naturally exists in four redox states and is found in dissolved form in the open ocean, rivers, lakes, and other aquatic environments. Its major forms include selenate (Se(VI)), selenite (Se(IV)), elemental Se (Se(0)), and selenide (Se(−II)). Speciation of Se in water is ruled by redox conditions and pH. It exists as Se(IV) in groundwater (anoxic environment) and Se(VI) in surface water (aerobic conditions) and leads to both long and persistent contamination when released into water [34]. Amongst these, Se(IV), present as selenite (SeO_3^{2-}), has a molecular weight of 126.96 g/mol and a hydrated radius of approximately 0.276 nm, whereas Se(VI), often in the form of selenate (SeO_4^{2-}), has a higher molecular weight of 142.96 g/mol and a larger hydrated radius of around 0.384 nm [35,36]. Se(VI) is the fully oxidized form and can be present in aqueous solution as biselenate ($HSeO_4^-$) or selenate (SeO_4^{2-}), with a pK_a value of 1.8 ± 0.1. Se(IV) exists as a weak acid in the specifications of selenious acid (H_2SeO_3), biselenite ($HSeO_3^-$), or selenite (SeO_3^{2-}), with corresponding pK_a values of 2.70 ± 0.06 ($H_2SeO_3/HSeO_3^-$) and 8.54 ± 0.04 ($HSeO_3^-/SeO_3^{2-}$). In the pH range (≈5–8.5) relevant to natural waters, selenite

($HSeO_3^-$ and SeO_3^{2-}) and selenate (SeO_4^{2-}) species are dominant. The Se speciation depending on pH and redox potential is presented as an example in the pE–pH diagram (Figure 2). While SeO_4^{2-} dominates under higher oxidizing conditions and pH (pE > 12.5, pH 5–8.5), $HSeO_3^-$ is the thermodynamically favored species in aerobic natural water (pE < 12.5, pH 5–8.5). Under reducing and acidic conditions, water-insoluble Se(0), as well as Se(−II), is favored [24].

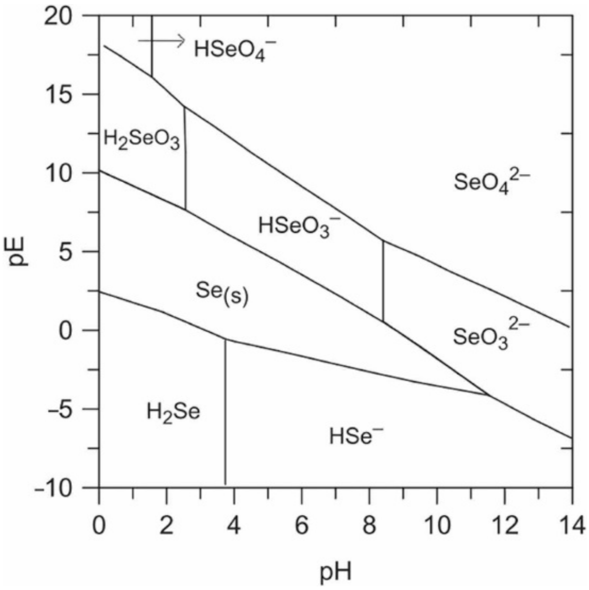

Figure 2. Selenium pE–pH diagram at 25 °C and 1 bar pressure in water (reproduced from [37], with permission from Elsevier).

1.3.2. Toxicity and Health Implications

Unlike other metalloids, Se exhibits dual properties; it is an essential micronutrient for human health but becomes toxic when ingested in excess, particularly through contaminated drinking water supplies. For instance, the daily tolerable intake of Se is 400 µg/day as per the United States National Academy of Sciences and endorsed by the World Health Organization (WHO) as well as by the United States Food and Agriculture Organization (FAO). According to the European Food Safety Authority (EFSA), an intake of 400 µg Se per day is tolerable for adults without any risk of harmful side effects [38]. Se plays a vital role in supporting thyroid function. However, excessive intake can cause a wide range of adverse effects, including diabetes, cardiovascular disease, reproductive and developmental disorders (such as fetal abnormalities), hair loss, myopathy, liver and kidney failure, an elevated risk of cancer, and, in extreme cases, death [39–41]. The underlying mechanisms of Se toxicity include overactivation of selenoproteins (e.g., glutathione peroxidase), endothelial dysfunction, and altered lipid metabolism under conditions of excessive selenium intake, which may contribute to the development of type 2 diabetes and cardiovascular disease [42]. Considering the difficulties in distinguishing the safe and required concentration of Se in drinking water, different regulatory agencies have fixed different permissible Se values. Among the various forms of selenium, Se(IV) is considered the most toxic and carcinogenic. Therefore, developing removal strategies that account for Se speciation is equally crucial for protecting human health and remains a significant global concern [43,44].

2. Conventional Selenium Removal Techniques

To remove Se(IV)/Se(VI) from water and wastewater, earlier studies have presented several conventional treatment options, including physical, chemical, and biological options, with different degrees of effectiveness [9,24]. This section provides a concise overview of the conventional Se removal techniques, while also highlighting their effectiveness and key technical limitations and identifying relevant research gaps.

2.1. Physical Methods

Physical methods are often used in Se elimination owing to their operational simplicity, excellent efficiency, and cost-effectiveness. Adsorption is among the widely applicable physical techniques for Se remediation from water. Various commercially available materials, including iron oxides, activated alumina, activated carbon, and ion exchange resins, have been used for Se removal from water. Amongst these, iron-based adsorbents such as derivatives of iron oxides (FeOOH, Fe_3O_4) have shown promising adsorption affinity towards Se oxyanions [9]. Iron oxides can form inner-sphere and outer-sphere surface complexes with Se(IV) and Se(VI) as they contain two types of surface sites, including amphoteric iron hydroxyl groups and unsaturated iron atoms with surface coordination [45]. Moreover, the high point of zero charge (pHpzc) values of various iron oxide forms (goethite: ~9.3, hematite: ~8.5, and ferrihydrite: ~8.5) enable them to attract negatively charged Se oxyanions in water, leading to better Se removal performance [46–48]. However, iron oxide and iron hydroxides are sensitive to Se speciation and are typically more effective for Se(IV) ions than Se(VI), which is highly mobile in surface waters, less readily adsorbed on iron oxide surface, and more bioavailable to aquatic life [49]. Other technical limitations include the need for a controlled pH range and frequent regeneration or even replacement of adsorbent material, which leads to increased operational costs and greater challenges related to sludge generation and disposal. Moreover, key research gaps include limited long-term field data across various water chemistries, inadequate selectivity for simultaneous Se(IV) and Se(VI) removal under neutral to alkaline conditions, and the need for effective regeneration methods that maintain the adsorbent's structural integrity and performance.

Another physical treatment method is membrane filtration, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), which have been used to remove Se from water. Amongst these, NF and especially RO have demonstrated greater than 85% Se(IV) removal efficiency under optimum conditions [50]. However, weaker interactions of Se(VI) species, particularly under neutral to alkaline conditions with NF membrane material, resulted in their significantly lower rejection rates, thus leading to higher levels in the permeate aqueous solution [50,51]. Therefore, pretreatment steps such as coagulation or adsorption followed by NF are often required for effective Se removal from water [50,51]. In contrast, reverse osmosis (RO) is highly effective for selenium removal. However, its application in decentralized decontamination systems is limited by high operational and maintenance costs, membrane fouling, low water recovery, and a typically low volumetric permeate flux (<100 $L/m^2/h$) [52,53]. Therefore, further research is required to advance membrane-based strategies for Se decontamination, with a particular focus on enhancing Se removal selectivity and mitigating membrane fouling, especially under low-resource conditions.

2.2. Chemical Methods

Chemical methods, including coagulation/flocculation, precipitation, chemical reduction, etc., are commonly employed treatments for producing fresh drinking water. For instance, coagulants such as aluminum chloride and ferric chloride and inorganic polyaluminum chloride flocculant have been used to remove Se(IV) and Se(VI) species from water [54]. Amongst these, iron-based coagulants have shown more promising (>98%) Se(IV) removal than (<40%) Se(VI) removal from water under similar applied dosages [54].

The negative influence of interfering oxyanions on Se(IV) removal was observed in the following order: $PO_4^{-3} > SiO_3^{-2} > CO_3^{-2} > SO_4^{-2}$, respectively. In comparison, monovalent ions such as NO_3^-, Cl^-, and HCO_3^- have minimal impact on Se removal, and their competitive effects are generally weaker and less relevant under typical environmental conditions. In addition, high iron dosage (up to 1 mM) and weak acidic pH conditions (<5.5) need to be considered for more iron hydrolytic flocs formation, thereby effectively eliminating Se(IV) from aqueous solution [54]. Still, Se(VI) removal cannot be effectively achieved using a single-step coagulation process. Therefore, another study explored a novel coagulation process comprising a reduction pathway via sulfite and ultraviolet (UV) light pretreatment followed by iron-based coagulation in a short time (1 h) for effective Se(VI) removal from water [55]. The addition of 5 mM sulfite combined with a UV dose of 16 J/cm^2 effectively reduces 99% of 10 mg/L Se(VI) to Se(IV) within 20 min in high sulfate (1000 mg/L) water. The produced Se(IV) is then efficiently removed via iron coagulation [56]. This two-step process works well for simulated wastewater, sulfate-rich synthetic solutions, and real smelting wastewater. The co-addition of salts like 1 mg/L K_2FeO_4 and 9 mg/L Mn(II) with iron enhances Se(IV) removal (89–98%) by co-precipitation at pH 4–8 within 2 min [56]. Another study achieved > 99% Se(VI) removal using barite co-precipitation at neutral pH over a wide concentration range. Despite improvements, coagulation faces challenges, including large solid waste generation, disposal challenges, and inconsistent achievement of safe Se levels [54,56,57]. Additionally, the cost of coagulation/precipitation with iron salts has been estimated at 357 EUR/kg Se(IV) removed [24,58]. Future research should focus on developing more efficient, cost-effective, and environmentally friendly coagulants selective for Se oxyanions under diverse water chemistries.

