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14. ABSTRACT
The Salton Sea in California, sustained by agricultural drainwater, has significantly declined, leading to new vegetated wetlands on the dry lakebed that provide habitat for wildlife, including the endangered Yuma Ridgway's rail and desert pupfish. However, these wetlands are contaminated with selenium. This literature review evaluates selenium removal technologies and their feasibility for the Salton Sea, using a decision matrix to compare effectiveness, cost, and ecological impact. We discuss integrated approaches combining new technologies with management practices to mitigate selenium risks throughout the Salton Sea agricultural and playa wetland system. Key findings suggest a multi-faceted approach may effectively reduce selenium hazards for wildlife, emphasizing the importance of stakeholder engagement in implementing these methods. Adaptive management strategies, incorporating continuous monitoring and community input, are essential for addressing selenium contamination in the Salton Sea wetlands.

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Cover Image –View of a Salton Sea wetland, demonstrating the natural beauty and diversity of landscape (K. Groover, U.S. Geological Survey).

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Recent Advances in Selenium Treatment Technologies & Application to Playa Wetlands

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Acronyms and Abbreviations

IID	Imperial Irrigation District
ESA	Endangered Species Act
MAMP	Management and Monitoring Plan
SHP	Shallow Saline Habitat Ponds
Se	Selenium
SCH	Species Conservation Habitat
CIT	Citation for relevant references
ZVI	Zero-Valent Iron
EDTA	Ethylenediaminetetraacetic Acid
GAC	Granular Activated Carbon
IFBR	Inverse Fluidized Bed Reactor
ABSR	Algal-Bacterial Selenium Removal
TDS	Total Dissolved Solids
PRBs	Permeable Reactive Barriers
SSFCW	Subsurface flow constructed wetlands

Symbols

µg/g	Micrograms per gram
µg/L	Micrograms per liter
mg/L	Milligrams per liter
mg/m^2/day	Milligrams per square meter per day
m	Meter (unit of length)
m^2	Square Meter
m^2/day	Square Meters per day
%	Percentage
±	Plus-minus (indicating variability)
H_2SO_4	Sulfuric Acid
SO_4^{2-}	Sulfate
Se(VI)	Selenate (SeO_4^{2-})
Se(IV)	Selenite (SeO_3^{2-})
Se	Selenium
N	Nitrogen

PO_4^-	Phosphate
TiO_2	Titanium Dioxide
Fe	Iron
Ni	Nickel
Co	Cobalt
Zn	Zinc
P	Phosphorus
N	Nitrogen
P	Phosphorus
Mn	Manganese
Mg	Magnesium

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Appendices

A-1 Treatment Technology Evaluations

Executive Summary

The modern Salton Sea is a shallow, land-locked saline lake in the lower Colorado River Basin in southern California, USA, that is sustained by irrigation return water and perennial river inflow. Due to agreements in 2003 and 2022 to redistribute water and increased irrigation efficiencies, and severe droughts in the West, agricultural runoff feeding into the Salton Sea has declined greatly. Agricultural drains no longer reach the Salton Sea and instead discharge their water onto the exposed lakebed or playa, forming new wetlands (hereafter "playa wetlands") in areas that were previously underwater. Playa wetlands can be highly productive and provide habitat for invertebrates, fish, and birds including the endangered Yuma Ridgway's rail (*Rallus obsoletus yumanensis*) and desert pupfish (*Cyprinodon macularis*); however, the playa wetlands also receive agricultural runoff that has high concentrations of selenium.

The issue of selenium contamination in aquatic systems presents a significant challenge, as selenium can be transformed and temporarily stored in sediment, detritus, and aquatic pools, which makes it more accessible to various wildlife consumers. Current research to remediate selenium focuses primarily on aqueous concentrations and neglects its accumulation in detritus and sediment components of the wetland food web. This gap highlights the scientific value of a comprehensive evaluation of potential technologies and management strategies that might mitigate selenium in agricultural drainwater as well as selenium stored in wetland sediment and detritus.

Thus, the purpose of this literature review is to evaluate advances in selenium removal technologies (from 2014 to mid-2024) and their feasibility for use in the Salton Sea environment. We address the following specific questions: (1) What advances in selenium removal treatment technologies have been made between 2014 to mid-2024? (2) How applicable is each technology to the Salton Sea playa wetland system based on scalability, cost, and effectiveness at reducing selenium hazards to aquatic and detrital food webs? (3) How and where could recent technologies in conjunction with management actions be used to help reduce selenium hazards in the environment?

We found over 5,480 records (books, journal articles, reports), 114 of which met our criteria for inclusion in our review. To evaluate technologies based on their cost-effectiveness, scalability, and applicability to the Salton Sea system, we developed a decision matrix, with each criterion ranked on a scale of 1 to 5. We summarized each technology and discussed current advancements in terms of their ranking. We then discussed potential integrated approaches to using new technologies in tandem with management practices to reduce selenium risks at various points in the linked Salton Sea agricultural and playa wetland system. Lastly, we identified knowledge gaps that could be evaluated to improve our understanding of the efficacy of different treatments and management actions at the Salton Sea.

The complexity of selenium dynamics in the Salton Sea playa wetland systems indicates that a combination of treatment and management approaches, including those that target source reduction as well as transformation of selenium into less harmful forms that are more easily removed from the environment, may produce the most effective results. An integrated approach could include field management practices, novel techniques for removing selenium from water in drains, constructed

wetlands to encourage selenium volatilization, and application of existing management practices to remove detritus from playa wetlands. While a stepwise effort such as this may reduce total selenium in the system, the reduction of bioavailable selenium will be necessary to achieve the goal of reducing hazards to Salton Sea wildlife, including the endangered Yuma Ridgway's rail and desert pupfish.

The findings emphasize the complexity of selenium dynamics in playa wetland systems. A multi-faceted approach combining treatment, management actions, adaptive management strategies, and stakeholder input are vital to address the challenges posed by selenium contamination in the changing Salton Sea environment. Given the projected growth of drain-fed playa wetlands and the associated selenium hazards for fish and wildlife, stakeholder engagement that leverages innovative new technological and management solutions offers a promising opportunity to foster collaboration and develop integrated strategies to reduce selenium hazards as the Salton Sea region evolves.

1.0 Background

The modern Salton Sea is a shallow, land-locked saline lake in the lower Colorado River region in southern California, USA. The Salton Sea is sustained by irrigation return water and perennial river inflow from the Whitewater River in the north and the New and Alamo Rivers in the south. The Salton Sea and its surrounding wetlands are a crucial migratory stopover location for over 450 species of Pacific Flyway waterbirds and provide habitat for federal and state listed endangered species such as the desert pupfish (*Cyprinodon macularis*) and Yuma Ridgway's rail (*Rallus obsoletus yumanensis*). The Salton Sea Basin, including the lakebed and adjacent land, is owned by three primary entities: the federal government (mostly the Bureau of Reclamation and the Bureau of Land Management), the Imperial Irrigation District (IID), and the Torres Martinez Desert Cahuilla Indians. The Bureau of Reclamation, Lower Colorado River Basin Branch manages approximately 90,000 acres of lakebed and adjacent land in the Salton Sea region.

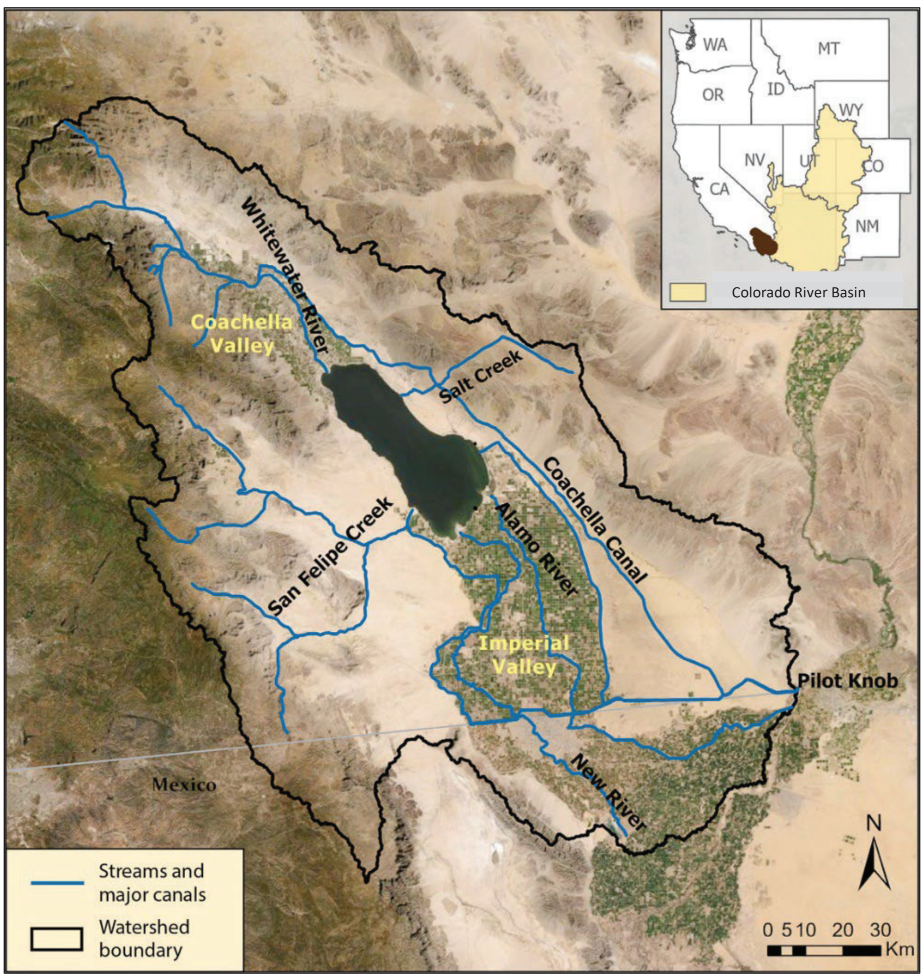

Figure 1. — The Salton Sea and surrounding watershed and landscape in southern California (figure from Bradley, Ajami, and Porter 2022).

Due to agreements to redistribute water, increased irrigation efficiencies, and pervasive droughts in the West, agricultural runoff feeding the Salton Sea has declined greatly since 2005 (Coachella Valley Water District et al. 2002; Ehlers 2018). As the Salton Sea water level drops, drains, canals and streams no longer reach the lake and instead discharge their water onto the exposed lakebed or playa (Rosen et al. 2023) forming new wetlands (hereafter "playa wetlands") in areas that were previously underwater. These playa wetlands can be highly productive and provide habitat for invertebrates, fish, and birds.

1.1. Selenium in Salton Sea Wetlands

Playa wetlands at the Salton Sea are affected by selenium contamination in the region. Selenium is a naturally occurring element in Quaternary marine and continental shales of the western United States. Selenium enters the Salton Sea region from the Colorado River at relatively low concentrations (average of 2 μg/L; Rosen et al. 2023) and then is concentrated through evaporation and evapotranspiration in agricultural fields, leading to high concentrations in drainage waters. Selenium elicits a biphasic dose response in organisms, such that a low dose has a beneficial effect, and a high dose has an inhibitory or toxic effect (Harding 2008). Selenium toxicity impacts egg hatchability and early life stage development in oviparous animals (i.e., amphibians, fish, birds, and some reptiles), and reproductive consequences of maternal transfer are among the most direct and sensitive predictors of the effects of selenium (Heinz 1996; Janz et al. 2010). Concentrations of total recoverable selenium in water exceeding 2.0 μg/L are expected to pose elevated risk to biota in wetland food webs (Hamilton 2004; U.S. Department of the Interior 1998). Water quality guidelines for protection of aquatic life have been recently updated for freshwater systems (U.S. Environmental Protection Agency 2016) as 1.5 μg/L for lakes (lentic systems) and 3.1 μg/L for rivers (lotic systems) as 30-day averages. However, the direct toxicity of waterborne selenium alone cannot predict the ecological risk as this is modulated by uptake and bioconcentration at the base of the food web, dietary exposure, assimilation efficiency, sensitivity, and trophic transfer through the food web (Stewart et al. 2010). In some biota using Salton Sea drains and shallow wetlands, selenium is elevated above concentrations expected to cause reproductive effects (Miles et al. 2009; Rosen et al. 2023; Saiki, Martin, and May 2010;).

1.2. Selenium Transformation and Bioavailability in Wetland Systems

The chemical form of selenium affects its bioavailability and uptake into living organisms (Fig. 2). Selenite (Se(IV)) or selenate (Se(VI)) are the dominant soluble forms of selenium in aquatic bodies, whereas organic selenides (selenoamino acids, selenoproteins, and methylselenides) are usually only present at very low concentrations (Fan et al. 2002). Selenate compounds are generally more soluble than selenite (Plant et al. 2004, Schiavon et al. 2017). Selenite is typically more quickly absorbed and accumulated by microalgae and vascular plants than selenate, although its bioavailability also depends on whether it is strongly adsorbed to mineral and organic-matter surfaces (Schiavon et al. 2017; Winkel et al. 2015). Selenite can also be further reduced to selenide, which is relatively insoluble and not easily transported in the environment. Elemental selenium is the least soluble form of selenium and is also the least mobile.

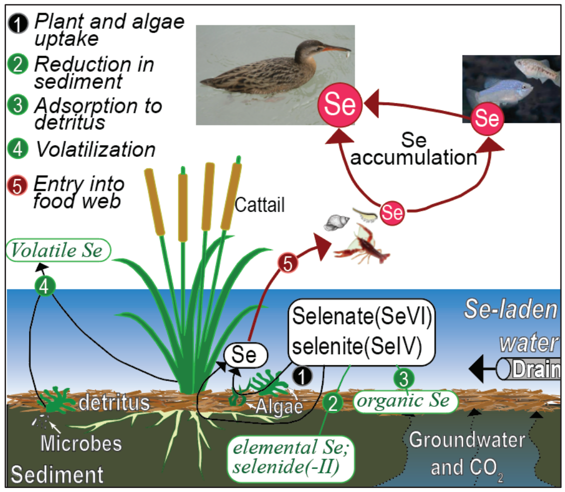

Figure 2. — Simplified conceptual model including pathways of selenium (Se) bioaccumulation in the Yuma Ridgway's rail (*Rallus obsoletus yumanensis*) and desert pupfish (*Cyprinodon macularis*) food web in Salton Sea wetlands (figure modified from Q. Zhao et al. 2020).

Figure 3. — Simplified selenium (Se) cycling and common selenium speciation associated with aerobic and anoxic conditions (from Simm 2021).

Table 1. Factors and variables that affect the state and mobility of selenium in soils (from El-Ramady et al. 2015).

Soil Factor	Variables	Major Se form	Mobility
Soil acidity (pH)	High (Alkaline) Medium (Neutral) Low (Acidic)	Selenates Selenites Selenides	High Moderate Low
Redox potential (Eh)	High (Aerobic) Low (Anaerobic)	Selenates Selenides	High Low
Organic matter	Undecayed Decayed Enhanced biomethylation	Adsorbed Complexed Volatilized	Low High High
Clay content[1]	High Low	Adsorbed Soluble	Low High
Hydroxides (Fe, Mn)	High content Low content	Adsorbed all forms of Se Slight adsorption	Low High

[1] Adsorption to clay minerals decreases with increasing pH values and is almost negligible at pH 8.

Factors such as pH, salinity, clay content and soil texture, organic matter content, redox potential, microbial processes, and the presence of other chemical constituents like sulfate affect the transformation of selenium in water and soils (Carsella et al. 2017; El-Ramady et al. 2015; Schilling, Villa-Romero, and Pallud 2018; Tuzen and Sari 2010; Villa-Romero 2015; Table 1). For example, microbial processes, redox conditions, and the presence of other compounds can affect selenium speciation, which in turn influences precipitation/dissolution, sorption/desorption, methylation, and volatilization in wetlands (Winkel et al. 2015). Redox potential can vary with hydrology, sediment depth, and water source, which can result in patchiness or gradients in the form of selenium. Selenium in oxygenated water entering a wetland is usually in the form of selenate but is typically converted slowly to selenite or elemental selenium by microbes in reducing conditions that typically exist in wetlands (Geering et al. 1968; Fig. 3). It can be further reduced to metal selenides or volatile methylated forms (primarily dimethylselenide). Metal selenides tend to be deposited in the wetland sediments, whereas volatile forms escape to the atmosphere (Winkel et al. 2015).

Wetting and drying cycles that occur in seasonal wetlands and during periodic water drawdowns in managed permanent wetlands can have a large influence on redox reactions and resulting selenium transformations (Hansen and Horne 2022; Masscheleyn and Patrick 1993; Winkel et al. 2015). In submerged wetlands, especially where large amounts of organic material are present, selenium tends to be present in reduced (and less mobile) forms, and volatilization is favored. When water levels recede, selenium becomes more oxidized. This oxidized selenium present in the wetland sediments and organic matter can be mobilized when the wetland is reflooded. Redox potential and pH also affect the speciation of selenium (Masscheleyn and Patrick 1993; Winkel et al. 2015; Mayland et al. 1989). In acidic conditions, selenium is more likely to be present in the form of selenate, while in alkaline conditions, selenium is more likely to be present in the form of selenite or selenide.

1.3. Selenium in Aquatic Food Webs

Selenium enters the food web through active uptake by primary producers, microbes, or invertebrates at the base of the food web, which is a step that is considered one of the most variable and important in determining selenium concentrations at higher trophic levels in aquatic food webs (Hamilton 2004; Schiavon et al. 2017; Ponton et al. 2020; R. Stewart et al. 2010). In general, selenium concentrations in algae, microbes, sediments, or suspended particulates are 100-500 times higher than in water from selenate dominated streams and rivers; however, in wetlands where selenite or organo-selenides are more abundant, the base of the food web may be 1,000 to 10,000 times higher (Luoma and Presser 2009).

When any form of selenium is taken up at the base of the food web by plants and microbes, it is converted to organo-selenides (Dolgova et al. 2016; Besser, Canfield, and La Point 1993). Organo-selenides can accumulate within plant tissues and transfer into the detrital pool and become recycled through the base of the food web. This accumulation of selenium is a key factor in the ecological risks posed by selenium, especially in environments with high levels of organic carbon and extended water residence times, as seen in wetlands and estuaries compared to rivers (Luoma and Presser 2009).

Thus, biogeochemical processes in wetlands can have a substantial impact on the environmental fate and bioavailability of selenium. While eliminating selenium risk for biota in the Salton Sea environment altogether is unlikely, emerging selenium removal technologies and wetland management strategies that lower selenium concentrations and bioavailability may lower risk for higher trophic level wildlife, such as the desert pupfish and Yuma Ridgway's rail, that rely on playa wetlands.

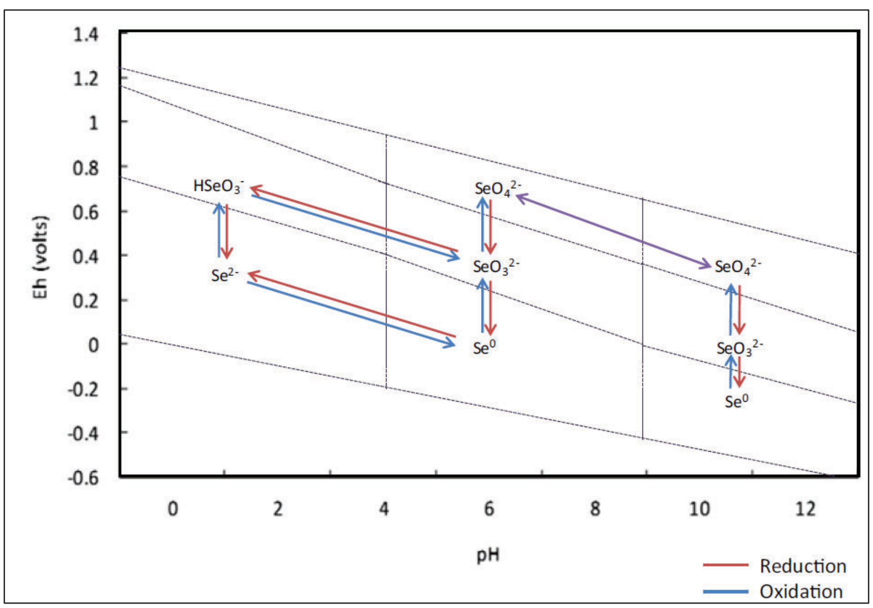

Figure 4. — Effect of soil pH (x-axis) and redox potential (y-axis) of soil on selenium (Se) speciation (from Mayland et al. 1989).

2.0 Purpose and Scope

Previous published reviews and studies have identified effective physicochemical and biological selenium treatment methodologies in agricultural, mining, and other settings (e.g., CH2M HILL 2010; Frankenberger Jr. et al. 2004; Gusek, Conroy, and Rutkowski 2008; Higashi et al. 2005; U.S. Army Corps of Engineers and California Natural Resource Agency 2013;); however, most are costly and complex and thus may not be applicable or feasible at the scale needed for playa wetlands (CH2M Hill 2010; U.S. Army Corps of Engineers and California Natural Resource Agency 2013). For example, several selenium removal technologies were considered for use in the Salton Sea Species Conservation Habitat (SCH) Project (Cardno Inc. and Environmental Science Associates 2015), which will use constructed wetlands to create suitable habitat for aquatic and avian wildlife, and to minimize fine particle dust emissions. Ultimately, it was concluded that direct physical and chemical treatments were not feasible for the SCH Project, but instead water management that maintains salinity at high enough levels to suppress emergent vegetation growth would thereby prevent the build-up of selenium-laden detritus, as well as minimize the input of selenium from drainwater (Cardno Inc. and Environmental Science Associates 2015).

While previously evaluated technologies have been deemed impractical at the Salton Sea because of their cost and complexity (e.g., U.S. Army Corps of Engineers and California Department of Water Resources 2011; U.S. Army Corps of Engineers and California Natural Resource Agency 2013) current technological and management advances over the last decade may hold promise for the Salton Sea region (Etteieb et al. 2021). The purpose of this literature review is to evaluate current advances in selenium removal technologies and their feasibility for vegetated wetlands at the Salton Sea. We address the following specific questions: (1) What are recent (particularly within the past 10 years) advances in selenium removal treatment technologies? (2) How applicable is each technology to the Salton Sea playa wetland system based on scalability, cost, and effectiveness at reducing selenium hazards to aquatic and detrital food webs? (3) How and where could recent technologies, in tandem with management actions at the Salton Sea, be used to help reduce selenium hazards in the environment? Given the projected growth of drain-fed playa wetlands around the Salton Sea and potential selenium hazards for fish and wildlife using them, this effort can help identify actions targeted at reducing risk to playa wetland food webs as the region evolves.

3.0 Methods

We searched Google Scholar™ for studies on selenium treatment technologies with an emphasis on studies conducted since 2012, although we included some papers published prior to 2012 if they were particularly relevant. We focused our search on methods useful for wetland environments. The following terms were used to find studies of methods used for removal or treatment of selenium in various forms from wetlands:

("selenium" OR "selenate" OR "selenite") AND ("removal" OR "treatment") AND ("wetlands" OR "wetland") OR (“constructed wetland”) AND (“selenium removal”)

We further limited the search to exclude review articles or those specific to treatment of drinking water. We then screened abstracts and text for relevance based on the following criteria: (1) The paper addressed selenium as a contaminant, not a beneficial nutrient. Articles related to selenium enrichment to treat selenium deficiency were discarded. (2) The method addressed in the paper had potential for implementation in agricultural or wetland environments. (3) The paper presented primary results (*i.e.*, no review papers or meta-analyses were included).

Next, we extracted data from the relevant articles. This included information on the treatment type, method used and mechanism of action. Chemical form of selenium treated, beginning concentration, amount removed, and pH were also extracted. A single reviewer (T. Graham) screened abstracts and extracted data.

To evaluate these technologies based on their cost-effectiveness, scalability, and applicability to playa wetland conditions, we developed a decision matrix, with each criterion ranked on a scale of 1 to 5. Cost-effectiveness was determined by grouping technologies according to treatment types: waste material treatments received a rank of 5 for their potential low-cost advantages, while clay remediation technologies were ranked 4 due to their relative affordability. Iron-based and carbon-based adsorbents were both assigned a rank of 3 (Benis, McPhedran, and Soltan 2022). Scalability was evaluated by considering the preparation and modification processes required. All technologies started with a rank of 5 and those necessitating extensive modifications were ranked lower, with 0.5 points deducted for each additional synthesis step. For instance, a technology requiring washing, drying, and grinding would incur a deduction of 1.5 points, resulting in a rank of 3.5. Applicability was assessed based on pH levels, with a pH of 7 and 8 receiving a rank of 5. Although the pH within the Salton Sea wetlands may range from 6 to 9, we used conservative neutral conditions as the highest applicability ranking. Values of pH above and below this range tapered off by 1 point per pH unit: a pH of 9 and 6 were both ranked as 4, while a pH of 5 and 10 received a rank of 3.

These scores were then weighted, assigning 50% to applicability, 30% to scalability, and 20% to cost-effectiveness. This weighting approach aimed to filter out technologies that would not be suitable for the Salton Sea and to assess how easily they could be scaled up. Given that cost-effectiveness is the most uncertain category—often because most technologies are evaluated at the laboratory scale, making it challenging to estimate field costs—this factor was weighted lower. When the scores were weighted, the final total score was calculated out of 100, allowing for a relative comparison of the technologies. The composite scores generated from these criteria and weighting enabled us to systematically identify selenium treatment technologies that would be most promising for further consideration and implementation in playa wetland environments.

4.0 Results and Discussion

We found over 5,480 peer-reviewed references, 114 of which met our criteria for inclusion in our study (Appendix A-1). Current capabilities for selenium removal from water include physicochemical (adsorption, coagulation and precipitation, membrane filtration, reduction, and permeable reactive barriers) and biological (microbial volatilization, microbial reduction in bioreactors, plant remediation, and constructed wetland) treatments (Li et al. 2022). Below we summarize selenium treatment technologies and discuss current advancements as well as their overall rankings based on our criteria of applicability, scalability, and cost-effectiveness. We then discuss potential integrated approaches to using new technologies to reduce selenium risks at various points in the linked Salton Sea agricultural and playa wetland system.

4.1. Current Selenium Treatment technologies

4.1.1. Physicochemical Treatments

Physicochemical treatments encompass the variety of treatment technologies that target removal of selenium from water either through physical separation, without changing its valence state or chemical form, or through chemical reactions that reduce selenium oxyanions to less toxic or less mobile forms. Methods we explored include adsorption, coagulation and precipitation, and membrane filtration, as well as selenite and selenate reduction using various reducing agents and catalysts. Our literature review identified several newer studies that have advanced each of these treatment technologies.

4.1.1.1. *Adsorption*

Selenium can be sorbed to the surfaces of inorganic mineral grains or organic particles. This adsorption process can be reversible, meaning that selenium can be desorbed from the surfaces of these particles. The extent of adsorption/desorption is affected by multiple factors, including the pH of the water, the concentration of selenium, and the type of soil or organic matter (Benis, McPhedran, and Soltan 2022; Okonji et al. 2020). In addition to its use in wastewater and drinking water systems, adsorption is also applied to selenium remediation in ground and surface water (Benis, McPhedran, and Soltan 2022) and is particularly useful for treating waters that have low pollutant concentrations. Effectiveness is largely determined by the adsorption capacity of substrate materials, which broadly includes metal oxides, various polymer microbeads or resins, carbon-based composites such as biochar, layered double hydroxides, which are often inorganic nanoclay particles, and other natural materials. Among the highly ranked adsorption treatments based on our review criteria (Appendix A-1) selenium removal ranged from 70% (selenate removal; Jordan et al. 2013) to 99% selenite removal using zero-valent iron (ZVI) in company with oxidants (Li et al. 2018). Other waste products have been studied as economical adsorbents including bivalve shells that enhance biofilm growth and microbial activity onto its porous surfaces (Yu et al. 2020), crushed orange peel with structures that enhance selenium adsorption (Mafu, Msagati, and Mamba 2014), and fish scale waste has been shown to provide jagged and variable surfaces for selenite adsorption (Kongsri et al. 2013).