2.3. Biological Methods

Various conventionally available biological techniques, including phytoremediation, bacterioremediation, and mycoremediation, have been used to effectively treat Se from contaminated water, utilizing mechanisms like biosorption and biodegradation. For instance, bioremediation using Se-reducing microorganisms, including *Pseudomonas stutzeri*, *Thauera selenatis*, and *Bacillus selenitireducens*, have presented up to 95% Se removal and recovery under anaerobic conditions [59–62]. Phytoremediation utilizing hyperaccumulator plant species such as *Brassica juncea* and *Stanleya pinnata* have shown varying Se uptake performances ranging from 60% to 90% depending on the Se oxyanion form, plant type, and growth conditions [63]. In addition, up to 75% Se remediation has been reported by aquatic plants, i.e., *Lemna minor*, from water bodies over a time duration of 10 to 14 days in a constructed wetland system [64,65]. Another biological approach, i.e., biosorption of Se onto dead biomass such as fungal and algal biosorbents (*Aspergillus niger* and *Chlorella vulgaris*), has demonstrated up to 85% Se(IV) and up to 70% Se(VI) removal under optimized conditions [18]. Conventional biological techniques generally demonstrate substantial selenium removal efficiency, coupled with favorable sustainability characteristics. Therefore, further research should aim to enhance their long-term performance and effectiveness under field-scale conditions.

3. Recent Developments in Selenium Remediation Technologies

3.1. Adsorption

3.1.1. Batch Mode Adsorption

Adsorption presents a widely favorable, cost-effective, and efficient method for selenium treatment due to its simplicity, non-toxicity, and high contaminant removal capacity [66]. Among the two modes of adsorption, batch mode serves as the foundational phase for adsorption studies, as it generates relevant data such as adsorption isotherms, kinetics, and capacity, without which dynamic systems cannot be accurately designed or optimized for effective industrial effluent treatment [67]. Recently, surface modification of adsorbents has garnered attention for enhanced porosity and surface area, leading to improved adsorption capacity towards Se oxyanions (data shown in Table 1). Carbonaceous materials are characterized by a high specific surface area and rich surface functionalities, but inherently low affinity for selenium oxyanions. However, their surfaces can be functionalized with materials like metal oxides, layered double hydroxides, or polymers to form composite adsorbents with enhanced selenium removal efficiency [9]. Surface complexation modeling represents a recent advancement in the adsorption mechanism, offering a mechanistic and chemically accurate pathway to predict heavy metal adsorption by accounting for adsorption speciation, active sites, and complexation constants, overcoming the limitations of traditional isotherm models [68]. The integration of artificial intelligence (AI) models, such as neural networks and support vector machines, with traditional isotherm models offers adaptive control, operational efficiency, and enhanced predictive accuracy [69]. Behera et al. employed the regression learner tool for bioremediation of selenium in batch mode adsorption; the Gaussian process regression yielded the best predictive performance, followed by neural network, support vector machines, and tree [70]. Ullah et al. predicted the adsorption performance of iron-modified biochar for Se under varying water chemistry conditions, including pH, temperature, and competing ions using a machine learning approach. They demonstrated robust performance across environmental gradients, suggesting strong potential for real-world applicability beyond controlled synthetic tests [71].

Table 1. Batch adsorption studies: recent developments in adsorbents for selenium removal.

Adsorbent	Se Form	Initial Concentration (mg/L)	Experimental Conditions	Adsorption Capacity (mg/g)	Removal Efficiency (%)	Reference
Aluminum-modified bamboo biochar	Se(VI)	50	120 min, pH 4.0, 1 g/L	37.6	99.6%	[72]
Nano-zerovalent zinc-functionalized biochar	Se(IV), Se(VI)	1–130	1440 min, pH 4.0–10.0, 2 g/L	23.83 (IV), 27.16 (VI)	93–94%	[73]
β-Cyclodextrin-functionalized LDH/rGO	Se(IV), Se(VI)	100	60–360 min, pH $\leq$ 7.0, 145.3 m^2/g, 0.01–0.1 g/L	169.6, 275.4	≥80%	[74]
Calcined layered double hydroxide of Mg/Al-CO_3	Se(IV)	1000	pH 5.0, 210 m^2/g	134.4	-	[75]
Zirconium-based metal organic framework	Se(IV), Se(VI)	5–150	360 min, pH 2.0–8.0, 0.5 g/L	107.1 (IV), 47.6 (VI)	74%	[76]
Ionic metal organic framework	Se(IV), Se(VI)	1–10	30 min, pH 7.0, 1 g/L	140.5 (IV), 73 (VI)	99.9%, 99.4%	[77]
Fe-oxide-impregnated activated carbon	Se(IV), Se(VI)	25	1920 min, pH 4.0, 1183 m^2/g, 10 g/L	-	70–85%	[78]
composite foam, incorporating chitosan, FeOOH and CNF	Se(IV)	0.2–5	180 min, pH 3.0–10.0, 0.16 g/L	90	-	[79]
Fe-Mn bimetallic micro composite	Se(IV), Se(VI)	0.1–10	60 min, pH 8.5, 59.345 m^2/g, 0.5 g/L	-	~95%	[80]
Amberlite, anion exchange resin with tertiary amine group	Se(IV)	100	10 min, pH 3.0, 2 g/L	18.52	80.3%	[81]

3.1.2. Continuous Mode Adsorption

A larger number of adsorbents have been evaluated through batch experiments; however, only a limited number of studies have assessed adsorbents using dynamic fixed-bed column experiments. Even when dynamic fixed-bed column experiments were conducted, they were mostly limited to bench-scale laboratory studies. Evaluation of adsorbents under real field conditions remains rare. As discussed in the earlier section on batch adsorption studies, iron-based adsorbents, including natural iron oxides such as hematite and goethite [82], as well as commercially available and laboratory-synthesized iron oxides and oxyhydroxides, are known for their high adsorption capacities, as determined from batch adsorption tests, due to selenium's strong affinity for iron oxides. Accordingly, more studies are available on these iron-based adsorbents.

Commercial iron oxyhydroxide (FeOOH)-based adsorbents such as Bayoxide and granular ferric hydroxide, GFH) have been tested for selenite and selenate removal in dynamic fixed-bed column experiments (data shown in Table 2). These FeOOH-based commercial adsorbents exhibited better adsorption capacities for Se(IV) under continuous-flow fixed-bed column conditions compared to Se(VI). However, their adsorption performance for Se(VI) was relatively poor. In these studies, adsorbents were evaluated based on their Q_{10} values, which is defined as the adsorption capacity at a residual selenium concentration of 10 µg/L in the column effluent. These commercial adsorbents are therefore considered unsuitable for effective removal of Se(VI). In contrast, the Q_{10} values for Se(IV) were significantly higher: 0.7 mg Se(IV)/g for GFH, 1.7 mg Se(IV)/g for Bayoxide, and 4.3 mg Se(IV)/g for FeOOH synthesized through precipitation of $FeSO_4$ at pH 2. Notably, the Q_{10} value of the laboratory-synthesized iron oxyhydroxide at pH 2 for Se(IV) was approximately 2 times higher than that of commercial Bayoxide and 5 times higher than that of GFH [58].

Table 2. Adsorption performance of various commercial and laboratory-synthesized adsorbents for selenite and selenate removal from water in fixed-bed adsorption filters.

Adsorbent	Water Matrix	Adsorption Performance for Se(IV)	Adsorption Performance for Se(VI)	Reference
Bayoxide (BET surface area = 135 m^2/g, IEP = 7.4)	Artificial groundwater at pH 7. Initial Se(IV) conc. = 50 µg/L or Initial Se(VI) conc. = 50 µg/L. EBCT = 3.5 ± 0.5 min.	Q_{10} = 1.7 mg/g	Q_{10} = 0 mg/g	[58]
GFH (BET surface area = 237 m^2/g, P = 7.2)		Q_{10} = 0.7 mg/g	Q_{10} = 4 µg/g	[58]
FeOOH (synthesized through precipitation of $FeSO_4$ at pH 2, BET surface area = 100 m^2/g, IEP = 5.7)		Q_{10} = 3.5 mg/g	Q_{10} = 17 µg/g	[58]
Activated Alumina	Deionized water at pH 7 ($NaHCO_3$ was added as pH buffer). Initial Se(IV) conc. = 10 mg/L or Initial Se(VI) conc. = 10 mg/L.	Q_{max} = ~2.1 mg/g	Q_{max} = ~0.8 mg/g	[83]
Aluminum–iron (Al–Fe) mixed oxide	Deionized water at pH 7. Initial Se(VI) conc. = 400 µg/L.	-	Q_{max} = 26.6 mg/g	[84]
Acrylic amine fiber (AAF)	Tap water at pH 7.2. Initial Se(VI) = 100 µg/L. EBCT = 4 min	-	900 BV *$_t$	[85]

Note: * Q_{10}: Total adsorption capacity to reach 10 µg/L residual concentration, Q_{max}: Maximum adsorption capacity, BET: Brunauer-Emmett-Teller, EBCT: Empty bed contact time, IEP: Isoelectric point and BV: Bed volumes.

Despite the effectiveness of commercial adsorbents like Bayoxide and GFH in removing Se(IV), their adsorption capacities for Se(IV) remain lower than those for arsenate (As(V)), another environmentally significant oxyanion [86]. These adsorbents are applied in real-world water treatment systems for arsenate removal, with Q_{10} values of 4.3 mg/g for Bayoxide and 1.7 mg/g for GFH [87], substantially higher than their corresponding values for Se(IV). As a result, the treated bed volumes (BV_t) achievable for arsenate typically range from 100,000 to 300,000 [88]. In comparison, significantly lower BV_t values are expected for Se(IV), reflecting its comparatively weaker adsorption on these materials. These findings highlight that FeOOH-based commercial adsorbents are relatively effective in removing Se(IV); their performance is not sufficient to support widespread application for selenium removal in real-world scenarios. On the other hand, laboratory-synthesized iron oxyhydroxides demonstrate significantly superior adsorption performance for Se(IV), highlighting the need for further material development and field-scale validation to enable effective and reliable selenium remediation in practical water treatment systems.