The majority of studies reviewed were conducted under controlled laboratory conditions, limiting their applicability to real-world scenarios. In particular, drainwater consists of a changing mixture of chemical compounds that could compete with selenium for adsorption sites, diminishing the adsorptive capacity and our overall ranking as a viable treatment technology (Appendix A-1). For example, phosphate (PO_4^-) is highly competitive with selenium oxyanions for adsorption sites because of its electronegativity and anionic properties (Benis, McPhedran, and Soltan 2022). Furthermore, costs associated with the production, recovery, and reusability of the adsorbents would also be a consideration in determining its applicability and feasibility.

4.1.1.2. *Coagulation/Precipitation*

The advantages of coagulation and precipitation methods include that they are easy to operate, economical, and fast. Unlike adsorption, trace elements such as selenium are structurally incorporated into a host mineral during coagulation and are not readily re-released into the aqueous phase until the host particulate dissolves (Prieto, Astilleros, and Fernández-Díaz 2013). Typically, coagulants include iron and aluminum, which react with selenium oxyanions to form precipitates that can be removed from solution. Coagulation is most effective for selenite from contaminated water, and additional steps or methods may be needed to remove selenate when it is the predominant form (Li et al. 2022). For example, Wang et al. (2018) used an ultraviolet light pre-treatment in combination with sulfite to first reduce selenate to selenite, and then used an iron coagulant to remove the resulting selenite. In another example of recent advancements in coagulation methods, Das et al. (2020) used barite at a neutral pH to sequester dissolved selenate through a series of coagulation and co-precipitation experiments. They successfully removed >99% of selenate from solution and showed that it was unlikely to be re-released due to the low solubility and stability of the final co-precipitate produced. Coagulation and precipitation processes generate large amounts of solid waste, which influenced the cost effectiveness and scalability ranking criteria, despite high ranking for applicability (Appendix A-1).

4.1.1.3. *Membrane Filtration*

Membrane separation technologies have proven some of the most effective selenium removal treatments to date and are frequently used in treatment of wastewater and drinking water (Lichtfouse et al. 2022). Filtration of selenate and selenite from water is most often achieved using reverse osmosis or nanofiltration. Reverse osmosis has been shown to remove as much as 99.9% of selenium from water and has been used extensively to treat wastewater and drinking water for selenium removal. While nanofiltration has not proven as effective as reverse osmosis, several recent studies have focused on improving nanofiltration membranes with a variety of polymers (He, Zhao, and Chung 2018; Zeeshan et al. 2020) to achieve as much as 98% removal of selenium from water. Both reverse osmosis and nanofiltration are conducted in pressurized systems that consume large amounts of energy and cannot filter large volumes of water (Lichtfouse et al. 2022). Additional complications include high rates of membrane fouling and disposal of concentrated selenium on filters (Lichtfouse et al. 2022; Ostovar, Saberi, and Ghiassi 2022). Thus, membrane filtration methods in general received low scalability and cost-effectiveness scores and overall ranks low to intermediately in our evaluation (Appendix A-1)

4.1.1.4. *Reduction*

Chemical treatment of selenium contaminated water is accomplished predominantly by altering redox conditions to reduce selenite and selenate into less toxic and less mobile forms such as elemental selenium. Chemical reduction methods are often combined with adsorption, filtration, or catalytic processes to remove selenium. The reduction process can be achieved by adding chemical reducing agents or using electrodes. Although overall the efficiency of this treatment is currently considered low compared to other methods (Ullah et al. 2023), redox methods are applicable to wastewater, surface water and groundwater; are economical; and do not produce substantial amounts of waste products. Thus, several recent studies have improved upon this technology. For example, many researchers have studied the applicability of using ZVI as a reducing agent for selenite and selenate in water (Ling et al., 2019; Shan et al., 2018; Suazo-Hernández et al., 2021; Appendix A-1). In one of the most highly ranked studies in our review, Li et al. (2018) used ZVI in company with oxidants to treat groundwater and were able to remove 4.49 mg/g or more than 85% of selenite in the sample.

Electrochemical reduction uses external electrodes and is categorized as direct or indirect. Zou and Mauter (2021) evaluated direct electrochemical reduction for selenium removal from complex wastewaters and found that moderate heating to 80 degrees C resulted in up 95% removal of selenite from solution. However, they suggest future work to enhance processing times, efficiency, and cost.

Catalysis is the process of adding a catalyst substrate to increase the reaction rate of redox treatments. Catalysis has rarely been used for selenium treatment; however, the process does not consume chemicals and the catalyst material is often reusable, and thus this method has gained interest in recent years. Photocatalysis in particular has been the subject of current investigations to reduce selenium oxyanions (Nakajima et al. 2011; Vohra and Labaran 2020). Labaran and Vohra (2017) investigated a solar photocatalytic degradation process using titanium dioxide (TiO_2) as photocatalyst and ethylenediaminetetraacetic acid (EDTA) as a scavenging agent and found that selenite and selenate could be reduced directly to elemental selenium at an optimum pH of 4. Although photocatalytic studies received relatively low rankings in our review due to cost effectiveness and applicability (Appendix A-1), this treatment process may be improved with additional research.

Selenium reduction is a reversible process, influenced by geochemical conditions. Therefore, selenium reduction must be paired with a mechanism allowing for the removal and disposal of the adsorbent, filtrate, or coagulant to remove selenium from the system and to prevent the re-dissolution of immobilized selenium.

4.1.1.5. *Permeable Reactive Barriers*

Permeable Reactive Barriers (PRBs) have typically been used to remove contaminants from groundwater, acid mine drainage, and agricultural wastes (Budania and Dangayach 2023; Scherer et al. 2000). Essentially PRBs are structures filled with replaceable reactive materials (i.e., activated carbon, bentonite mixture,ZVI, organic substances, and other by-products), and as contaminated water passively passes through the reactive material, contaminants are immobilized or transformed to less harmful compounds (Budania and Dangayach 2023). Full scale implementation of PRBs have been constructed to remove nutrients (nitrates and phosphates), as well as dissolved constituents associated with acid mine drainage (sulfates, iron (Fe), nickel (Ni), cobalt (Co), and zinc (Zn)); however, the removal of selenium has only been conducted in laboratory scale experiments (Blowes et al. 2000). This new technology could be promising although the long-term sustainability of PRBs for selenium removal is largely unknown and would require field testing and monitoring to assess sustainability over time.

4.1.2. Biological Treatments

Biological treatment methods include the processes of selenium removal from water via uptake and volatilization via microbial remediation (including bacteria, fungi, and biofilms), phytoremediation (including microalgae, macroalgae, vascular plants), and constructed wetland systems. Plant and microbial volatilization of selenium is particularly attractive because it removes selenium entirely from the aquatic system, thereby reducing the bioavailable selenium in plants, detritus, and soil and reducing selenium transfer into the food web (Higashi et al. 2005).

4.1.2.1. *Microbial (i.e. Bacteria, Fungi, Microalgae) Volatilization*

Microbial remediation in waste or drainwater is achieved through bacterial or fungal mediated reduction of selenium oxyanions. Microbial-mediated selenium removal includes the reduction of selenium oxyanions into elemental selenium (Se), volatilizing the selenium (dimethyl selenide or hydrogen selenide) or directly incorporating selenium into selenium-amino acids (methyl selenocysteine; Kagami et al. 2013; Singh, Tripathi, and Mishra 2021). Selenium can also be volatilized to the atmosphere through microbial activity or through direct release by aquatic plants (Eggert et al. 2008; Winkel et al. 2015). Plants and microbes metabolize the inorganic forms of selenite and selenate into volatile and non-toxic forms, mainly dimethyl selenide and dimethyl diselenide (Kagami et al. 2013; Winkel et al. 2015). Microalgae have a high capacity to take up excess macro-nutrients (e.g., nitrogen and phosphorus) and micro-nutrients (e.g., Fe, manganese (Mn), magnesium (Mg), and Zn; Arashiro et al. 2019; Gan et al. 2019) and thus are receiving greater attention for wastewater treatment systems. Microalgae can also incorporate selenium into amino acids such as selenomethionine and selenocysteine, which may be used as a beneficial supplement added to animal feed or to crops to alleviate selenium deficiencies (Li et al. 2021; Umysová et al. 2009).

Liu et al. (2019) tested selenium removal with microalgae (*Chlorella vulgaris*) under different selenium concentrations, algal densities, temperature, and pH levels in experimental microcosms. The authors found that removal efficiency peaked at 90% when selenium concentration in water was 1000–3000 µg Se/L, but removal efficiency decreased when selenium concentrations were higher or lower than this range (59% at 8000 µg Se/L and 51% at 500 µg Se/L). Selenium volatilization by microalgae increased at higher temperatures (59% of the added Se was volatilized at 25 °C, compared to only 49% at 20 °C). Due to the simple ways of increasing selenium volatilization with increased temperature, this treatment method scored relatively high for applicability and cost effectiveness, but scalability was lower because this has only been tested in laboratory experiments (Appendix A-1).

4.1.2.2. *Microbial Reduction using Bioreactors*

Bioreactors are specialized controlled systems that have most often been used to remove selenium from wastewater within treatment plants. Bioreactors utilize a combination of microbial and microalgal remediation processes to facilitate the biological reduction of selenium to less harmful forms, such as elemental selenium nanoparticles. Microbes are usually used for remediation in various types of bioreactors including fluidized sludge beds (Fadaei and Mohammadian-Hafshejani 2023; Sinharoy, Saikia, and Pakshirajan 2019; Yan et al. 2020;), fungal pelleted reactors (Espinosa-Ortiz et al. 2015), algal-bacterial systems (Quinn et al. 2000), granular activated-carbon (GAC) bioreactor (Arias-Paic et at. 2022), and similar methods. An inverse fluidized bed bioreactor (IFBR) is similar to other fluidized sludge beds but has a unique flow pattern to enhance the mixing and contact between wastewater and microorganisms to help break down selenium (Sinharoy, Saikia, and Pakshirajan 2019). In a laboratory study, microbial-mediated selenite removal was enhanced with the carbon sources glucose and lactate, to achieve a 96% and 98% selenite reduction to elemental selenium, respectively, after 5 days of treatment (Sinharoy, Saikia, and Pakshirajan 2019). The addition of these organic amendments was thought to provide energy for the microbial reduction of selenates and selenides to elemental selenium, thereby enhancing selenium removal from the water (Zhang, Zahir, and Frankenberger 2003; Sinharoy, Saikia, and Pakshirajan 2019; Zhang and Frankenberger 2014).

Depending on environmental conditions, the use of fungi or bacteria bioreactors to remove selenium can be advantageous. For example, fungi can be grown under acidic to neutral pH ranges (3.0 - 7.0) as well as in environments that are low in moisture, phosphorus, and nitrogen, all of which are conditions that are less favorable for bacteria. Espinosa-Ortiz et al. (2015) found that a fungal (*Phanerochaete chrysosporium*) based bioreactor removed up to 70% of total soluble selenite (10 mg Se/L) from synthetic wastewater and that the reactor was resilient to spikes that doubled the selenium concentration. Despite the high rates of selenate and selenite removal, most of these bioreactor experiments occurred in a laboratory setting and ranked relatively low on scalability and cost effectiveness (Appendix A-1). A full-scale granular activated carbon bioreactor ranked high on scalability due to its ability to achieve sub-5-μg/L selenium concentrations from agricultural drainwater, while the cost-effectiveness ranked intermediate due to the potential need for secondary ultrafiltration and the generation of hazardous waste products (Arias-Paic et al. 2022; Appendix A-1). Although most of the bioreactors for the treatment of agricultural drainwater are in the development phase, below we summarize two examples from full scale bioreactors at treatment facilities in California.

4.1.2.2.1 Granular Activated Carbon (GAC) Bioreactor

A full-scale granular activated carbon (GAC) bioreactor was operational for almost three years at the San Luis Demonstration Treatment Plant in Firebaugh, California, USA (Arias-Paic et al. 2022). This demonstration project was the first of its kind to remove selenium from actual agricultural drainwater, which consisted of high total dissolved solids (up to 22,350 mg/L of total dissolved solids (TDS)) and variable concentrations of chloride, nitrate, phosphorus, selenium, selenate, selenite, calcium sulfate, arsenic, boron, and other constituents (Arias-Paic et al. 2022). The GAC bioreactor treated drainwater containing a range of total selenium (111 to 332 μg/L) using a two-stage bioreactor amended with a carbon source (glycerin) to facilitate selenate reduction to elemental selenium. The contact time of the reactor ranged from 3.4 to 5.0 hours, resulting in an average effluent concentration of 12 μg total selenium/L, for an overall average of 86% total selenium removal. Effluent was further purified using a downstream ultrafiltration membrane system to capture selenium nanoparticles as needed to achieve a threshold of <5 μg of total selenium/L. This study demonstrated that a full-scale GAC bioreactor achieved substantial selenium removal from drainwater using a series of controlled processes; however, the use of bioreactors requires high operational monitoring and maintenance to detect issues that might disrupt the bioreactor, such as pH-induced calcium carbonate scaling in drainwater containing high calcium sulfate, potential formation of hydrogen sulfide gas, and insufficient concentrations of carbon source. Despite this successful full-scale, multiyear demonstration, this bioreactor overall had an intermediate score due to the high operational monitoring and maintenance, the potential need for secondary ultrafiltration, and the generation of hazardous waste products (Arias-Paic et al. 2022; Appendix A-1).