Fixed-bed adsorption regeneration studies using 0.01 N NaOH solution (pH = 12 ± 0.5) have been conducted to assess the reusability of FeOOH-based commercial and laboratory-synthesized adsorbents, with the goal of reducing material costs. The regeneration process was carried out by passing approximately 110 BV of NaOH solution through the adsorption column. The regenerated adsorbents were still effective, maintaining effluent Se(IV) concentrations well below 10 µg/L. However, the Q_{10} value of regenerated Bayoxide dropped to 1.3 mg Se(IV)/g, compared to 1.7 mg Se(IV)/g for the fresh material, indicating a 25% decline in adsorption efficiency. Nevertheless, the implementation of regeneration can reduce the overall material cost for Se(IV) removal by at least 50% [58].

Zero-valent iron (ZVI), including nano-ZVI (nZVI), is widely studied for selenium removal due to its low cost, strong Se affinity, and redox capability. ZVI forms a core–shell structure with metallic Fe at the core and iron oxides or (oxy)hydroxides in the shell. This structure enables multiple removal mechanisms, such as adsorption, reduction, and precipitation, making ZVI-based adsorbents highly effective for Se remediation [24,89,90]. Its performance has been evaluated under various operating parameters in fixed-bed adsorption columns, revealing a decrease in efficiency with increasing filter velocity, higher influent Se concentrations, and reduced filter depth. Moreover, the water matrix significantly affects performance due to the presence of organic matter and competing inorganic species, which can interfere with selenium adsorption. In particular, the removal of Se(VI) by ZVI is inhibited in the presence of sulfate (SO_4^{2-}). Due to their similar chemical properties and the smaller size of SO_4^{2-} compared to selenate (SeO_4^{2-}), sulfate ions effectively compete for the same reactive adsorption sites on the ZVI surface [91].

Another commercial adsorbent that has been used for selenium removal from water is activated alumina (AA). The adsorption capacity of activated alumina for Se(IV) is significantly higher than that for Se(VI). A continuous-flow reactor packed with activated alumina was able to reduce Se(VI) concentrations effectively from 10 mg/L to below 0.1 mg/L, with a maximum adsorption capacity (Q_{max}) of approximately 0.8 mg Se(VI)/g. In contrast, Se(IV) adsorption plateaued at 2.1 mg/g after 42 days of continuous operation, falling well short of the maximum adsorption capacity of 7.2 mg Se(IV)/g recorded under batch conditions. To improve Se(VI) removal, the reactor was inoculated with *Shigella fergusonii* strain TB to promote the biological reduction of Se(VI) to Se(IV), thereby enhancing the overall removal via subsequent adsorption. In this configuration, AA beads functioned both as the adsorbent and as the attachment medium for microbial cells. This biologically assisted system achieved significantly higher Se(VI) removal than the control reactor [83]. These findings highlight the potential of activated alumina, particularly when integrated with microbial processes, for effective selenium remediation. However, to assess its true efficacy and to enable robust comparisons with iron oxide-based adsorbents, further investigations using real water matrices and field-scale studies are necessary.

In a recent study by Jadhav et al., iron oxide and aluminum oxide materials were combined to enhance both the Q_{max} and the rate of adsorption for selenite (Se(IV)) and selenate (Se(VI)) removal from water. These materials, individually known for their effectiveness in removing various pollutants from industrial wastewater and drinking water, were investigated in a fixed-bed adsorption column. The column was packed with pellets (0.5–1.0 mm in diameter) composed of mixed iron and aluminum oxides, with a total bed volume of 2.36 mL. The filter was able to treat 85 L of water, reducing the Se(VI) concentration from 400 µg/L to 40 µg/L—meeting the WHO guideline limit for drinking water. The material achieved a BV_t of ca. 36,000 until the breakthrough concentration of 40 µg/L was reached and exhibited a Q_{max} of 26.6 mg/g at pH 7 (Table 1). It is important to note that the fixed-bed column tests were performed only for Se(VI). However, batch adsorption experiments evaluated the removal of both Se(IV) and Se(VI), yielding Q_{max} values of 33.1 mg/g for Se(VI) and 6.2 mg/g for Se(IV) [84]. These results indicate that the adsorption capacity for Se(VI) was nearly five times greater than that for Se(IV). Overall, the Al–Fe mixed oxide adsorbent demonstrated significantly enhanced selenium removal performance, particularly for Se(VI), compared to adsorbents based on individual iron oxide or aluminum oxide.

Activated carbon (AC) is a widely used adsorbent for the removal of various pollutants from water and wastewater due to its high surface area, porous structure, and abundance of functional groups. In selenium removal applications, AC is primarily utilized as a support material for the deposition of iron oxides [9,92,93]. AC-based composites compared to standalone iron oxides offer better separation from water and can be formed into larger particles with tunable physicochemical properties tailored for selenium adsorption [94]. Typically, the surface area of AC decreases after metal impregnation—for instance, from 620 to 531 m^2/g—while the maximum adsorption capacity can increase by up to threefold [95]. In one study, iron oxide-impregnated granular activated carbon (GAC) was employed in a fixed-bed column for Se(IV) removal [96]. However, the primary focus of the study was on modeling Se(IV) breakthrough behavior using a pore and surface diffusion model, rather than evaluating adsorption capacity or reporting treated bed volumes. As such, key performance metrics such as Q_{max} and BV_t were not provided.

Bleiman et al. examined chitosan–montmorillonite composite to treat well water containing ~0.10 mg/L Se in a semi-pilot column and showed robust Se removal performance below the WHO level despite the presence of competing ions such as sulfate (~13 mg/L) [97]. A study by Chan et al. demonstrated effective Se(IV) removal (lowering levels from 2 mg/L to <0.010 mg/L) from simulated drinking water samples using hydrated ferric-oxide (HFO)–polymer hybrid resin (HFO-201) in a fixed-bed column with field scalability potential [98]. Losev et al. synthesized functionalized silica-based adsorbents and achieved 2.21 to 3.16 mg/g Se(IV) and Se(VI) extraction potential from natural waters in field conditions using in situ solid-phase extraction columns [99]. Although studies on Se removal from real water matrices via adsorption remain limited, recent findings illustrate significant progress toward field-level application of adsorptive materials in real drinking water systems.

Agricultural residues can be converted into value-added products like biochar through thermal processes. Biochar is a versatile material used for soil improvement, energy production, and contaminant adsorption from water. Untreated biochar is generally not recommended for water treatment applications due to its limited adsorption efficiency. To enhance its performance, chemical modification is commonly employed [9,72,73,92,100,101]. One such modified biochar composite, ZnFeBC—impregnated with zinc (Zn) and iron (Fe) oxides—was synthesized and tested for Se(IV) removal from a real water matrix using fixed-bed adsorption. The column packed with ZnFeBC successfully reduced Se(IV) concentrations from 5000 μg/L to below 250 μg/L at a bed height of 2.5 cm, demonstrating promising performance [100]. However, to evaluate its suitability for drinking water applications, further studies are required at lower Se(IV) concentrations, particularly to draw meaningful conclusions about its performance in comparison with commercial adsorbents.

The development of advanced adsorbents with both high adsorption capacity and efficient regeneration potential remains a key focus in current water treatment research [73]. Surface functional groups significantly influence the sorption behavior of adsorbents, thereby governing the interfacial chemistry mechanisms responsible for contaminant removal. Among various functional groups, amines, mainly secondary and quaternary amines, have recently achieved attention for their effectiveness in removing a range of contaminants from aqueous solutions [84,102,103]. Notably, amine groups have also demonstrated promising regeneration properties after saturation, making them attractive candidates for reusable sorbent materials.

One such amine-functionalized material, acrylic amine fiber (AAF), has been evaluated for its performance in both batch and dynamic fixed-bed filters. AAF was shown to reduce selenate concentrations from 100 μg/L to below 10 μg/L in tap water under neutral pH conditions (pH 7.2) with EBCT of 4 min, thereby achieving compliance with stringent drinking water standards for selenium. Furthermore, regeneration studies using a 0.5 mol/L HCl solution demonstrated a regeneration efficiency exceeding 95%. However, the bed volume (BV) of the fresh adsorbent was 900 BV, which decreased to 810 BV after regeneration, indicating a slight decline in material properties and performance [85]. Despite the high regeneration efficiency, the relatively modest BVs underscore the need for continued research focused on developing adsorbents with higher treatment capacities without compromising their reusability.

3.2. Photocatalysis

Recent developments in photocatalytic technologies have shown substantial improvement in Se oxyanion removal using a photocatalyst from aqueous environments. Several contemporary studies have demonstrated the effectiveness of photocatalytic nanocomposite materials for the reduction and subsequent adsorptive recovery of Se under ultraviolet and visible (UV/Vis) light irradiation, highlighting their potential as a promising water treatment strategy [104–108]. Amongst these, titanium oxide (TiO_2)-based nanocomposites have received substantial attention due to their excellent photocatalytic activity and better stability and suitability in conjunction with other functional groups [104–107]. For instance, Holmes et al. (2022) provided a good documentation of the influence of competing ions, i.e., NO_3^- and SO_4^{2-} on Se(VI) removal and speciation using photocatalytic TiO_2 in water. The reduction of Se(VI) to Se(0) and then potentially to H_2Se gas was observed using photocatalytic TiO_2, while NO_3^- inhibited H_2Se gas formation via CO_2 radical scavenging. Moreover, SO_4^{2-} decreases both Se reduction to Se(0) or Se(-II) and NO_3^- effects through competitive adsorption, thereby influencing both Se speciation and the removal process [107]. Another study showed over 99.3% Se(VI) removal using anatase (tetragonal) TiO_2 during 15 reuse cycles under UV irradiation in synthetic mining-influenced brine, with no washing or regeneration between cycles. The mechanism involved in situ formation of Se–TiO_2 heterojunctions, thus causing dynamic variations in Se oxidation state, properties, and crystal size, thereby drastically impacting Se reduction products, pathways, and overall removal process, as also illustrated in Figure 3 [105]. Holmes et al. (2020) utilized noble metals, including gold (Au)-, silver (Ag)-, platinum (Pt)-, and palladium (Pd)-based TiO_2 nano-photocatalysts, for selective Se(VI) reduction to solid Se(0) and gaseous H_2Se in water. Amongst these, Pd–TiO_2 acted as an electron sink to promote solid Se^0 formation while other noble metals with a TiO_2 photocatalytic system showed high selectivity towards H_2Se via a direct Z-scheme electron transfer [104]. Ahmed et al., focusing on photocatalytic degradation and removal of selenocyanate ($SeCN^-$) from industrial wastewater using an integrated UV–TiO_2/Fe(III)–SiO_2 system, also presented optimal performance based on degradation via UV-TiO_2 coupled adsorption onto Fe(III)/SiO_2 [106]. Another research work utilizing a heterojunctioned rutile–brookite TiO_2 nano-photocatalyst achieved 95% Se(VI) removal via a two-step UV-assisted mechanism, including reductive adsorption of Se(VI) to Se(IV) followed by photoreduction to Se^0. Moreover, the elemental Se deposition further auto-catalyzes the photocatalytic process by enabling visible light activity with simultaneous suppression of charge recombination and suppressing charge recombination [108]. Additionally, these photocatalysts revealed excellent Se removal and recovery potential as well as operational adaptability. However, a photocatalyst with a high activity, stability, and reusability potential is crucial for Se reduction and removal for real-world water treatment. Further research should therefore focus on recyclability, scalability, and stability for long-term operation under real water conditions to enable large-scale deployment.

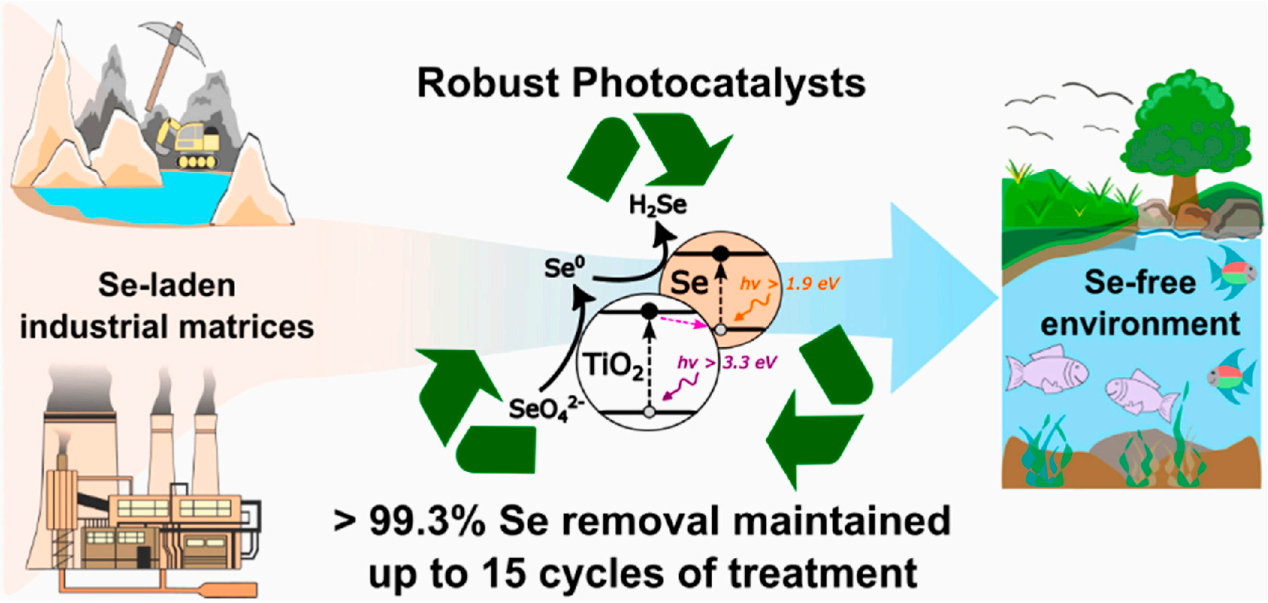

Figure 3. In situ formed Se–TiO_2 as a highly reusable photocatalyst for selenium reduction and removal from industrial wastewater (reproduced from [105], with permission from Elsevier).

3.3. Membrane Technology

3.3.1. Se Removal by Pressure-Driven Membranes

Among the various pressure-driven membrane separation technologies, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), only NF and RO have demonstrated high effectiveness in the removal of selenium from contaminated water sources [109,110]. These membrane processes provide distinct benefits, including consistent performance despite fluctuations in water quality, elimination of the need for chemical additives (except antiscalants and possible re-mineralization), and a compact system design that requires less space [11,110,111].

NF and RO are pressure-driven membrane separation processes that utilize dense semi-permeable membranes to remove contaminants. NF is effective for rejecting multivalent ions and micropollutants with larger molecular masses (in general >100 Da), while RO is typically employed for the removal of smaller monovalent ions. In both processes, the separation of inorganic compounds is primarily governed by steric hindrance (sieving), solution-diffusion, and electrostatic interactions [112–114]. The high rejection of selenium species, such as selenite (SeO_3^{2-} with a MW of 126.96 g/mol and hydrated radius of 0.276 nm) and selenate (SeO_4^{2-} with a MW of 142.96 g/mol and hydrated radius of 0.384 nm), by NF and RO membranes has been widely reported. It is worth mentioning that the pore size of NF membranes typically ranges from 0.5 to 2 nm, while RO membranes (in the case of considering pores instead of continuum material) have even smaller pores (<0.5 nm), which enables effective rejection of Se species based on size exclusion [36]. The primary mechanisms responsible include size exclusion (governed by ions bigger than membrane pore size), Donnan exclusion (charge-based electrostatic interactions), and dielectric exclusion (energy barrier-based) [110,115]. The observed variations in selenium species retention across different pH levels illustrate how the dominant mechanism shifts depending on selenium speciation. In addition, membrane surface charge is an important factor influencing Se separation, as functional groups introduced during membrane fabrication, such as unreacted acyl chloride groups that hydrolyze to form negatively charged carboxyl groups, and amine groups introduced through reaction with amines, significantly affect Se removal via electrostatic interactions [36].

The contributions of these exclusion mechanisms, namely steric, Donnan, and dielectric effects, have been explored by several researchers. The observed trends in selenium species retention across different pH levels reflect how the dominant mechanism shifts depending on the Se speciation. Common NF membranes such as Dow FILMTEC NF90 (a thin-film composite (TFC) polyamide (PA) membrane) showed high retention of both Se species across a broad pH range (2–12), maintaining low permeate Se concentrations that meet or are close to EU/WHO guidelines. In contrast, the NF270 TFC PA membrane, which has larger pores, shows lower effectiveness and generally cannot meet selenium guidelines except at high pH (10–12) for Se(IV). The difference in performance between NF90 and NF270 is mainly due to their molecular weight cut-off (MWCO), with NF90 providing greater steric exclusion because of its tighter membrane structure [110]. In general terms, selenium rejection is typically higher with denser membranes with tighter polymeric structures.

In terms of selenium species removal, researchers have reported that Dow FILMTEC NF270 and NF90 membranes exhibit higher retention rates for bivalent selenium ions (SeO_3^{2-} and SeO_4^{2-}) compared to their monovalent forms ($HSeO_3^-$ and $HSeO_4^-$) [110]. Similar results have been observed using thin-film nanocomposite (TFN) polyamide nanofiltration membranes embedded with polyhedral oligomeric silsesquioxane (POSS). With a molecular weight cut-off (MWCO) of 302 Da, these membranes achieved high removal efficiencies of 93.9% for SeO_3^{2-} and 96.5% for SeO_4^{2-} [116]. Selenium retention increases with rising pH, especially for selenite, whose rejection improves from around 40–60% to up to 98% as the divalent SeO_3^{2-} becomes dominant. Selenate shows even higher rejection across all pH levels due to the prevalence of SeO_4^{2-} above pH 4. Additionally, the enhanced rejection of Se(VI) with increasing pH is influenced by the surface charge of polyamide membranes, which becomes more negatively charged at higher pH levels, strengthening electrostatic repulsion of the negatively charged selenium species. In the case of looser (less dense) membranes, Donnan exclusion becomes particularly important, contributing to improved separation efficiency by providing charge-based electrostatic repulsion [110,115,116]. The mechanisms of ion rejection in nanofiltration and reverse osmosis are illustrated in Figure 4.

The performance of dense membranes is influenced by operating conditions such as applied transmembrane pressure, water recovery, temperature, and pH [36,109,114]. Selenium removal increases sharply with rising operating pressure up to approximately 15 kg/cm^2 (~14.7 bar); however, further increases in pressure beyond this point do not significantly enhance selenium rejection. As the water flux increases with transmembrane pressure, the solute flux does not increase proportionally, thus resulting in higher solute rejection efficiency at higher transmembrane pressures.