4.1.2.2.2 Algal-Bacterial Selenium Removal Bioreactor

Several microbes, including algae and bacteria, can metabolically transform selenate or selenite to elemental selenium under various conditions (Ostovar, Saberi, and Ghiassi 2022; Ullah et al. 2023). The combination of microalgae and bacteria was explored in an algal-bacterial selenium removal (ABSR) treatment facility demonstration project to remove selenium from agricultural drainwater in the San Joaquin Valley, California, USA (Panoche Drainage District; Quinn et al. 2000). The ABSR process applies stepwise processes typical of wastewater treatment technologies and uses a similar sequence of pond treatment and removal systems. In the initial step, microalgae is grown to take up nitrates in the water, helping ameliorate the competitive inhibition of nitrate on selenate reduction (Hunter and Manter 2009; Quinn et al. 2000; Schiavon et al. 2017;. Nitrates stimulate microalgae growth and as the microalgae decomposes, it is consumed as a carbon source for selenium reducing bacteria. Under anoxic conditions, the selenium reducing bacteria reduces selenate and selenite to elemental selenium, which is less mobile and more easily removed with the sludge at the bottom of the pond (Quinn et al. 2000; Ullah et al. 2023). Water then moves to another pond where it is re-oxygenated and further purified by algae or plants. Throughout the two-year project, the ABSR system with carbon amendment (molasses) was able to remove an average of 80% of the total selenium, but without an additional carbon amendment (using algae as the only carbon source), the average total selenium removal was only 45% (Quinn et al. 2000).

While the ABSR system did remove about 80% of the total selenium, over 30% of the selenium remaining in the system effluent consisted of selenite and organo-selenium, which are more bioavailable and thus more harmful to wildlife (Luoma and Presser 2009). Also, invertebrates exposed to treated water accumulated more selenium than those in untreated water (Li et al. 2022), a severe limitation for ABSR. For these reasons, additional processes are needed to remove the nanosized or colloidal elemental selenium (Se0) particles from treated water before it is released into aquatic environments to prevent uptake in food webs (Li et al. 2022; Amweg, Stuart, and Weston 2003). Additional technologies or treatment processes may be required to remove residual selenite or particulate selenium from the ABSR bioreactor. These may include settling ponds or dissolved air flotation (Quinn et al. 2000), electrocoagulation using an iron electrode, which demonstrated 97% removal (Staicu, van Hullebusch, Lens, et al. 2015), or coagulation using ferric chloride and aluminum sulfate, which can remove 92% (Staicu, van Hullebusch, Oturan, et al. 2015)

4.1.2.3. *Plant Remediation*

There has been considerable effort in identifying both wetland and terrestrial plants that can be used for selenium remediation. Species have varying rates of selenium accumulation, transformation, sequestration, and volatilization, and may have different levels of selenium tolerance. Each of these factors can contribute to their suitability for use in remediation.

4.1.2.3.1 Macroalgae

In the Salton Sea, Hennequin et al. (2022) conducted a 2-year experiment using periphytic macroalgae to remove nutrients and trace metals (including selenium) from water in an "algal flow-way." They constructed a 270-m long flow-way and continuously filled it using pumped source water from a settling basin containing water from the Alamo River, and harvested algae approximately every seven days. The algae flow-way consisted of approximately 30% diatoms and 70% green algae and removed an average of 0.071 mg total selenium/m^2/day, although selenium uptake in algal biomass was highly variable and ranged from 1.14 to 2.39 mg total selenium/kg. Although the algal flow-way did remove notable nitrogen (530 ± 190 mg N/m^2/day) and phosphorous (14 ± 6 mg P/m^2/day), the authors concluded that the algae did not have a high selenium bioaccumulation factor.

Although the authors did not examine selenium speciation, the uptake and transformation of selenium to organo-selenium increases its bioavailability to wildlife, especially to invertebrates that could bioaccumulate selenium and be consumed by higher trophic level wildlife (Li et al. 2022; Palace, Graves, and Brandt 2024; Fan et al. 2002; Amweg, Stuart, and Weston 2003; Higashi et al. 2005). This potential issue represents a limitation of algae flow-way systems. One way of mitigating this would require regular removal of accumulated algae, and placement of nets to prevent higher trophic organisms from feeding in drains. Ultimately, although this treatment method scored high for cost-effectiveness, scalability, and applicability according to our criteria, it was limited by its moderate ability to remove selenium from the system (Appendix A-1).

4.1.2.3.2 Emergent and submergent wetland vegetation

Several wetland plant species have been evaluated to determine their efficacy for remediation. For example, Lin and Terry (2003) found that selenium volatilization was highest (9.4% removal over a 2-year period) in wetland mesocosms planted with rabbitfoot grass (*Polypogon monspeliensis*) compared to cattail (*Typha latifolia*), Baltic rush (*Juncus balticus* Willd.), smooth cordgrass (*Spartina* alternifolia Loisel), saltgrass (*Distichlis spicata* (L.) Greene), tule (*Scirpus lacustris* L.), and widgeon grass (*Ruppia maritima* L.) and that volatilization was greater during the growing season compared to winter. Furthermore, selenium volatilization rates in rabbitfoot grass can vary by season with recorded rates up to 48% during the summer and less than 5% during the winter (Lin and Terry 2003).

Huang, Passeport, and Terry (2012) used wetland mesocosms to test the effect of different plant species (broadleaf cattail, *Typha latifolia*; saltmarsh bulrush, *Scirpus robustus*; California bulrush, *Schoenoplectus californicus*; rabbitsfoot grass, *Polypogon monspeliensis*; and slough sedge, *Carex obnupta*) on selenate, selenite, and selenomethionine removal from water. The authors conducted additional experiments testing the effect of organic amendments (alfalfa hay, steer manure, whey, soy protein), and substrates (mixture of sand and peat moss, cattail litter, and a combination of cattail litter with sand and peat moss substrates) on cattail growth and selenium removal. The authors reported that cattail and saltmarsh bulrush had the highest selenium removal at 89% over three weeks. The addition of organic amendments was thought to provide energy for the reduction and removal of selenate and selenite, enhance microbial reduction of organoselenides to elemental selenium in water and soil (Zhang and Frankenberger 2014; Zhang, Zahir, and Frankenberger 2003;) and increase selenium removal through volatilization. Alfalfa hay or alfalfa meal amendments were beneficial in lowering selenium levels (even in unplanted wetlands), while steer manure, whey, and soy protein were not (Zhou et al. 2019). The most efficient constructed wetlands design was obtained using cattails growing in a substrate of cattail litter overlying sand and peat moss substrate (water column selenium was reduced from 15 µg Se/L to <0.1 µg Se/L in 72 h).

At the Salton Sea, one of the most dominant plants in wetlands include cattail (*Typha* spp.), which has shown promise in selenium volatilization. Other dominant plant species in Salton Sea wetlands include salt cedar (*Tamarisk* spp.) and common reed (*Phragmites australis*; Rosen et al. 2023), but have not been studied for their ability to volatilize selenium to the atmosphere.

4.1.2.3.3 Floating aquatic vegetation

Floating mats of aquatic vegetation have also been used within constructed wetlands to promote volatilization of selenium into the atmosphere (e.g., using floatingheart, *Nymphoides* spp., Zhou et al. 2019); cattails, *Typha angustifolia*, Zhao et al. 2020). This method has been particularly effective in areas with high water residence times such as ponds. Zhou et al. (2019) demonstrated that floating aquatic vegetation gradually removed approximately 40% of the selenium from the water over a 21-day period. Nearly 75% of the removed selenium accumulated in the sediment, and almost half of this sediment-bound selenium was found in the organic form. The detritus-bound and sediment-bound selenium represent entry points to the detrital-sediment food web, where it may become available to demersal feeders such as benthic and epibenthic invertebrates, crayfish, and higher trophic wildlife (Palace, Graves, and Brandt 2024; Zhou et al. 2019).

Another mesocosm experiment was conducted to test seven vegetative treatment systems (floating cattail system, a reed subsurface flow system, and other surface flow systems using different vegetation [reed, cattail, iris], and pond systems with elodea and water lily) over a one- and two-day hydraulic residence time with an initial concentration of 65 µg Se/L selenate or selenite (Q. Zhao et al. 2020). For a one-day hydraulic residence time, the floating cattail system had the highest selenite and selenate removal rate, compared to six other vegetated treatments (Q. Zhao et al. 2020). After a two-day hydraulic residence time, the cattail floating system achieved almost complete removal of selenite and a 95% removal rate for selenate in the summer growing season, compared to a selenate removal rate of 72% and a selenite removal rate of about 100% in the winter (Q. Zhao et al. 2020).

4.1.2.3.4 Terrestrial vegetation

Several terrestrial plant species have been evaluated for their ability to extract selenium from the environment. Notably, terrestrial plants were used to dissipate selenium through bioaccumulation and volatilization as part of the remediation solution at Kesterson Reservoir in California, USA, where selenium in subsurface agricultural drainage water resulted in deformities in wildlife (Bañuelos et al. 1997; Ohlendorf 2002). In the Salton Sea region, agricultural soils have comparatively low levels of selenium, while the soil selenium from the Salton Sea itself and shoreline are higher (Rosen et al. 2023). As the Salton Sea recedes, the exposed playa lakebed, when wetted by agricultural drainwater, forms playa wetlands, which may expose wildlife to selenium hazards. Terrestrial phytoremediation has been studied in agricultural systems, but might be a consideration for the playa lakebed, if appropriate plants species can be identified.

In agricultural systems, rotation of crop plants has been explored to evaluate best practices for selenium removal. Considerations for which crops to use include the variability in selenium bioaccumulation among plant species and the range of environmental factors that may influence selenium bioavailability across growing regions and seasons. Bañuelos et al. (1997) found four-year rotations of Indian mustard (*Brassica juncea* L.), tall fescue (*Schedonorus arundinaceus*), birdsfoot trefoil (*Lotus corniculatus* L.), and kenaf (*Hibiscus cannabinus* L.) reduced soil selenium by 60%. Dhillon and Dhillon (2009) evaluated different cropping systems composed of multiple plant combinations and found that that rapeseed (*Brassica napus*) followed by pigeon pea (*Cajanus cajan*), sunn hemp (*Crotalaria juncea*), or cotton (*Gossypium arboretum*) led to significant reductions in selenium in contaminated soil over 2–3 years. Selenium removal through harvested biomass at maturity was between 1.7 and 13.2% of total selenium in the soil down to a depth of 120 cm. Recent studies have focused on using transgenics to enhance selenium tolerance, accumulation, and volatilization using the traits from wild selenium hyperaccumulating plants in crop plants (Hasanuzzaman et al. 2020), as well as studies on the role of microbe interactions with plant rhizospheres to enhance plant selenium uptake, translocation, metabolism, and volatilization (Yasin et al. 2015).

4.1.2.4. *Constructed Wetlands*

Constructed wetlands are engineered wetland systems that incorporate multiple physicochemical and biological mechanisms to improve water quality. Constructed wetlands have been used for decades as phytoremediation to treat municipal and industrial wastewater and in recent years have been studied to address selenium contamination. These systems leverage phytoremediation processes and wetland dynamics involving wetland plant species, soils, or engineered substrates, and associated microbial communities, to mediate the removal of selenium in the water column. Selenium removal mechanism includes sequestering selenium in sediments, promoting microbial reduction of selenate to selenite, adsorption onto clay particles or organic matter, chemical coprecipitation, accumulation in plant tissues, and volatilization to the atmosphere (Etteieb et al. 2021). The overall performance of constructed wetlands depends on many factors that include vegetation type (refer to sections above), type of wetland, water chemistry, design specifications, substrate, microbiology, temperature, hydrology, pH, temperature, initial selenium concentration, and flow conditions. (Santos et al. 2015; Jones et al. 2023). The disposal of sediment and detritus, and plant biomass introduces additional maintenance and cost (Santos et al. 2015).

Several constructed wetlands have been implemented throughout the United States to evaluate their capacity for selenium removal (Etteieb et al. 2021; Gao et al. 2003; Jones et al. 2023; Kadlec and Wallace 2008; Lin et al. 2010; Lin and Terry 2003), including in the Salton Sea region (Johnson et al. 2009; Tetra Tech 2006). Two demonstration treatment wetlands were constructed along the New River (Brawley and Imperial wetlands) in 2000 to quantify the removal of selenium and other pollutants, and to evaluate the potential hazards to wildlife due to chemicals that may bioaccumulate in constructed wetlands (Tetra Tech 2006). The Imperial constructed wetland included two parallel sedimentation basins followed by a series of four wetland cells (4.7 ha, 25% vegetated with bulrush, *Schoenoplectus californicus*). The Imperial wetland received average annual inflow of 0.18 cm^3/s of agricultural drainwater per day with an estimated water residence time of 18 days (Johnson et al. 2009). The Brawley wetland was smaller and had a long and narrow basin and pond features, but more sinuous channels to maximize the footprint of a single sedimentation pond and two wetland cells (1.8 ha, 25% vegetated area with bulrush). The Brawley wetland received an average annual inflow of 0.031 cm^3/s of water from the New River, with an estimated water residence time of approximately 9 days (Johnson et al. 2009; Tetra Tech 2006).

By 2006 and 2007, the sediment basins from both constructed wetlands retained >94% of the suspended sediment load (Tetra Tech 2006). Selenium removal efficiencies, in terms of concentration was 22% at the Imperial wetland and 42% at Brawley wetland, while selenium mass removal efficiencies were 56% at the Imperial wetland and 70% at the Brawley wetland (Johnson et al. 2009). Although both wetlands were unlined and experienced some seepage of selenium into the ground, estimated mass balance for six years of operation showed that most of the selenium was retained in the sediment, with 17–61% of the selenium lost from the system, presumably through volatilization to the atmosphere, and <1% of selenium was accumulated in plant tissues (Johnson et al. 2009). Ultimately, these constructed wetlands demonstrated their effectiveness at removing selenium (and major nutrients not presented here) from riverine and agricultural drainwater sources;

however, the concentrations of selenium in most invertebrates and whole fist samples at both the Imperial and Brawley wetlands sites were within the range where reproductive impairment may be expected in birds that consume fish and aquatic invertebrates (National Irrigation Water Quality Program criteria of 3–8 mg Se/kg dry weight; (U.S. Department of the Interior 1998), indicating that reproductive effects may be a concern.