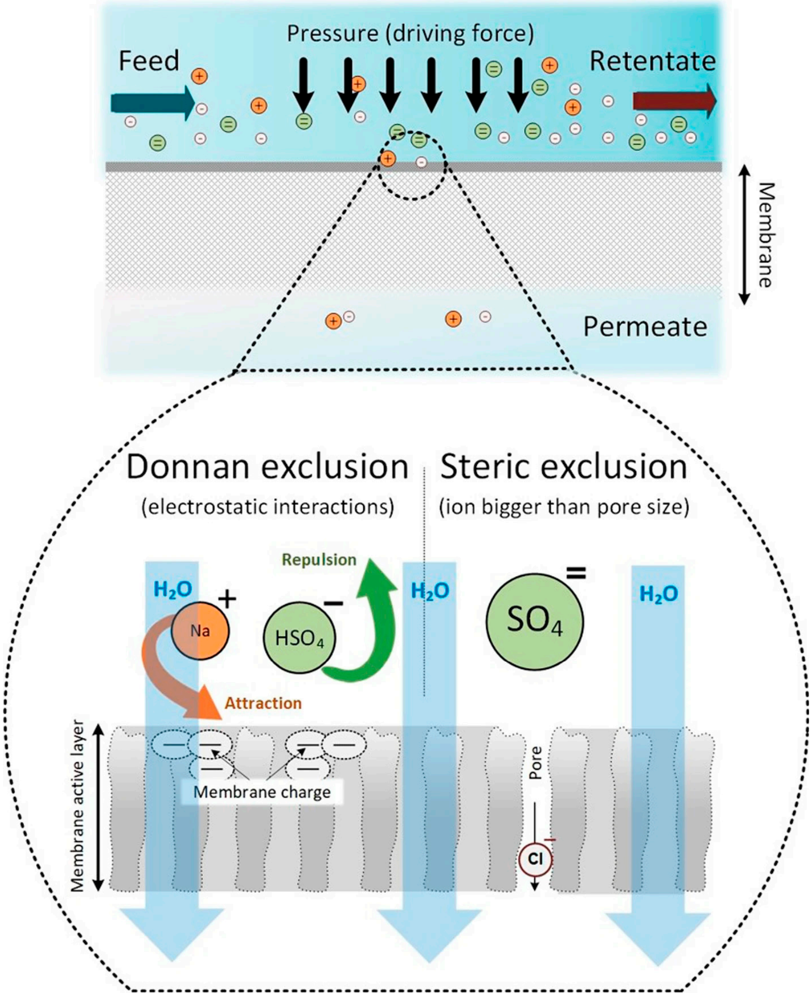

Figure 4. Mechanisms on rejection in nanofiltration/reverse osmosis (reproduced from [36], with permission from Springer Nature).

Regarding the effect of pH on the performance of various nanofiltration (NF) membranes, pure water flux increases with pH in a similar trend across different membrane types. At a constant transmembrane pressure, fluid flow rate, and feed concentration, maximum water flux values of 130 L/m^2·h, 166 L/m^2·h, and 281 L/m^2·h have been reported for tight NF membranes (such as Veolia Water Technologies, VWT, NF1), and loose NF membranes such as NF20 and NF2 (VWT), respectively [109]. In aqueous systems, selenite and selenate ions undergo protonation and deprotonation depending on the pH. As pH increases, selenite becomes increasingly deprotonated, acquiring a greater negative charge. This enhances selenium rejection by negatively charged NF membranes through increased electrostatic repulsion. Additionally, the superficial pore radii of polyamide nanofiltration membranes are known to vary with solution pH, and earlier studies have reported a significant increase in membrane surface charge concentration with rising pH [117].

Various dense polymeric membranes have been studied for their ability to reject selenium, with investigations spanning from laboratory experiments to full-scale pilot studies and across diverse water matrices. Table 3 provides a summary of key findings related to selenium removal using these membranes. Overall, tight NF membranes such as NF1, NF90, and RO membrane BW30 demonstrate significantly higher selenium rejection compared to looser membranes like NF2 and NF20. This trend can be attributed to differences in MWCO, which governs the extent to which size exclusion and charge repulsion contribute to solute separation. Therefore, selecting membranes with suitable MWCO and surface charge properties is critical for achieving high selenium rejection.

Table 3. Selenium rejection with different commercial NF and RO membranes.

Membrane	Water Matrix	Pressure (Bar)	Flux (L/m^2·h)	Se Removal	Reference
NF90	Groundwater, Se = 15 µg/L,	9	23.1	≥93%	[114]
NF1	Groundwater, Se(VI) = 1600 µg/L, pH = 8	≈15	125	94%	[109]
NF2			280	67%	
NF20	Groundwater, Se(VI) = 1600 µg/L, pH = 8	≈15	164	74%	
BW30	Groundwater, Se = 15 µg/L,	15	15.5	≥94%	[114]

3.3.2. Se Removal by Electrodialysis

Electrodialysis is an electro-membrane process in which the driving force is an applied electrical potential across a membrane stack, generating a direct electric current. Under this field, anions migrate toward the anode, while cations move toward the cathode. Ion exchange membranes selectively allow the passage of counter-ions while repelling co-ions, thereby enabling the separation of charged species. As electrodialysis targets only charged ions, it is generally ineffective for the removal of uncharged species from water streams [36,118].

In the neutral pH range, both common selenium species such as selenite and selenate exist as anions, suggesting that electrodialysis can, in principle, remove these forms of selenium [11]. However, published studies on selenium removal via electrodialysis remain limited. Among the few available, Onorato et al. [119] investigated the performance of electrodialysis for treating real brackish groundwater containing 20 µg/L selenate and a conductivity of 8290 µS/cm. This water also contained various monovalent and divalent ions in addition to selenate. The study confirmed that the removal of multivalent ions was influenced by pH to varying degrees. Arsenate, an oxyanion of arsenic, was consistently removed at high rates (>90%) and largely unaffected by pH, whereas selenate was clearly pH-dependent, with the highest removal observed in the acidic range (pH 3–5). Increasing the applied voltage (i.e., the driving force) from 12 V to 18 V improved selenate removal from 33% to 48%, indicating that electromigration is the dominant transport mechanism. Furthermore, pH variation in the real water led to maximum selenate removal under both acidic and basic conditions (pH 3–5 and 9–11), with the lowest removal occurring near neutral pH. Furthermore, pH variation in the real water resulted in the highest selenate removal under acidic conditions, followed by basic conditions (pH 9–11), with the lowest removal observed near neutral pH. However, due to the complex chemistry of the real groundwater and the presence of scale-forming ions such as calcium, magnesium, and carbonate, Se separation remains challenging [119]. Nonetheless, the findings suggest that electrodialysis can effectively remove selenate and other ionic contaminants from real water sources, provided that optimal pH conditions and applied voltage are maintained. In accordance with this, this study also presented the working principle of an electrodialysis process for Se removal as shown in Figure 5.

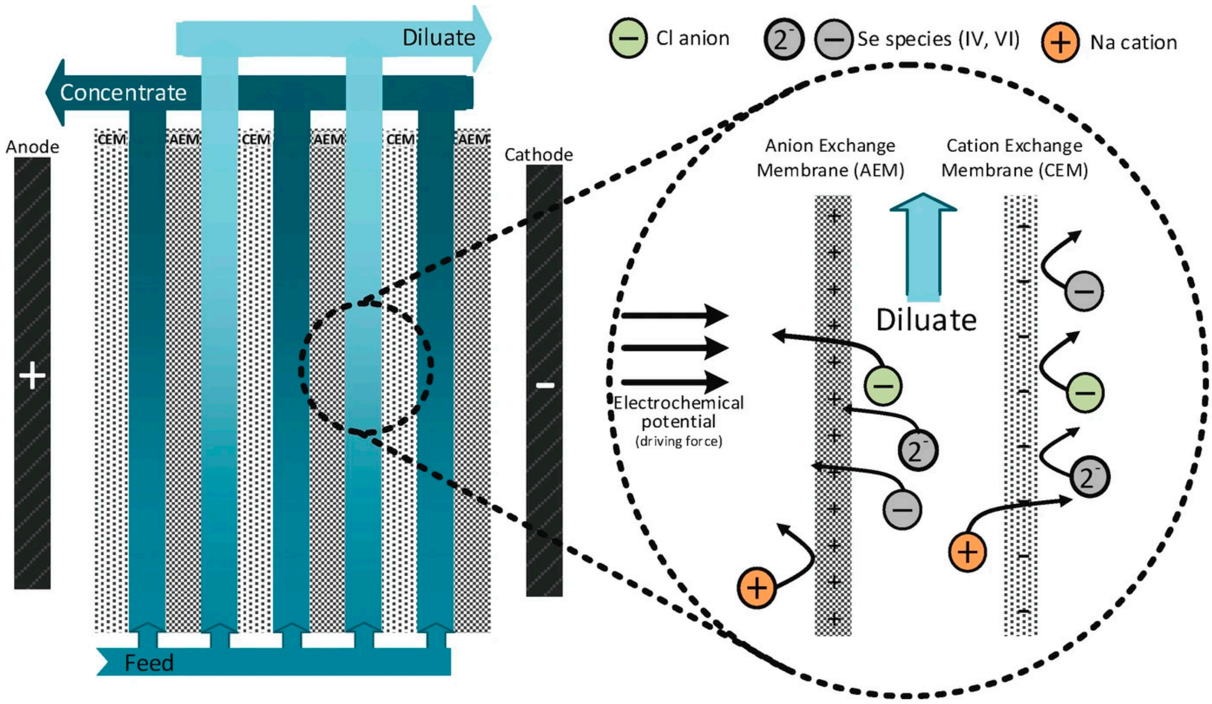

Figure 5. Working principle of electrodialysis for Se(IV, VI) removal from water (reproduced from [120], with permission from Springer Nature).

Aliaskari et al. showed that electrodialysis effectively removes selenium from synthetic brackish groundwater, achieving molar fluxes up to 1 μmol/m^2·s at 15 V, particularly under acidic conditions due to enhanced ion mobility [11]. Selenite and selenate removal reached 60–70% and 40–50%, respectively, but dropped below 40% at pH 9, which was attributed to reduced mobility from larger hydration shells. Higher voltages significantly improved removal: efficiencies exceeded 90% at 25 V, confirming electromigration as the dominant mechanism when selenium remains charged. The WHO guideline for Se oxyanions was met in the diluate stream after one hour at 25 V. Beyond 15 V, extended runtime had little effect, though removal remained high. Performance was stable across feed concentrations (250–1000 μg/L), with molar flux increasing linearly. Higher salinity slightly reduced flux due to ion competition [11]. Flow rate had minimal influence (<5%) on removal efficiency. While electrodialysis shows strong potential, further research is needed to address operational challenges like membrane fouling and scaling under real-world conditions.

3.4. Electrochemical Methods

A few studies have utilized electrochemical methods, particularly electrocoagulation and electrochemical reduction for Se removal from water, in addition to its high selectivity, low reagent requirements, and environmental compatibility [121,122]. Baek et al. indicated effective Se(VI) removal using an iron anode in both aerobic and anoxic environments, with higher efficiency at higher current rates and low initial Se(VI) concentrations. The mechanism involved ferrous hydroxide formation under applied current density, thus transferring electrons to Se(VI) and thereby reducing it to Se(IV) and then probably to insoluble Se(0). However, other parameters, including electrolyte concentration and dissolved oxygen, limit Se(VI) removal, keeping levels above regulations, but the process still effectively lowered Se in groundwater [123]. Another recent study demonstrated up to 99.96% Se removal and 97.9% strontium (Sr) using three stages: four iron electrode-based reactor with integrated pH control with a 25 A current, 15 min of operational time per phase (cycle), and a middle range of pH values. These outperforming parametric conditions of electrocoagulation enable formation of metal hydroxides, which thus resulted in efficient coagulation and sedimentation of both Se and Sr in water [124]. Hao et al. showed further development in electrochemical methods and showed up to 90% Se(IV) removal potential of tin-doped RuO_2 ($Ru_{0.9}Sn_{0.1}O_x$) supported on titanium plates under a current density of -2 mA cm^{-2}, with high tolerance to co-existing anions, i.e., Cl^-, $NO_3{}^-$, and $SO_4{}^{2-}$ [125]. Such techniques may be useful specifically for the treatment of real water and wastewater as they contain the potential for recovery of insoluble Se(0) via sedimentation or filtration. Although these electrochemical methods have revealed excellent Se removal potential, further research should focus on operational adaptability and scalability for large-scale operation under real water conditions.

3.5. Biological Advancements

The biological treatment and transformation of selenium oxyanions—selenate ($SeO_4{}^{2-}$) and selenite ($SeO_3{}^{2-}$) from aquatic environments has garnered increasing attention in recent years, owing to its alignment with green technology principles, sustainability, and cost-effectiveness. This review synthesizes the most recent advancements in the biological methods for the remediation of selenium oxyanions in water, highlighting comparative treatment efficiencies as well as the underlying biochemical and microbial mechanisms involved.

3.5.1. Anaerobic Biological Reduction of Selenium Oxyanions

Anaerobic bacteria, particularly those involved in dissimilatory metal reduction, play a pivotal role in biotransforming selenium oxyanions by using them as terminal electron acceptors, reducing selenate and selenite to elemental selenium (Se^0), a less toxic and less mobile form suitable for environmental remediation [126]. Microbial reduction of selenate to selenite has been performed by several enzymatic systems, including membrane-bound nitrate reductases, periplasmic nitrate reductases, and selenate reductases [127]. The conversion of selenite to elemental selenium is mediated by a variety of reductases such as nitrite reductase, sulfite reductase, glutathione, and selenite reductase [128]. In bioreactor systems, the microbial bio-reduction potential is strongly influenced by factors such as carbon sources, electron donor, pH, temperature, residence time, microbial community composition, biofilm formation, initial concentrations, and the influence of competing ions [129].

Depending on the selenium concentration, wastewaters containing Se oxyanion often require supplementation in terms of electron donors and carbon sources for effective biological treatment. Various carbon sources, including simple compounds like glucose, sucrose, lactate, acetate, malate, methanol, and ethanol, as well as hazardous compounds and complex organics like phenol, molasses, and sewage, have been studied to support the microbial reduction of selenium [130]. Recent studies have explored the use of granular sludge as a carbon-rich matrix, owing to its diverse microbial community that facilitates various biotransformation processes. He et al. employed a glutathione (GSH)-enhanced granular sludge technology for the simultaneous removal and recovery of heavy metals and Se from wastewater [131]. High removal efficiencies for copper (Cu), cadmium (Cd), and Se were achieved with removal rates above 99%, while metal recovery efficiencies ranged from 73.2% to 87.9%. Another study demonstrated the simultaneous removal of lead and selenium through the biomineralization of lead selenide (PbSe) using anaerobic granular sludge. The presence of lead has no inhibitory effect on microbes but rather enhanced selenium removal efficiency with a removal efficiency of approximately 90% [132]. Similarly, anaerobic granular sludge was employed to effectively remove selenium from wastewater and resulted in the achievement of a removal efficiency of 99.94 ± 0.05%. The microbial community within the anaerobic granular sludge rapidly reduced selenite to elemental selenium until a saturation threshold of 5.68 g Se/L, indicating a potential limitation in long-term operation [133]. Microcosms simulating selenium-laden coal power plant effluent and community-based biofilm were developed to evaluate selenium reduction using glycerol, molasses, and methanol as carbon amendments to enhance microbial activity. The microbial community composition was found to be correlated with carbon amendment and selenium reduction [134].

Organic electron donors such as acetate, lactate, glucose, sucrose, methanol, and ethanol, as well as complex phenol and gaseous hydrogen, can catalyze selenium reduction across a range of bacteria and fungi [135]. Sinharoy et al. used hydrogen (H_2) to evaluate the reduction of selenite and selenate by activated sludge [130]. Complete removal was achieved within 8 days of incubation while thermophilic conditions (50 °C) were found to be more favorable with H_2, resulting in a 0.8–13.5% increase in overall Se removal efficiency. Gullet et al. used a homogeneous iron complex as a catalyst for stochiometric reduction of selenate and selenite [136]. The catalytic reduction led to the formation of iron-oxo and amorphous red selenium through a multi-electron/multi-proton process converting toxic wastewater into a useful product. Chi et al. evaluated the influence of co-existing nitrogen and selenium pollutants, along with hydraulic retention time (HRT), on their simultaneous removal efficiency in constructed wetland systems [137]. The results showed that increasing nitrate levels and extending the HRT enhanced selenate removal efficiency. The co-existence of selenium and sulfur in contaminated water was investigated for bio-reduction. The bacterial generation of sulfide increased the selenite reduction rates through sulfide chemical reaction with selenite to form selenium disulfide but slightly decreased the selenate reduction rates [138]. Among other factors, thermophilic conditions can enhance removal efficiency; however, mesophilic microorganisms are more commonly applied in the reduction of selenium oxyanions due to their lower energy requirements and better operational feasibility. Selenium oxyanion bio-reduction is typically favored under neutral pH and low-salinity conditions, while elevated salinity can inhibit microbial reduction efficiency [129]. Biological treatment studies indicate that the reduction rates can vary significantly, with some systems achieving over 90% removal of selenium oxyanions from contaminated environments.

3.5.2. Microbial Immobilization on Matrices for Selenium Removal

Recent studies also highlight the use of immobilized microbial systems, where Se-reducing bacteria are entrapped in gels or attached as biofilm on support matrices with the aim of improving Se removal efficiency and the robustness of the treatment system. For instance, a study by Lenz et al. demonstrated that *Sulfurospirillum barnesii* immobilized in polyacrylamide gel beads and applied in an upflow anaerobic sludge bed (UASB) reactor treating a solution containing approximately 790 µg/L of Se(VI) achieved effluent concentrations as low as ~39 µg/L, corresponding to a removal efficiency of over 97% [139]. Another study by Lu et al. achieved >90% Se(VI) removal in membrane biofilm reactors fed with hydrogen when influent Se ranged from 1000 to 11,000 µg/L, with elemental Se visibly precipitated in the biofilm matrix [140]. Wang et al. presented hybrid bacterial biofilm immobilized on iron-modified zeolite columns as an effective Se remediation approach where an initial Se(IV, VI) removal of 34–89% was observed and reached nearly 99% removal over approximately 2 weeks as the microbial films were matured [141]. Therefore, these recent developments in microbial remediation processes indicate superior microbial cell stability, inhibitory shock resistance, and sustained high-efficiency Se reduction, showing potential for treating high-strength Se-laden wastewater.

3.5.3. Microalgae-Based Selenium Accumulation

Phycoremediation, which involves the use of microalgae-based treatment systems, is an emerging approach that offers a promising alternative for selenium removal due to its low energy consumption, ease of operation, rapid microalgae growth rates, low land requirement, and high surface-area-to-volume ratios [142]. Biosorption and bioaccumulation represent the two ways in which microalgae can be used to remove selenium from wastewater. Biosorption is the adsorption of selenate or selenite onto biomass surface or active sites whereas the bioaccumulation involves a metabolic pathway process for conversion of selenium oxyanions by incorporating them into amino acids followed by their reduction to elemental selenium, which is then stored within the cells [143,144]. The microalgal accumulation process not only removes selenium from the environment but also converts it into a less toxic form. Studies have demonstrated that species such as *Scenedesmus* Sp. and *Chlorella vulgaris* can accumulate substantial amounts of selenium from wastewater. However, a variety of factors such as light intensity, nutrient availability, bioreactor design, air supply, and the initial selenium concentration in the medium can significantly influence the efficiency of selenium removal by microalgae [145,146].

Bioreactors play a critical role in efficient removal of selenium oxyanions by enabling the use of diverse microorganisms or seed sludges, effective mass transfer, operational ease, and high efficiency based on area [143,147]. The optimization of bioreactors is dependent on the design of case-specific bioreactor configurations offering flexibility in manipulating operating parameters [148]. Bioreactor-based treatments are setting standards as an emerging cost-effective option having multisectoral applications [126]. Membrane biofilm-based reactors, tubular photobioreactors, algal ponds, airlift bioreactors, stirrer tanks, and bubble column bioreactors represent common bioreactors currently utilized for wastewater treatment purposes [129]. Fungal bioreactors have emerged as an interesting alternative for their ability to survive harsh environments, while these systems effectively treat selenium-laden wastewater, bacterial contamination limits their large-scale application [149].