Treatment wetlands that remove selenium via vegetation and microbial-based volatilization to the atmosphere or by microbial reduction may be more desirable because they lead to a net loss from aquatic systems or conversion to less bioavailable forms, thereby reducing selenium entry into food webs. However, about half of the selenium retained by constructed wetlands were reported in detritus and sediment compartments, with minor amounts of selenium found in plant tissues (<1%), volatilized to the atmosphere (2%), or in the water outflow (35%; Gao et al. 2003), which corresponds to patterns of the selenium pool in other constructed wetlands (Salton Sea region, California, Johnson et al. 2009; Pariette Wetlands, Utah, Jones et al. 2023). Other constructed wetlands in San Francisco Bay reported 89% selenium removal with 10–30% attributed to volatilization (Hansen et al. 1998). Recent studies have focused on enhancing selenium removal via volatilization by selecting appropriate wetland plant species (Nattrass et al. 2019; X. Zhao et al. 2020; Lin and Terry 2003) or by adding carbon sources and substrates to enhance bacterial reduction thereby lowering selenium bioavailability (Sinharoy, Saikia, and Pakshirajan 2019; Yu et al. 2020;Zhang, Zahir, and Frankenberger 2003)

Despite the ability of constructed wetlands to remove selenium from the water and its cost-effectiveness, a major concern for this type of treatment wetland is the potential of increasing risk to biota because the majority of selenium is retained in the detritus and sediment pool (Gao et al. 2003; Huang, Passeport, and Terry 2012; Johnson et al. 2009; Jones et al. 2023; Tetra Tech 2006; Zhou et al. 2021;). Selenium that is incorporated into detritus and sediment may be in organic form and thus more bioavailable (Amweg, Stuart, and Weston 2003; Fan et al. 2002; Higashi et al. 2005; Johnson et al. 2009; Li et al. 2022; Palace, Graves, and Brandt 2024; Tetra Tech 2006;). Management actions such as litter and soil removal, as well as harvesting plants, could lower the selenium risk for wildlife in constructed wetlands (Palace, Graves, and Brandt 2024). Advances in subsurface flow constructed wetlands may also help address this problem by reducing exposure of wetland biota to the selenium removal process and its by-products (Etteieb et al. 2021).

4.1.2.4.1 Subsurface flow constructed wetlands

Subsurface flow constructed wetlands (SSFCW) are shallow basins with substrate (i.e., natural substrates such as soil, sand, gravel; or fabricated substrates such as activated carbon and ceramics) to facilitate microbial treatment of water below the ground surface (Plaimart et al. 2022; Rehman et al. 2024).

Although SSFCW have been effective for treating municipal and organic wastewater, and for removing pharmaceuticals, their ability to remove selenium remains largely unexplored, therefore its applicability to the Salton Sea region is unknown.

4.2. Integrated Approaches to Selenium Removal at the Salton Sea

Colorado River water supports a productive agriculture industry in the Salton Sea Basin via an extensive irrigation and drain system. Approximately 1,456 miles of drains (open channel and closed pipeline) convey tailwater and tilewater from the agricultural fields into the Alamo and New Rivers or to the dry Salton Sea lakebed where they form playa wetlands (Imperial Irrigation District 2024; Rosen et al. 2023). Standard farm irrigation practices within this desert climate promote high rates of evapotranspiration that concentrate selenium leading to elevated levels in drainwater (Setmire et al. 1993) that flows into playa wetlands (Rosen et al. 2023). Here we consider the potential application of emerging selenium treatment technologies identified in the sections above at multiple points in the Salton Sea agricultural and wetland system, including fields, drains, lined waterways, and playa wetlands (Fig. 5). In addition to emerging treatment technologies, we also consider existing agricultural and wetland habitat management practices that were not identified in our literature review but may have implications for selenium remediation. Ultimately, integration of treatment and management approaches across the entire linked agricultural and wetland system may enable the creation of a broad strategy for reducing selenium hazards for biota in playa wetlands.

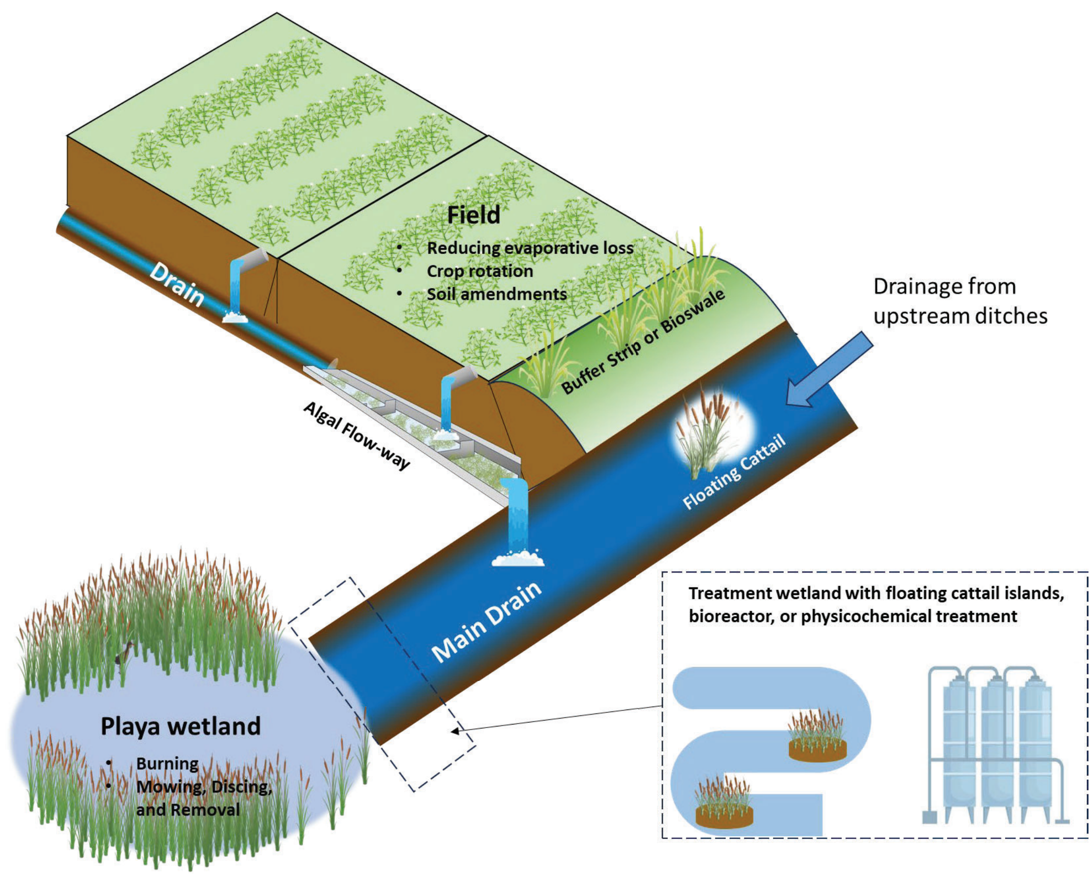

Figure 5. —A conceptual model that illustrates potential strategies to incrementally reduce selenium loads from the Salton Sea playa wetlands.

Strategies may be possible at multiple steps including field practices (reducing evaporative loss, crop rotation, soil amendments), within the drain treatments (algal flow-way or floating cattail, depending on size of drain), a buffer strip or bioswale between the field and drain, constructed wetland at end of a main drain, and playa wetland vegetation management (burning or mowing/discing/vegetation removal). A combination of selenium removal strategies for the whole system may enhance selenium removal from the system.

4.2.1. Field Management Practices

Opportunities for selenium remediation in agricultural fields require collaboration with growers and managers to test and implement modified irrigation and crop management practices that minimize selenium buildup, promote volatilization, or facilitate direct removal from soils.

4.2.1.1. *Reducing Evaporative Loss*

Because high evaporation rates of Colorado River irrigation water tend to concentrate the selenium in agricultural drains, irrigation practices that can reduce evaporation loss might be one strategy to improve selenium concentrations found in drainwater. Overall, studies to determine whether efficient irrigation practices would lower selenium concentrations in agricultural return water that flows into playa wetlands are generally lacking. However, in a region with complex water and stakeholder interests, greater water efficiency also may lead to a decreased volume of drainwater that is available to sustain playa wetland habitat for endangered species.

4.2.1.2. *Soil Amendments*

The application of sulfuric acid (H_2SO_4) in agricultural soils is a practice that aims to improve soil fertility by increasing the mineralization of nitrogen and carbon, decreasing nitrogen immobilization, and increasing phosphorus availability (Zireeni, Jones, and Chadwick 2023). However, few studies document the effects of this type of soil acid treatment on selenium transformation and availability. One study examined the effects of soil acidification on selenium enriched tea in the eastern coastal region of China and found that increased soil acidification led to the conversion of selenium complexes with manganese oxides and aluminum (Yang et al. 2023). Other studies have reported adsorption or sorption of selenate and selenite on soils was related to organic matter content, clay content, as well as the presence of other soil metals and constituents such as aluminum and iron compounds (Amrhein and Doner 2014; Li et al. 2015; Lessa et al. 2016; Yang et al. 2023). Dhillon and Dhillon (1999) conducted a laboratory study and found that the sorption capacity of selenite was greater in acidic soils with positive correlations with organic carbon content and iron. Another study examined acid rain from volcanic activity from Mt. Etna, Italy, and although volcanic reaches have unique soil and local environmental characteristics, the authors found that in areas with low organic matter and aluminum compounds, the acidic rainfall mobilized selenate in soils (Floor et al. 2011).

These findings underscore the complex interplay between selenium dynamics, soil physical properties, and soil chemistry. The effect of agricultural practices that acidify fields in the Salton Sea region on selenium transformation and bioavailability are unclear due to the specific nature of the soils in the region and represents a data gap in the initial stages of selenium entering the drain-fed playa wetlands.

4.2.2. Field Drains

A system of agricultural drains collects and moves water away from fields. Field drains can be relatively small with low flow rates and intermittent water supply. Multiple field drains often feed into a main drain that empties onto the playa wetland.

4.2.2.1. *Saturated Buffer or Bioswale*

Saturated buffer strips allow agricultural water to percolate through a vegetated buffer to remove nutrients and contaminants before the water reaches a canal or other waterway. Saturated buffers have four main components: a non-perforated drainpipe, a water control structure, a perforated distribution pipe, and a vegetated buffer. The tile drained water is directed to the control structure via the drainpipe. That water is then diverted into the perforated distribution pipe, where it is slowly pushed through the vegetated buffer. While crossing the buffer, denitrification occurs (a microbial facilitated process of nitrate being converted to nitrogen gas) along with nitrate uptake by the plants within the buffer. Initial pilot results have shown that these saturated buffer strips can be effective at reducing excess nitrate and phosphate in agricultural drainwater (Sands et al. 2017) and heavy metals in stormwater (Anderson et al. 2016; Melville 2016). Although no studies have been performed on the efficacy of this treatment for reducing selenium, it may be a promising method to evaluate and consider for future use. Saturated buffers remove little to no land from production, require little maintenance, and do not affect crop yields when placed in ideal sites (U.S. Department of Agriculture Research Service 2018), indicating this method could be scalable and cost effective for the Salton Sea region.

4.2.2.2. *Macroalgae Flow-way*

Macroalgae flow-ways designed to remove nutrients and trace metals (including selenium) from water have been tested experimentally in the Salton Sea environment (Hennequin et al. 2022) and could potentially be scaled to agricultural drain systems as part of a multi-step scheme, in which selenium is incrementally removed as water flows from drains to larger canals and eventually to playa wetlands. Findings from Hennequin et al. (2022) showed that while notable removal of nitrogen, phosphorus, and some metals occurred, selenium uptake by algae was highly variable in the tested system, and the authors concluded that the flow-way as currently designed did not have substantial capacity to remove selenium. Because the upper range of selenium removal was thought to be attributed to algae tissues reaching a selenium toxicity threshold (Hennequin et al. 2022), additional work to improve this method could focus on using different algae species for selenium bioaccumulation. Although the authors did not examine selenium speciation, the uptake of selenium and transformation to organo-selenium by algae in this system could be detrimental to biota using drains (Li et al. 2022; Palace, Graves, and Brandt 2024) and represents a limitation of this system. Drains managed as macroalgae flow-ways would require regular removal of accumulated algae or nets to prevent higher trophic organisms from feeding in them.

4.2.2.3. *Small Scale Adsorption*

Selenium removal in smaller drains may be enhanced with the use of bio-adsorbents (Benis, McPhedran, and Soltan 2022). For example, Mafu et al. (2014) examined the adsorption capacity of crushed orange peel and crushed and chemically treated orange peel for the removal of total selenium in a laboratory experiment. Although the adsorption capacity of chemically treated and crushed orange peel seems promising when tested on domestic wastewater samples (74.8% removal of total selenium), further studies are warranted to test its efficacy for agricultural drainwater, which contains multiple compounds that could compete with selenium for adsorption sites. Improving the water contact with the bio-adsorbent could also help with removal efficiency.

4.2.3. Main Drains

Main drains or waterways receive drainwater from multiple field drains and convey water to the outflow playa wetland. These main drains can be relatively deep with perennial flow. Because they collect water from multiple sites, they may represent feasible locations to install larger scale treatment options that can process higher water volumes.

4.2.3.1. *Physicochemical Treatments*

The variety of physicochemical treatment options for selenium remediation in water discussed earlier in this document are most often implemented in large-scale treatment plant facilities that process bulk volumes of water, often from multiple sources. Thus, application of these treatments to the Salton Sea system could be most feasible in areas where multiple drains or waterways converge into large main drains. We ranked each physicochemical method reviewed based on applicability, scalability, and cost and identified several highly ranked treatments that could achieve up to 99% removal of selenite or selenate from water under ideal conditions. Other considerations when evaluating physicochemical treatment types to implement include the availability of power and raw materials, start-up costs, troubleshooting and adjusting methodology, and volume of waste generated for each method (Srinivasan et al. 2014). Additionally, implementation of centralized treatment facilities may necessitate re-routing of water to that facility and could ultimately reduce direct drain flow to multiple playa wetlands, thereby reducing habitat for endangered and migratory species. Relatively low-cost materials such as bivalve shells can enhance biofilm growth and microbial activity onto its porous surfaces (Yu et al. 2020), or crushed orange peel with structures that enhance selenium adsorption (Mafu, Msagati, and Mamba 2014), may incrementally help the remove selenium from main drains.