Morais et al. assessed the selenium uptake potential of *Chlorella vulgaris* when cultured in 1000 µg Se/L of wastewater [146]. *Chlorella vulgaris* accumulated up to 323 mg Se/kg of dry biomass with potential applications in animal feed supplementation and crop biofortification. Zhang et al. revealed that low-level selenium treatment enhances oxyanion biomass accumulation in *Chlorella vulgaris* with a carrying capacity of 154 µg/g DW [150]. Gaussian process regression analysis confirmed enhanced growth response, highlighting its potential for Se-enriched industrial applications. Liu et al. developed an algal treatment system for selenium oxyanion removal operating at initial Se concentrations ranging between 1000 and 3000 µg/L [151]. The algal-based treatment system achieved up to 90% selenium removal efficiency and exhibited high tolerance to selenium toxicity, withstanding levels up to 6000 µg/L. Future research should explore microalgae–bacteria consortia potential as a synergistic approach for achieving high selenium removal from wastewater, leveraging their complementary metabolic capabilities, algae addition as a carbon source, and encountering the nitrate inhibition effect for enhanced bioremediation.

3.5.4. Phytoremediation: Plant-Based Selenium Removal

Phytoremediation employs plants to remove selenium oxyanions from the aquatic environment through mechanisms such as phytoextraction and phytovolatilization. Phytoextraction involves the ability of plants to absorb selenate and selenite from water and soil through roots and accumulate them in vacuoles, whereas phytovolatilization involves complete removal in volatile form to the atmosphere [152,153]. Brassica species have demonstrated high selenium accumulation capacity in their tissues and exhibited growth traits linked to root length, biomass, and plant height when cultivated in Se-laden microbial contaminated soils [154,155]. These experiments have also exhibited reduction in selenium soil contamination, highlighting phytoremediation potential for sustainable long-term selenium reduction. Deepali et al. demonstrated that inoculating maize plants with selenium-tolerant bacteria can enhance plant growth by acting as biofertilizer while simultaneously limiting soil contamination by reducing Se uptake by maize [156].

Genetic engineering offers a promising avenue to further enhance the phytoremediation potential of plants by improving traits such as selenium root uptake, translocation and volatilization capacity [157]. Jiang et al. identified the optimal selenium concentration for enhancing the growth and nutritional quality of *Lilium lancifolium*, while also providing insights into the combined effects of selenium on gene expression and metabolite accumulation [158]. Li et al. highlighted that gene encoding in plants significantly enhances their tolerance to selenium [159]. The transgenic plants exhibited enhanced selenium accumulation, with increases of 38.5% selenate and 128.6% selenite removal compared to wild-type counterparts, indicating a substantial improvement in tolerance to selenium and accumulation capacity.

A passive strategy for selenium removal in aquatic environments involves the use of constructed wetlands, which integrates bio-reduction through microbes, phytoextraction and volatilization by plants, and mineral adsorption [57,160]. Etteieb et al. highlighted the effectiveness of *Typha latifolia* in selenium removal, reporting a maximum removal efficiency of 54.13% from contaminated environments together with the effective removal of ammonia and orthophosphates [64]. The application of wetlands for selenium removal is constrained by significant limitations, such as extensive land requirements, identification of rate-limiting steps, vulnerability to environmental variability, potential ecotoxicological effects, and the risk of groundwater contamination [159,161]. Integrating these approaches, possibly through hybrid systems such as incorporating algal treatment into wetlands, could enhance the overall efficiency of selenium removal and contribute to sustainable environmental management practices. A comparative overview of these biological methods is presented in Table 4.

Table 4. Comparative overview of biological methods.

Method	Efficiency (%)	Advantages	Limitations
Anaerobic Microbial Reduction	High (>90%)	Effective in diverse environments	Requires controlled conditions
Phytoremediation	Moderate	Sustainable, low-cost, enhances soil quality	Limited by plant growth cycles
Microalgae-Based Accumulation	Moderate	Rapid growth, versatile applications	Requires large-scale cultivation

The comparative summary of emerging treatment techniques for Se is presented in Table 5.

Table 5. Comparative summary of emerging Se removal technologies.

Technology	Removal Efficiency (%)	Selectivity	Operational Feasibility	Scalability	Key Advantages	Reference
Adsorption	70–95	Moderate–High	High	High	Simple, low cost, effective at low Se concentration	[24]
Photocatalysis	80–98	High	Moderate	Moderate	Light-driven, can degrade other pollutants	[105]

Table 5. *Cont.*

Technology	Removal Efficiency (%)	Selectivity	Operational Feasibility	Scalability	Key Advantages	Reference
Membrane Filtration	85–98	High	Moderate–High	Moderate	High purity removal, compact system	[9,110]
Electrochemical Methods	85–95	High	Moderate	Moderate	On-site treatment, no added chemicals	[124]
Biological Advancements (Free/Immobilized)	80–99	High	Moderate	Moderate–High	Eco-friendly, Se recovery possible	[9,162]

4. Challenges in Emerging Selenium Remediation Technologies

Various physical, chemical, and biological methods have been explored for the removal of Se from water, including pressure-driven membrane technologies (particularly NF/RO), adsorption, ion exchange, electrochemical methods (e.g., iron electrocoagulation, and electrodialysis). Among these, iron oxide-based adsorption has shown promise for Se removal; however, selectivity remains a challenge, particularly for Se(VI), which generally exhibits low adsorption affinity. Even for Se(IV), the adsorption capacities of many iron-based adsorbents are limited. Beyond iron oxides, adsorption studies have investigated a range of materials, including zero-valent iron (ZVI), composite adsorbents, activated alumina (AA), metal-impregnated granular activated carbon (GAC), chemically modified biochars (e.g., with metal oxides), and amine-functionalized materials. Despite their potential, all these adsorbents face selectivity limitations, especially in complex water matrices. Therefore, the selection and design of an appropriate adsorbent must be carefully tailored to the specific selenium species present and the composition of the water matrix.

Most adsorption studies are conducted under ideal laboratory conditions using small volumes of synthetic solutions in batch mode, often reporting high initial removal efficiencies. However, these studies rarely address long-term performance or scalability. While adsorption-based methods hold promise for selenium removal, they may present sustainability concerns, particularly due to the generation of selenium-laden spent adsorbents that pose risks of secondary pollution [24]. Regeneration and reuse studies, especially those considering economic feasibility, are limited. Although small-scale fixed-bed filters have shown effective Se removal, scaling up to continuous, large-scale drinking water treatment systems remains a significant challenge. Without routine monitoring and timely replacement, exhausted adsorption beds may continue to release Se into the treated water, potentially compromising water safety without users' knowledge [24].

Electrodialysis has shown promise as a treatment method, particularly due to its consistent performance regardless of selenium concentration. However, its effectiveness has been demonstrated primarily for water containing selenate. Moreover, the long-term practical applicability of electrodialysis remains insufficiently explored. Further research is needed to address operational challenges, such as membrane scaling and fouling under real-world conditions, as well as its ability to consistently maintain selenium concentrations below permissible drinking water standards.

RO technology has proven to be highly effective in rejecting selenium species from water [114]. However, its primary limitation is high operational cost, mainly due to significant energy demand. In contrast, NF technology has gained increasing attention in recent years as a more energy-efficient alternative, while still providing high separation efficiency for selenium species. Commercial NF membranes (see Table 2) have demonstrated effective separation of both selenite and selenate, primarily governed by Donnan exclusion and size exclusion mechanisms. NF membranes with tighter polymeric structure have shown remarkable Se separation efficiencies (>90%), though this comes at the expense of higher energy requirements compared to the use of looser (more open) NF membranes.

To address these limitations, functionalized NF membranes have been developed. For example, one approach involves the polymerization of a polypiperazine amide barrier layer onto a polyvinylidene fluoride (PVDF) hollow fiber (HF) substrate [163]. These membranes exhibited enhanced hydrophilicity, resulting in a high-water permeability of 8.08 L/(m^2·h·bar), a MWCO of 378 Da, and a strong negative surface charge (~43.96 mV). Such modifications show potential for overcoming conventional challenges in NF applications, including membrane fouling and low permeability, ultimately contributing to lower energy consumption. Nevertheless, brine disposal and treatment is still a critical issue to be solved in RO/NF.

5. Prospects for Selenium Remediation

5.1. Integrated Approaches

Considering current technology limitations, including high operational costs, incomplete Se removal and solid waste generation, there exists a growing need for multifaceted strategies combining physical, chemical, and biological methods. In lieu of this, recent studies have also highlighted the requirement of hybrid treatment systems for Se remediation from aqueous environments. Moreover, a few studies have also demonstrated the incorporation of hybrid systems like biologically supported adsorption processes, bio-electrochemical systems (BES), ion exchange membrane bioreactors (IEMB) and photocatalysis coupled adsorption processes. Integrated systems may offer promising pathways to enhance Se recovery and removal within guideline limits from drinking water. Therefore, the current section highlights the prospects in the development of hybrid treatment systems for efficient Se recovery and removal from water.

5.1.1. Biologically Supported Adsorption Processes

Biologically supported adsorption processes may offer a sustainable and effective treatment strategy when dealing with ionic contaminants such as Se from water. It involves incorporation of immobilized microorganisms or biofilms (mostly anaerobic or anoxic) on the adsorbent surface or porous surface to improve metal reduction capacity into more adsorbable or volatile forms. The solid insoluble Se(0) may then be easily separated via an adsorption and sedimentation process. Piacenza et al. demonstrated that biofiltration with microbial consortia immobilized on granular activated carbon effectively reduced up to 97% Se(IV, VI) to elemental selenium (Se^0), with Se^0 deposited within the biofilm as sub-micrometer particles [162]. Another emerging concept based on a column biofilter combining iron oxide-coated zeolite with immobilized Se-reducing microbes achieved ~99% Se oxyanion removal, where initial adsorption onto biogenic iron oxides followed by microbial reduction to Se^0 after 14 days was identified as a major removal mechanism [141]. Therefore, it may be suggested that biological adsorptive filtration of Se-laden drinking water and wastewater can be an alternative simpler, sustainable, and efficient approach for removal and recovery of Se^0 as compared to standalone technologies. Further research should therefore focus on the scalability, adsorbent and microbial leaching aspects, process optimization, and long-term operational stability in the removal and recovery of Se by bio-adsorptive filters from aqueous solutions.