4.2.3.2. *Bioreactors*

Bioreactors are biological treatment methods that are typically housed in large-scale facilities and could be situated on a centralized waterway or collector drains. Bioreactors are often combined with physicochemical methods to achieve maximum selenium removal from wastewater or agricultural drainwater (Fadaei and Mohammadian-Hafshejani 2023). Demonstration projects featuring bioreactors to treat agricultural drainwater or selenium removal in other agricultural regions of California have shown relatively high selenium removal rates from water (80 – 86%; Arias-Paic et al. 2022; Quinn et al. 2000). Limitations such as the generation of waste material and high maintenance costs remain. Similar to physicochemical treatment facilities, rerouting drainwater to a centralized location would minimize flow to playa wetlands and could lead to reduced habitat.

4.2.4. Constructed Wetlands

A constructed wetland placed at the outflow of a main drain may be a way to help decrease the selenium in drainwater reaching playa wetlands. The constructed wetlands near the Salton Sea achieved selenium mass removal efficiencies of 56% at the Imperial wetland that received agricultural drainwater and 70% at the Brawley wetlands that received water from the New River (Johnson et al. 2009; Tetra Tech 2006). Although the overall configuration of the Imperial wetland was linear and the Brawley wetlands were more compact and sinuous, both wetlands utilized design features such as a sedimentation basin that removed >94% suspended sediment load from the water, vegetated baffles to reduce and direct flow through the constructed wetland system, and vegetated perimeters along each treatment cell to enhance plant contact with the water, thereby enhancing biological processes (i.e., volatilization by plants and microbes; Tetra Tech 2006). Potential elements for a constructed wetland that incorporates selenium removal technologies could include the following.

- Pre-treatment sediment basin: Sediment basins can be effective in capturing sediment-bound selenium and removing >94% of the suspended sediment concentration from the water column (Tetra Tech 2006).
- Floating cattails: Floating cattails could be deployed in sedimentation basins or wetland channels to promote the volatilization of selenium into the atmosphere, uptake by plant tissues, and transformation of selenium by microbes associated with fine roots. This method reported particularly effective removal of selenate and selenite (almost 100% and 95%, respectively) in a ponded mesocosm with a 2-day water residence time with a load of selenium/L (Zhou et al. 2019). These floating cattails mats may be more easily harvested and disposed of compared to rooted vegetation.
- Water control structures: Water control structures to manage water levels, flow, and residence times within each wetland cell would be a useful feature to emulate anaerobic conditions to promote selenate and selenide reduction to elemental selenium, or to dewater cells for biomass removal as necessary.
- Baffle substrate: Vegetated baffle structures have been used in constructed wetlands to help direct flow and increase the contact time between water and vegetation to promote plant uptake, volatilization, and microbial reduction of selenium. Baffles can be made of different substrates including porous compounds to facilitate microbial growth and have been used in subsurface constructed wetlands to improve overall water quality (Cheng et al. 2021; Jain et al. 2023). Although no literature has been published on the efficiency of using different baffle materials specifically for the removal of selenium, this area of research could result in improved wetland design for selenium removal.
- Wetland substrates: similar to baffles, wetland substrates represent a potential to enhance rselenium removal. Substrates can be amended with compounds that enhance selenium adsorption and promote microbial activity to transform selenium to less mobile or less toxic forms (Benis, McPhedran, and Soltan 2022). Some examples of substrates could include iron oxide coated sand or gravel (Jordan et al. 2013), granulated activated charcoal (Arias-Paic et at. 2022), biochar, crushed orange peel (Mafu, Msagati, and Mamba 2014), or facilitate microbial/biofilm growth (i.e., bivalve shells, Yu et al. 2020), which could then facilitate selenium transformation and reduction.

- Vegetation planting: In freshwater marshes, species such as cattail, bulrushes, and duckweed have demonstrated ability to accumulate selenium in plant tissues and/or enhance selenium volatilization to the atmosphere (Nattrass, Morrison, and Baldwin 2022; Pilon Smits et al. 1999; Zhou et al. 2019).

Constructed wetlands are typically considered a passive biological treatment method and are appealing for their ability to remove nutrients and contaminants from the water column while providing wildlife benefits; however, because selenium remains in the plant detritus and soil, periodic management to removal selenium-laden soils, algae, and plants would be required to decrease the selenium risk to wildlife (Tetra Tech 2006; Johnson et al. 2009). In addition to the cost of removal, one of the major impediments to the use of constructed wetlands for selenium removal is that the frequency of sediment, litter, and vegetation removal to minimize selenium hazards to wildlife is largely unknown.

4.2.4.1. *Drain System as Linear Constructed Wetland*

At the Salton Sea, the field and main drains are unlined and often colonized by aquatic vegetation and associated detritus, algae, and microbial mats. In this way, the drains can be considered analogous to a linear treatment wetland. The concept of drains functioning in the capacity of a constructed wetland may facilitate slight changes in current drain management in ways that would enhance selenium removal from drainwater via volatilization, plant uptake, and concentration of selenium in detritus and sediment. The addition of bio-adsorbents or other substrates may increase biofilm and microbial activity to facilitate selenium transformation and reduction.

The accumulation of aquatic vegetation, litter, and sediment can impede water flow, necessitating periodic “drain cleanout.” This process physically removes vegetation biomass, as well as litter and detritus-bound selenium from the system. This existing practice offers a key advantage by removing substantial amounts of selenium prior to reaching playa wetlands. Preventative measures, such as sedimentation curtains may help to mitigate the remobilization and downstream transport of selenium-laden particulates.

Although sedimentation basins are commonly used as a pre-treatment method to reduce suspended particulates in flowing water in constructed wetlands, saturated buffers or bioswales may function in a similar way. These green infrastructure approaches could potentially provide similar benefits as traditional sedimentation basins, although further research would be needed to validate its effectiveness at removing selenium. These approaches could be conducted in partnership with irrigation districts or others in charge of drain management to ensure potential modifications or enhancements to remove selenium from the system would not disrupt on-going agricultural practices.

4.2.4.2. *Water Management*

Using blended water sources to lower selenium inputs in constructed wetlands is an approach that has been actively used in the Salton Sea system. For example, in a 2006 study, a series of four flow-though, shallow saline habitat ponds (SHP) were constructed to examine the ecological risk of restoring wetlands at the Salton Sea using freshwater from the Alamo River blended with salt water from the Salton Sea (Miles et al. 2009). Miles et al. (2009) found that total selenium in sediments was higher at the SHP (1.8 µg/g dry weight) compared to reference sites (1.0 µg/g dry weight), while selenium in water was similar to reference sites (2.2 µg/L; Miles et al. 2009). Black-necked stilts(stilt;

Himantopus mexicanus) were used as an indicator species to determine ecological risk. Although 47% of stilt eggs at the SHP exceeded the predicted 6.0 µg/g egg selenium toxicity threshold during the study, compared to 39% stilt eggs at reference sites, the authors did not detect any relationship between selenium and embryonic malpositioning or post-hatch survival of stilt chicks, or a high frequency of embryonic deformities associated with selenium toxicity. The authors concluded that the blended water SHP habitat could be a viable alternative for restoration of wetlands at the Salton Sea, paving the way forward for larger scale implementation.

Results from Miles et al. (2009) were used in the development of a water management plan for the Salton Sea Species Conservation Habitat Project (SCH Project) located along the southern shore of the Salton Sea. This project will use freshwater inputs from the New River blended with salt water from the Salton Sea to create unvegetated saline impoundments on the exposed playa that support fish and wildlife (Cardno Inc. and Environmental Science Associates 2015). Sickman et al. (2011) used the modeling approach of Presser and Luoma (2010) to predict selenium concentrations in avian eggs under various water management scenarios for the SCH. Based on the results of this modeling effort, salinity in the ponds will be managed to maintain an optimal salinity range between 20 and 40 ppt. These salinity levels are expected to suppress emergent vegetation growth, thereby preventing the buildup of selenium-laden detritus, as well as minimize the input of selenium from drainwater. Experimental operations scenarios will be tested to determine a more specific salinity regime that results in the best balance of invertebrate and fish productivity, bird use, seasonal fish survival, and vegetation and mosquito suppression while minimizing selenium hazards and risks
(Cardno Inc. and Environmental Science Associates 2015).

4.2.5. Playa Wetlands

Although a series of selenium treatment methods may help incrementally remove selenium from water in the linked agriculture and wetland system of the Salton Sea, each method has specific limitations related to cost, scalability, and applicability to the surrounding environment. Thus, it is expected that even with upstream technologies in place, water draining to playa wetlands may have elevated selenium concentrations. In addition, playa wetlands are situated on exposed Salton Sea lakebed soils containing selenium that was previously sequestered underwater in anaerobic conditions (Ricca et al. 2022) and could be remobilized with the addition of water (Byron and Ohlendorf 2007; Schroeder, Orem, and Kharaka 2002). These drain-fed playa wetlands are productive with dense vegetation that can volatilize some selenium, but the vegetation can also die back creating detrital-bound selenium.

4.2.5.1. *Wetland Management Techniques*

Although there are few feasible emerging selenium treatment technologies to apply in playa wetlands themselves due to their inaccessibility and lack of infrastructure, some commonly used wetland management techniques from other areas may inform possible future actions, if any.

For example, in other wildlife management areas, mechanical vegetation removal methods such as discing, mowing, and prescribed burning are often used to thin dense areas of vegetation in managed wetland habitat and create open water areas accessible to waterfowl and other species (De Szalay and Resh 2000; Gray et al. 1973). Current California Department of Fish and Wildlife and U.S. Fish and

Wildlife Service practices to improve densely constructed wetlands for Yuma Ridgway's rail habitat at wildlife refuges in the Salton Sea include mowing, discing, and burning. Similar management actions have been used to improve water quality and lowm er mosquito production. For example, Thullen et al. (2002) found that burning above ground plant parts and thinning rhizomes in shallow zones, while physically removing emergent biomass and sediment to create shallow vegetation hummocks surrounded by deeper water, improved ammonia-nitrogen removal efficiency and reduced mosquito production.

Physical removal of vegetation and sediment is expected to decrease vegetation bound selenium, and burning could mineralize or volatilize selenium; however, few studies have evaluated the effect of these practices on selenium transformation and bioavailability in wetlands. Considerations for physical removal of vegetation include ensuring that plant rhizomes, which are a main selenium storage site for many plant species (Dhillon and Dhillon 2009), also are removed from the site during plant harvesting.

Results from laboratory studies indicate that burning might be applicable for selenium remediation. Liu et al. (2019) conducted microcosm studies and found that burning microalgae-laden selenium to ashes reduced the biomass of selenium by 99%, and moreover organo-selenium was entirely converted to inorganic selenium, lowering its bioavailability.

Our extensive literature review revealed no studies specifically examining the effects of burning wetland systems on selenium bioavailability. Existing research on the effects of burning on selenium is limited, primarily focusing on terrestrial systems. The burning process can affect physical and chemical properties several centimeters below the soil surface. High soil temperatures may kill soil microbes and plant roots, change soil organic matter content, and affect soil nutrient content as well as water holding capacity (Natali et al. 2023; Terzano et al. 2021), all of which may have implications for selenium bioavailability. Beyene et al. (2023) assessed the effects of fire intensity on trace element loading into watersheds by comparing concentrations of selenium and other contaminants in streams draining areas affected by wildfires and prescribed fires in the Western United States. They observed significant increases in trace element concentrations in streams burned by large, high-severity wildfires, while they found no change in streams draining watersheds where lower-intensity prescribed fires occurred. Significant drivers of post-fire trace element concentrations in streams were burn area, burn severity, post-fire weather, surface lithology, watershed physiography, and land cover. This study measured total selenium in water but did not consider selenium transformation or speciation, thus it was not clear whether selenium became more bioavailable after a terrestrial burn. The authors noted that prescribed burns may help lessen the effect of intense wildfires on trace element concentrations by limiting the vegetation buildup that fuels fires. Potential effects on human health from smoke and volatilized selenium are considerations for any use of fire to manage wetlands.

4.3. Data Gaps and Limitations

Our review focused on recent technological advances and management actions that may have potential to remove selenium from the Salton Sea environment and thereby lower selenium associated hazards for fish and wildlife. Several of the identified physicochemical and biological technologies and management actions have associated data gaps and limitations that influence their applicability, scalability, and cost-effectiveness for the Salton Sea.

4.3.1. Physicochemical

Many of the recent advances in selenium removal have been achieved through physicochemical processes. Overall, most physicochemical treatments had high applicability scores in our ranking system (Appendix A-1), but several had lower cost-effectiveness and scalability scores. Research efforts to evaluate lower material costs, improve process efficiencies, and reduce the overall footprint of treatment facilities could fill data gaps and potentially identify ways to make technologies in this category more feasible for use in the Salton Sea. Physicochemical treatments are most often implemented in large-scale treatment plant facilities that would require placement in a central location with large throughputs of water, which may reduce water flow to playa wetlands. A major data gap is the identification of optimal locations for these facilities that balance the need to process water at one site with the need to maintain playa wetland habitat for endangered and trust species.

In addition, for many physicochemical technologies specific data gaps remain. For example, many new adsorption technologies have not been tested with agricultural drainwater, which contains multiple constituents that could compete with selenium for adsorption sites. Furthermore, nitrates can inhibit selenate reduction (Hunter and Manter 2009; Schiavon and Pilon-Smits 2017), while the presence of iron may facilitate the coagulation of selenides (Wang et al. 2018). Thus, the efficacy of these new methods for application to agricultural drainwater at the Salton Sea is unclear. Membrane technologies are some of the most effective for selenium removal, but several types of membranes need pressurized systems that consume large amounts of energy. To date little research has addressed this limitation, but resolving this could fill an important data gap.

Permeable reactive barriers have been used successfully in tandem with constructed wetlands to remediate heavy metals, but this technology has only been tested in the laboratory for selenium removal and thus its feasibility for this application warrants further investigation. Scaling-up for testing and monitoring in the field could improve our understanding of how well permeable reactive barriers would perform for selenium remediation in the Salton Sea system.