5.1.2. Bio-Electrochemical Systems (BES)

Another innovative technology includes bio-electrochemical systems (BES) for Se recovery and removal from contaminated water. These systems may exploit microbial metabolic activity alongside electrochemical gradients to facilitate Se reduction to insoluble

Se^0 precipitates. In addition, BES contains additional benefits of low energy consumption under optimum conditions and even generation of electricity and value-added by-products. For instance, an earlier study designed and operated BES with Se species as a terminal electron acceptor in an abiotic cathodic chamber and microbe-fed anodic chamber separated by a proton exchange membrane utilizing graphite electrodes on both sides [164]. This study observed the dual property of recovering 26.4% insoluble Se(0) with a total of 73.6% Se(IV) removal in the cathodic chamber and 74% organic degradation in the anodic chamber. A maximum power density of 0.034 W/m^2 was also observed with an increase in initial Se(IV) concentration owing to a proportional increase in dehydrogenase activity, thereby increasing anodic electrogenic activity [164]. Riveros et al. developed a hybrid system by coupling electricity-driven, chemical free flow electrode capacitive deionization (FCDI) with BES and showed further improvements in total Se removal up to 76% followed by up to 66% and 54% reduction of Se(VI) and Se(IV) to elemental Se(0), respectively [165]. However, a 14% enhancement of Se(VI) reduction and a 21% decrease in Se(IV) reduction were observed with the addition of acetate as a carbon source, thus suggesting the organic substrate-dependent and bio-electrochemical-driven nature of Se species transformation in the system [165]. Therefore, these findings highlight the promising nature of hybrid bio-electrochemical technologies as an efficient, scalable, and sustainable Se remediation solution, paving the way for future research and development in this area.

5.1.3. Ion Exchange Membrane Bioreactors (IEMB)

Ion exchange membrane bioreactors (IEMB) can be an alternative hybrid treatment technology especially when focusing on both removal and recovery of solid Se from contaminated waters. This technology can provide innovative solutions with the aid of ion exchange membranes in a heterotrophic/autotrophic biological system for drinking water treatment. Previous studies also suggested the biological reduction of harmful oxyanions in an IEMB process [166–168]. For instance, earlier research by Ricardo et al. presented excellent bio-reduction performance of nitrate and perchlorate, achieving contaminant levels below permissible limits using an anoxic microbial culture and ethanol as an electron donor in an anionic IEMB process. The mechanism involved diffusion of both contaminants through the anion exchange membrane into a membrane-supported biofilm, where spatial stratification enabled sequential reduction of perchlorate to chloride on the outer biofilm and nitrate to nitrogen gas by denitrifiers near the membrane [166]. Another study showed effective mercury removal > 98% from polluted source water in an IEMB process. The study demonstrated that mercury as a divalent cation (Hg^{2+}) from a polluted water source diffuses through a cation exchange membrane (CEM) to a receiving bio-medium compartment at the expense of counterions (e.g., sodium, magnesium, calcium) by Donnan dialysis. In the anoxic bio-medium compartment, the transferred Hg^{2+} was being biologically reduced to Hg^0, while the source water remains physically separated from the bio-medium compartment containing Se-reducing microorganisms, thus avoiding any microbial contamination of feedwater [167]. Similarly, the transport of arsenic oxyanions has also been reported in an integrated anion exchange membrane (AEM) reactor, where chloride ions served as counterions [169,170]. In general, prior research work based on the IEMB process presented strong potential in the removal of oxyanions from contaminated water bodies; however, removal and recovery of Se using this approach remain largely unexplored. Further research should therefore be undertaken to investigate the potential of the IEMB process for Se(0) recovery.

5.1.4. Photocatalysis Coupled Adsorption Processes

A detailed overview of recent practices utilizing a photocatalyst coupled with adsorption techniques has already been presented in Section 3.2. However, further development pathways considering innovative, sustainable hybrid photocatalytic coupled adsorptive materials and their Se removal capability and a mechanistic overview are discussed in the current section. For instance, Badoni et al. indicated the detailed overview concerning the potential of TiO_2–graphene oxide (GO) composites for environmental applications, including water treatment [171]. It is likely that TiO_2–GO under UV irradiation can achieve excellent Se(VI) removal through the reduction of Se(VI) to elemental selenium (Se^0). The presence of GO may present a dual property by first enhancing electron transfer from TiO_2 to Se(VI), thereby forming Se^0, followed by facilitating the adsorption and separation of Se^0 precipitates at the solid–liquid interface. Recently, another innovative graphitic carbon nitride (g-C_3N_4)/TiO_2-based heterojunction nanocomposite has garnered attention for organic pollutant degradation and mercury removal owing to its superior photocatalytic activity, high charge separation, and transfer efficiency [172,173]. Therefore, it will be critical to explore Se oxyanion removal using g-C_3N_4/TiO_2 Z-scheme photocatalyst under visible light irradiation. The strong interfacial interactions between g-C_3N_4 and TiO_2 might result in effective charge separation and targeted Se(VI) and Se(IV) reduction to Se^0, followed by subsequent adsorption onto a g-C_3N_4 surface. Such synergistic photocatalysis along with the adsorptive property of innovative materials may contain potential in improving Se recovery and removal from contaminated streams alongside reducing chemical usage and sludge generation. However, the fabrication of high-performance photocatalytic treatment systems remains crucial to achieving innovative, sustainable, and practical solutions that offer enhanced activity, efficiency, stability, scalability, and selectivity for real-world applications.

In general, an integrated and hybrid treatment technology may enhance Se oxyanion removal and recovery potential, thereby contributing to a more sustainable and adaptable treatment framework. A more detailed investigation is therefore needed into the design and development of effective and scalable hybrid treatment systems along with deep understanding of interactions within combined processes to ensure long-term operation. Furthermore, lifecycle assessments and cost–benefit analyses are essential to guide real-world applications.

5.2. Resource Recovery and Circular Economy Aspects

Selenium has garnered increasing attention in the context of circular economy-driven wastewater treatment, owing to its critical industrial applications and biological relevance. This strategy not only ensures compliance with selenium regulatory standards but also strengthens the sustainability and circularity of wastewater treatment. Recent studies have shown the Se recovery strategy achieving a good yield for potential reuse applications, as indicated in Table 6. The potentially recovered Se, typically in elemental form or as metal selenides, can be reused in manufacturing glass, electronics, pigments, and metal alloys, reducing dependence on primary Se extraction. Amongst these, recovered elemental Se from various wastewater treatment strategies, including chemical, electrochemical, or microbial reduction, can be reused in the development of photovoltaic cells and semiconductors, including CdSe and $Cu_{1.08}$Se solar materials [126,131]. Additionally, Se-rich biomasses or products may contain potential as animal feed and fertilizers in Se-deficient regions [146]. The capturing of generated volatile Se compounds like dimethyl selenide in industrial emissions and its further processing into high purity Se contains potential for industrial reuse applications [174]. Therefore, such practices not only ensure compliance with Se regulatory standards buts also strengthen the sustainasbility and circularity of wastewater treatment.

Table 6. Recovery strategies for selenium from wastewater and their potential applications.

Recovery Strategy	Recovery Yield	Recovered From	Potential Reuse	Reference
Chemical or microbial reduction	Up to 99%	Elemental selenium (Se^0)	Glass, pigments, electronics	[126,131]
Precipitation as metal selenides	73–88%	CdSe, $Cu_{1.08}Se$	Photovoltaic cells, semiconductors	[131]
Biosorption into algae (e.g., *Chlorella*)	43–52% uptake	Se-enriched biomass (up to 323 mg/kg dry weight)	Feed additives, biofertilizers	[146]
Bio-volatilization (e.g., *Pseudomonas* spp.)	~79–88%	Dimethyl selenide (DMSe)	Refined Se compounds for industrial reuse	[174]

5.3. Research Trends and Emerging Areas:s

Recent research in Se remediation is increasingly driven by advancements in material science, microbial biotechnology, and engineering practices. Novel nanomaterials, such as doped metal oxides and carbon-based composites, are being explored for their high adsorption capacities and photocatalytic activity. Simultaneously, engineered microbial systems offer targeted and selective bio-reduction of Se oxyanions under mild conditions. Reflecting the review details, one can say the following: A growing emphasis is placed on developing sustainable, low-cost, and scalable technologies suitable for real-world applications. Emerging integration with mathematical modeling approaches, specifically AI, is also gaining attention. AI tools are being used to optimize adsorbent synthesis, predict Se speciation, and identify ideal operating conditions in complex treatment systems. These trends reflect a shift toward more intelligent, efficient, and environmentally friendly approaches for Se removal and recovery from contaminated streams.

6. Conclusions

The removal and recovery of Se oxyanions, especially Se(IV) and Se(VI), is challenging and poses a significant threat to environment and human health. The current review therefore critically examines the research efforts undertaken to date to mitigate Se contamination and improve its recovery from drinking water sources. In addition, conventionally available treatment technologies have demonstrated limited success in eliminating more mobile and persistent Se oxyanions, particularly Se(VI), and emerging technologies may offer practical solutions. Amongst these, advances in membrane filtration, nanomaterial-based adsorption, photocatalytic reduction, and bio-electrochemical systems have demonstrated improved efficiency, selectivity, and potential for Se recovery. However, there still exist operational challenges, including scalability, cost-effectiveness, and adaptability under heterogeneous water matrices. Therefore, further research should focus on the integration of multifaceted technologies into hybrid treatment systems, with consideration of efficiency, recovery, and sustainability. Moreover, a more detailed understanding of Se speciation, transformation mechanisms, and long-term environmental behavior is critical to optimize treatment design, thereby ensuring safe, sustainable, and Se-free drinking water production systems.

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