4.3.2. Biological

Many biological treatment methods for the removal of selenium have been explored in the laboratory or at the mesocosm scale or in more controlled environments such as wastewater treatment facilities. Despite many advancements in our understanding of selenium movement, speciation, and bioavailability, substantial data gaps remain regarding biological treatment effectiveness at larger scales and applicability in agricultural settings.

Bioreactors such as the algal-bacterial selenium removal system or the granular activated carbon bioreactor are composed of a suite of controlled processes within a treatment plant. Although bioreactors are capable of removing substantial amounts of selenate and selenite by encouraging microbial activity, they often scored relatively low on scalability and at times lacked information regarding cost-effectiveness because secondary treatment is required to remove small nanosized particles of elemental selenium (Dessì et al. 2016; Appendix A-1). Information on whole system costs would improve the ability to assess cost effectiveness.

For areas that lack the infrastructure (or ability to incorporate infrastructure) for a bioreactor, future studies that integrate more passive treatment options, such as a constructed wetland, may yield promising results. Constructed wetlands include surface flow and subsurface flow types. For surface flow constructed wetlands, there is a need to integrate different technologies at the whole systems scale. For example, a sedimentation basin is a common component of a constructed wetland, which could be designed to support floating cattail islands to enhance selenium removal. Selenium removal may also be improved using a suite of different carbon amendments or substrates to enhance microbial volatilization or selenium reduction to less harmful forms. One of the major impediments to the use of surface flow in constructed wetlands for selenium removal is that the selenium becomes concentrated in detritus and sediment, requiring its removal to minimize selenium hazards to wildlife. The frequency of the removal of plant biomass, detritus, sediment needed is largely unknown. Other ways to discourage wildlife use, such as nets, could also be explored. Subsurface constructed wetlands are another option where the water is treated below the ground, which would help mitigate the impacts to wildlife. However, subsurface treatment wetlands rely on the efficacy of membrane or natural media to bind selenium and facilitate microbial transformation to less bioavailable forms. The longevity of the media prior to being replenished is largely unknown, although pre-treatment to remove suspended sediments can help reduce clogging of the media. Ultimately exploring new hybrid systems and innovative designs that highlight overall treatment efficiency, adaptability and sustainability may be warranted to fit local needs and limitations.

4.3.3. Potential management actions

We have highlighted several existing and potential agricultural and wetland management practices that may have affect selenium transformation and bioavailability at the Salton Sea; however, in most cases there is not a clear understanding of the direction and magnitude of such effects. Some of these potential actions that could be applied at the field level include installation of a saturated buffer zone, minimizing evaporative loss, and managing soil amendments. Although research has progressed in each of these areas, several data gaps related to application in the Salton Sea system remain. Research to evaluate what soil amendments affect selenium bioavailability or plant growth, and what microbes might enhance selenium uptake could help advance our understanding of the feasibility of such management actions. Additionally, considerations include how agricultural operations may be affected.

Also unclear is the role of drain management in selenium remediation. Existing practices include clearing main or collector drains of vegetation and sediment to improve flow (Fig. 5). Although such management actions have the potential to remove selenium from drainwater, it is unknown if they may also remobilize sediment bound selenium in the system and if modifications in clean-out timing, methodology, or drain infrastructure may influence selenium mobilization or speciation.

The U.S. Fish and Wildlife Service and California Department of Fish and Wildlife manage wetland parcels at the Salton Sea for wildlife specific needs. Management practices in these constructed wetlands include the use of Colorado River water (not agricultural drainwater) as well as vegetation management practices such as mowing, discing, and burning vegetation (Fig. 5). Although some studies have shown these vegetation practices can improve water quality by reducing nutrient loads in wetlands, it is unclear what their effect is on selenium chemistry and bioavailability, and whether these types of management activities also would be feasible on unmanaged playa wetlands. We found no studies that looked at the effects of mowing and discing on selenium biogeochemistry. Most previous work on the effects of burning on selenium come from laboratory or terrestrial studies, thus whether burning wetlands could result in selenium removal from aquatic plants and sediments is unclear. Studies that measure selenium mass balance and bioavailability in playa wetlands before and after actions such as mowing or burning could elucidate the effects of these existing practices. In addition, evaluation of the effects of parameters such as water level, burn temperatures, or time of year on selenium transformations as a result of managem0ent actions could improve the ability of managers to adjust practices to help achieve desired selenium remediation in playa wetlands.

4.3.4. Waste Disposal

Most of the physicochemical and biological treatment technologies discussed in this review produce selenium laden waste products that must be contained or disposed of to prevent reintroduction into the environment. A major data gap for each of these technologies is how to achieve sustainable disposal strategies. Given that selenium is both an essential nutrient and a widely used industrial raw material, recycling and reusing selenium by-products has become an important research topic. In addition to the use of phytoremediation products in biofortification processes as discussed above, selenium containing sludge from bioreactors has been used to produce selenium-fortified fertilizer, whereas selenite by-products from treatment methods have been used in semiconductors, and elemental selenium has been used for adsorption of heavy metals such as mercury (Li et al. 2022). Although important advances have been made in recent years, there are still many knowledge gaps to fill to close the selenium treatment and management cycle.

5.0 Conclusions

Selenium contamination is a persistent problem in the Salton Sea environment that can create hazards for wildlife. Selenium originates in the Colorado River and is concentrated through evaporation and evapotranspiration in agricultural fields, leading to high concentrations in drainwater that flows to playa wetlands. In wetland systems, selenium can be transformed or temporarily stored in detrital, sediment, and aquatic pools, and can be bioaccumulated in wetland food webs. In this review, we summarized recent advances between 2012 and 2024 in selenium removal technologies and their feasibility for use in the Salton Sea system to help lessen hazards for trust species. We described physicochemical and biological treatment options, with particular attention on studies conducted since 2012, and developed a scoring system to quantify how each technology might perform at the Salton Sea based on applicability, scalability, and cost-effectiveness. Finally, we evaluated how and where some recent technologies might be used in tandem with management actions at the Salton Sea to help reduce selenium hazards and we identified data gaps to inform future efforts.

We found that many of the recent technical advances in selenium removal have been made in the wastewater or mining industries using both physicochemical and biological methods for physical separation of selenium or reduction to less toxic forms. Physicochemical advances have been propelled by new materials for improvements in adsorption and membrane filtration processes as well as experimentation with novel reducing agents such as zerovalent iron (Appendix A-1). Advances in biological treatments include expansion of bioreactor capabilities through use of newly discovered microbe species and carbon sources to enhance selenium reduction, and the application of this technology to agricultural systems has now been tested in California (Arias-Paic et al. 2022). Other advances in biological treatments include macroalgal remediation in drain flow-ways, experimentation with floating cattails and other vegetation to improve selenium volatilization in constructed wetlands (Appendix A-1). Through our ranking process, we identified that several of these new methods show promise for adaptation to the Salton Sea environment, while others may be difficult to scale to the appropriate size or may not be cost-effective in their current form.

The complexity of selenium dynamics in the linked Salton Sea agricultural and playa wetland system indicates that a combination of treatment and management approaches, including those that target source reduction as well as transformation of selenium into less harmful or more disposable forms, may produce the most effective results. An integrated approach could include field management practices, novel techniques for removing selenium from water in drains, constructed wetlands to encourage selenium volatilization, and application of existing management practices to remove detritus from playa wetlands. Although a stepwise effort such as this may reduce total selenium in the system, the reduction of bioavailable selenium will be necessary to achieve the goal of reducing hazards to Salton Sea biota, including the endangered Yuma Ridgway's rail and desert pupfish.

It is important to recognize that enacting tailored treatment and management methods for successful selenium reduction may require on-going engagement with local communities, industries, and policymakers. Adaptive management strategies that incorporate stakeholder input and continuous monitoring would enable flexibility and be vital for effectively addressing the challenges posed by changing environmental conditions at the Salton Sea. Several data gaps regarding methods remain that would benefit from integrated studies to identify best practices for selenium remediation at the Salton Sea. Given the projected growth of drain-fed playa wetlands in the region and potential selenium hazards for fish and wildlife using them, targeted stakeholder actions that use innovative new technological and management solutions to remediate selenium offer the opportunity to reduce hazards to biota as the Salton Sea region evolves.

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Appendix A-1 Treatment Technology Evaluations

Biological or physicochemical selenium treatment or removal methods and technologies potentially applicable to Salton Sea playa wetlands, published from 2013 through 2023, with additional older citations included where applicable. Cost-effectiveness, scalability, and applicability measures were used to evaluate a final score indicating viability for use in the Salton Sea. Abbreviations: Activated carbon - AC; nZVI – nano zero-valent iron; Selenium – Se; Selenite – Se(IV); Selenate – Se(VI); Selenocysteine – SeCys; Selenomethionine – SeMet; ZVI – zero-valent iron. 1mM = 0.0788g/L where M = Molality of Se. The molality of a solution is the number of moles of solute dissolved in 1 kg of solvent. A mole (mol) is a unit of measurement that represents the exact quantity (6.022 x 10^23 or Avogadro's number) of atoms of selenium.

Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Activated Carbon	Adsorption	Granular activated carbon; laboratory	Se(VI)	5 mg/L	95%	4, 6	3	5	4	82	Okonji et al. 2020
Activated Carbon	Adsorption	Granular activated carbon; laboratory	SeMet SeCys	5 mg/L	SeCys 96.1% SeMet 86.7%	4, 7, 9	3	3	5	80	Okonji et al. 2021
Activated Carbon	Adsorption	Copper impregnated activated carbon; mixing with $CuCl_2$ solution, filtration, drying	Se(IV) Se(VI)	1 mg/L	0.25 mg/g	7	3	3.5	5	83	Jegadeesan, Mondal, and Lalvani 2015
Activated Carbon	Adsorption	Magnetite impregnated activated carbon; mixing w/ $FeCl_2$ and $FeCl_3$ solution, drying	Se(IV)	20 μg/L	0.04 mg/g	6	3	3.5	4	73	Kwon, Wilson, and Sammynaiken 2015
Activated Carbon	Adsorption	Iron oxide-impregnated granular AC; mixing AC w/ $FeCl_2$ solution under N_2 atmosphere, adding NaClO solution, washing, drying	Se(IV) Se(VI)	1 - 4 mg/L	Se(IV) 0.93 mg/g Se(VI) 3.06 mg/g	5	3	2	3	54	Yan et al. 2013
Activated Carbon	Adsorption	Iron oxide-impregnated granular AC; mixing w/ FCl_2 under N_2 atmosphere, adjusting pH to 4.3, adding NaOCl solution, washing, drying	Se(VI)	1 mg/L	0.48 mg/g	5	3	2	3	54	Zhang et al. 2018

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Activated Carbon	Adsorption	Cu-coated activated carbon from artificial water	Se(VI)	-	88%	6	3	3.5	4	73	Zhao et al. 2020
Algae	Algae	Periphytic algae flow-way in Salton Sea	Se total	-	0.071 $mg/m^2/day$	8 to 9	5	4.5	4.5	92	Hennequin et al. 2022
Algae	Algae	Filamentous macroalgae (*Oedogonium* sp.) as biosorbent	Se(VI)	82 µ/L	84.14%	4	4.5	3	2	56	Kidgell et al. 2014
Algae	Algae	Microcosm experiment using algae (*Chlorella vulgaris*) to remove Se; algae then burned to volatilize Se; post-algae water filtered by bivalves (*Anodonta woodiana*) to remove remaining Se	Se(IV) Se(VI) SeMet	500 - 8000 µg/L	51 - 90%	6.5, 8, 10	-	3.5	5	-	Liu et al. 2019
Binary iron-based	Adsorption	Fe-Al binary oxide; mixing $FeCl_3$ and $AlCl_3$ solutions, adding NaOH, filtration, washing, drying, grinding, sintering	Se(VI)	100 mg/L	79.2 mg/g	6	3	1.5	4	61	Hong et al. 2017
Binary iron-based	Adsorption	Iron oxide-carbon nanotubes composite; washing with HNO_3, filtration, washing, drying, adding the mixed solution of $FeCl_3$ and $FeSO_4$, adding NaOH, washing, drying	Se(IV) Se(VI)	5 - 100 mg/L	Se(IV) 13.1 mg/g Se(VI) 6.13 mg/g	-	3	1	-	-	Lee and Kim 2016
Binary iron-based	Adsorption	Al@Fe-MOF; mixing $FeCl_3$ and H_3BTC, heating, washing, adding to $AlCl_3$ solution, heating, washing, drying	Se(IV)	0 - 200 mg/L	75.3 mg/g	3 to 7	3	1	-	-	Wang et al. 2019
Binary iron-based	Adsorption	Layered double hydroxide coated ZVI; mixing ZVI and $AlCl_3$ solution	Se(VI)	15 mg/L	35.0 mg/g	-	3	4	-	-	Xu and Huang 2019
Binary iron-based	Adsorption	Fe-Mn double oxide; mixing $Mn(NO_3)_2$ and $Fe(NO_3)_3$ solutions, adding Na_2CO_3, adding NaOH, heating, drying, calcination	Se(IV)	-	55.3 mg/g	-	3	2	-	-	Otgonjargal et al. 2019
Binary iron-based	Adsorption	$CuFe_2O_4$; mixing $Cu(NO)_2$ solution with $Fe(NO_3)_3$ solution, heating, drying, washing	Se(IV) Se(VI)	1 - 25 mg/L	Se(IV) 14.1 mg/g Se(VI) 5.97 mg/g	-	3	3	-	-	Sun et al. 2015

Appendix A-1.

Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Binary iron-based	Adsorption	$CoFe_2O_4$; mixing $Co(NO_3)_2$ solution with $Fe(NO_3)_3$ solution, heating, drying, washing	Se(IV) Se(VI)	1 - 25 mg/L	Se(IV) 11.6 mg/g Se(VI) 5.55 mg/g	-	3	3	-	-	Sun et al. 2015
Binary iron-based	Adsorption	$MnFe_2O_4$; mixing $MnCL_2$ solution with $Fe(NO_3)_3$ solution, heating, drying, washing	Se(IV) Se(VI)	1 - 25 mg/L	Se(IV) 3.90 mg/g Se(VI) 5.27 mg/g	-	3	3	-	-	Sun et al. 2015
Binary iron-based	Adsorption	Fe(III)-Mn(III) hydrous oxides; mixing F and iron(II) and manganese(II) solutions, hydrothermal decomposition in the presence of urea	Se(IV) Se(VI)	5 - 500 mg/L	Se(IV) 41.0 mg/g Se(VI) 19.8 mg/g	4	3	3.5	2	53	Chubar 2014; Szlachta and Chubar 2013
Binary iron-based	Adsorption	Fe-bentonite; mixing with Fe or Al solution, drying, calcination	Se(IV)	3.5 mg/L	71.9 mg/g	3	3	3.5	1	43	Wang et al. 2015
Binary iron-based	Adsorption	FeOOH-bentonite; mixing with Fe or Al solution, drying, calcination	Se(IV)	3.5 mg/L	113 mg/g	3	3	3.5	1	43	Wang et al. 2015
Binary iron-based	Adsorption	AlOH-bentonite; mixing with Fe or Al solution, drying, calcination	Se(IV)	3.5 mg/L	60.1 mg/g	3	3	3.5	1	43	Wang et al. 2015
Biomass and biochar	Adsorption	*Ganoderma lucidum* biomass from artificial waters	Se(VI)	-	126.99 mg/g	5	5	5	3	80	Nettem and Almusallam 2013
Biomass and biochar	Adsorption	Olive mill solid waste biochar; sieving, pyrolysis	Se(VI)	50 pp	≤8%	5.2	5	4	4	84	Abdelhadi et al. 2017
Biomass and biochar	Adsorption	Commercial biochars	Se(IV)	0.9 mM	0.32 mg/g	4.5	5	5	2.5	75	Clemente et al. 2017
Biomass and biochar	Adsorption	Macroalgae biochar	Se(VI)	0.1 mg/L	14.9 mg/g	-	5	5	-	-	Johansson et al. 2015
Biomass and biochar	Adsorption	Starch biochar; mixing starch and $FeCl_3$ solution, drying, pyrolysis at 500°C	Se(VI)	0.1 - 6 mg/L	0.63 mg/g	-	5	3.5	-	-	Minzatu et al. 2019
Biomass and biochar	Adsorption	*Aspergillus* sp. J2	Se(IV)	-	5.67 mg/g	4 to 10.7	5	4	2 to 5	-	Li et al. 2013
Biomass and biochar	Adsorption	*Gracilaria* sp. seaweed waste biomass from wastewater	Se(VI)	-	2.72 mg/g	2.5 to 8	5	3.5	1 to 5	-	Roberts et al. 2015
Biomass and biochar	Adsorption	Rigid silica cell wall of diatom used to synthesize a composite by immobilizing Zr and Fe	Se(IV)	-	227 mg/g	8	5	1	5	76	Thakkar and Mitra 2017

Appendix A-1.

Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
		oxides on its surface and in pores; from artificial water									
Biomass and biochar	Adsorption	Poly(allyltrimethylammonium) grafted chitosan and biochar composite; mixing chitosan with biochar, adding allyltrimthylammonium chloride, adjusting pH to 6-7, drying, crushing, sieving	Se(VI)	0 - 500 mg/L	99.0 mg/g	-	5	2.5	-	-	Zhang et al. 2021
Biomass and biochar	Adsorption	*Lemna minor* aquatic weed biomass	Se(VI)	0.02 mg/L	0.002 mg/g	6	5	5	4	90	Rodríguez-Martínez et al. 2016
Biomass and biochar	Adsorption	*Eichhornia crassipes* aquatic weed biomass; washing with water and HCl, solution, drying, grinding	Se(VI)	0.02 mg/L	0.00085 mg/g	6	5	3	4	78	Rodríguez-Martínez et al. 2016
Biomass and biochar	Adsorption	Iron-impregnated wheat straw biochar; Mixing commercial biochar with $Fe(NO_3)_3$ solution, heating	Se(VI)	10 - 300 mg/L	14.9 mg/g	5	5	4	3	74	Godlewska et al. 2020
Biomass and biochar	Adsorption	Iron-impregnated food waste biochar; squeezing, drying, grinding, mixing with $FeCl_3$ solution, drying, pyrolysis	Se(VI)	100 - 300 mg/L	11.7 mg/g	-	5	2.5	-	-	Hong et al. 2020
Biomass and biochar	Adsorption	Iron-impregnated cattle manure biochar; mixing cattle manure with $FeCl_3$, drying, pyrolysis	Se(VI)	5 - 700 mg/g	55.6 mg/g	7	5	3.5	5	91	Lee et al. 2021
Biomass and biochar	Adsorption	Iron-impregnated wood chips biochar; pyrolysis at 550C, drying, sieving, mixing with $Fe(NO_3)_3$ solution, drying	Se(VI)	490.4 mg/L	8.30 mg/g	-	5	3	-	-	Satyro et al. 2021
Biomass and biochar	Adsorption	Iron-impregnated wood chips steam-activated biochar; pyrolysis at 550C, steam activation at 1200°C, drying, sieving, mixing with $Fe(NO_3)_3$ solution, drying	Se(VI)	490.4 mg/L	5.90 mg/g	-	5	2	-	-	Satyro et al. 2021
Biomass and biochar	Adsorption	Ferrihydrite-loaded magnetic sugar cane bagasse biochar; washing biomass, drying, mixing with $FeCl_3$ solution, drying, mixing with deionized	Se(IV)	12 - 120 mg/L	95.1 mg/g	3	5	1.5	1	39	Xin et al. 2021

Appendix A-1.

Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
		water, adjusting pH to 7-8, drying, pyrolysis at 500°C									
Bioreactor	Microbial or Algal	Algal-Bacterial Selenium Removal (ABSR) demonstration facility. The addition of molasses or algae as carbon source for bacterial reduction enhanced Se removal. Dissolved air flotation clarification with ferric chloride coagulant may be needed to remove residual selenite and particulate selenium from effluent	Se(VI)	variable for drainwater influent, mean 431 µg/L	2 year removal rate: 45% in low cost mode; 80% in high-removal efficency mode	-	4	4	-	-	Quinn et al. 2000
Bioreactor	Micro-organisms	Fungal-pellet bioreactor (*Phanerochaete chrysosporium*)	Se(VI)	-	70%	4.5	-	1	2.5	-	Espinosa-Ortiz et al. 2015
Bioreactor	Micro-organisms	Inverse fluidized bed bioreactor	Se(IV)	-	98%	7	-	1	5	-	Sinharoy, Saikia, and Pakshirajan 2019
Bioreactor	Micro-organisms	Full-scale anaerobic granular activated-carbon bioreactor on agricultural drainage water with downstream ultrafiltration membrane system	Se total	111 - 332 µg/L	97 - 99%	6.6	3	4	5	86	Arias-Paić et al. 2022
Clay minerals	Adsorption	Al-modified bentonite from artificial water	Se(IV)	-	60.1 mg/g	3	4	2.5	1	41	Albukhari, Salam, and Abukhadra 2021
Clay minerals	Adsorption	Tamusu clay; grinding, sieving	Se(IV)	0.5 - 5 mg/L	0.32 mg/g	7.8	4	4	5	90	He et al. 2019
Coagulation	Coagulation	Sequestration of dissolved Se(IV) via co-precipitation in barite for range of concentrations in near-neutral pH	Se(VI)	0 - 8650 mg/L	>99%	5.5 to 6.5	-	-	4	-	Das, Essilfie-Dughan, and Hendry 2020
Coagulation	Coagulation	UV light pre-treatment in combination with sulfite to reduce selenate to selenite, iron coagulant to remove the resulting selenite. Hydrated electron reduction for Se(VI) removal from sulfate-rich water (1000 mg/L SO_4^{2-})	Se(IV) Se(VI)	1000 mg/L	>99%	7 to 11	3	3	5	80	Wang et al. 2018

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Constructed wetland	Constructed Wetland	Organic amendments (cattail and reed litter) and porous media (gravels and clamshells) on Se removal efficiency of horizontal subsurface flow constructed wetlands	Se(IV)	300 μg/L	96.3%	6 to 7	5	3.5	5	91	Yu et al. 2020
Constructed wetland	Constructed Wetland	Floating-leaved macrophyte (Nymphoides) mesocosm after 21 days. After treatment, 74.4% of selenium concentrations was in the sediment, 24% in plants, and 1.5% in biota (fish and snails)	Se(IV)	600 mg/L	40.4%	-	5	3	-	-	Zhou et al. 2019
Electrochemical reduction	Electrochemical reduction	Direct electrochemical reduction with moderate heating (80°C)	Se(IV)	0.001 - 10 mM	95%	4 to 7	3	4	5	86	Zou and Mauter 2021
Electro-coagulation	Electro-coagulation	Electrocoagulation of colloidal biogenic selenium using Fe electrodes	Se0	310 mg/L	93%	7	3	4	5	86	Staicu et al. 2015
Graphene-based adsorbents	Adsorption	Graphene oxide hydrogel beads; injecting the mixed solution of chitosan-polyethylenimine-graphene oxide to NaOH solution, separation, washing	Se(IV)	5 - 250 mg/L	1.62 mg/g	-	3	3	-	-	Bandara et al. 2019
Graphene-based adsorbents	Adsorption	Poly allylamine-modified magnetic graphene oxide; mixing potassium phosphate solution with suspension, dialysis freeze-drying, dropwise adding to $FeCl_2$/$FeCl_3$/HCl solution	Se(IV) Se(VI)	4 mg/L	Se(IV) 120 mg/g Se(VI) 83.7 mg/g	5.8	3	2.5	4	67	Lu et al. 2017
Graphene-based adsorbents	Adsorption	Dendrimer functionalized graphene oxide (GO); mixing 3-aminoproplytriethoxysilane with GO solution, filtration, washing, drying, mixing with methanol, adding methylacrylate, centrifugation, washing, drying	Se(IV) Se(VI)	40 mg/L	Se(IV) 60.9 mg/g Se(VI) 77.9 mg/g	6	3	0.5	4	55	Xiao 2015
Iron oxides	Adsorption	Fe_3O_4; laboratory	Se(IV) Se(VI)	5 mg/L	Se(IV) 84.5% Se(VI) 99.9%	4, 6	3	5	4	82	Okonji et al. 2020

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Iron oxides	Adsorption	FeOOH nanoparticles; hydrolysis of $FeCl_3$	Se(IV) Se(VI)	-	Se(IV) 95.0 mg/g Se(VI) 15.1 mg/g	4	3	4.5	2	59	Zelmanov and Semiat 2013
Iron oxides	Adsorption	Green rust; mixing $FeSO_4$ and $Fe_2(SO_4)_3$ solutions, titration with NaOH, centrifuging, washing	Se(IV) Se(VI)	500 mg/L	Se(IV) 29.7 mg/g Se(VI) 29.0 mg/g	8	3	2.5	5	77	Onoguchi et al. 2019
Iron oxides	Adsorption	α-FeOOH nanorods; adding NaOH solution to FeCl3 solution, stirring at 60C, filtration, drying	Se(VI)	-	4.75 mg/g	7.2	3	2.5	5	77	Amrani et al. 2020
Iron oxides	Adsorption	Fe_5OH_3; adjusting pH of $FeCl_3$ solution to between 7 and 8 with KOH	Se(VI)	1 mM	71 mg/g	5	3	4	3	66	Favorito, Eick, and Grossl 2018
Iron oxides	Adsorption	α-FeOOH; natural goethite	Se(IV)	50 - 250 μg/L	7.74 mg/g	4	3	5	2	62	Jacobson and Fan 2019
Iron oxides	Adsorption	γ-FeOOH; Adding solution to $FeCl_3$ solution, filtration, washing, drying	Se(VI)	0.3 - 10 mg/L	40.1 mg/g	-	3	3	-	-	Jadhav et al. 2020
Iron oxides	Adsorption	α-Fe_2O_3; mixing $FeCl_3$ solution with NaOH solution, heating	Se(IV) Se(VI)	50 μM	Se(IV) 7.26 mg/g Se(VI) 2.86 mg/g	5.5	3	3.5	3.5	68	Jang, Pak, and Kim 2015
Iron oxides	Adsorption	ɤ-Fe_2O_3; commercial	Se(VI)	0.0005 M	70%	7.5	3	5	5	92	Jordan et al. 2013
Iron oxides	Adsorption	ɤ-Fe_2O_3; commercial	Se(IV)	0.0005 M	5.72 mg/g	11	3	5	2	62	Jordan et al. 2014
Iron oxides	Adsorption	Iron oxy-hydroxides from natural waters	Se(IV) Se(VI)	-	Se(IV) 4.3 mg/g Se(VI) 10 μg/g	2 to 9	3	1 to 5	1 to 5	-	Kalaitzidou et al. 2019
Iron oxides	Adsorption	FeOOH; oxidation-hydrolysis of $FeSO_4$-H_2O	Se(IV)	100 - 1000 μg/L	3.6 - 23.0 mg/g	6 to 7	3	4	4.5	81	Kalaitzidou, Zouboulis, and Mitrakas 2020; Kalaitzidou et al. 2019
Iron oxides	Adsorption	α-FeOOH;Mixing $Fe(NO_3)_3$ solution w/ NaOH solution under CO_2 atmosphere, aging at 90°C	Se(VI)	0.1 mM	5.72 mg/g	3	3	3	1	40	Kersten and Vlasova 2013

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Iron oxides	Adsorption	α-Fe_2O_3; adding $Fe(NO_3)$ solution to boiling water, cooling, freeze drying	Se(IV) Se(VI)	0.2 mg/L	Se(IV) 17.9 mg/g Se(VI) 7.47 mg/g	6.5	3	3.5	4.5	78	Lounsbury et al. 2016
Iron oxides	Adsorption	α-Fe_2O_3; co-precipitation method under basic conditions	Se(IV)	1 - 120 mg/L	15.3 mg/g	7	3	4.5	5	89	Ma et al. 2018
Iron oxides	Adsorption	α-Fe_2O_3; heterogeneous nucleation technique; hematite coated magnetic nanoparticle from water	Se(IV)	1 - 120 mg/L	97%	7	3	4	5	86	Ma et al. 2018
Iron oxides	Adsorption	α-FeOOH; neutralizing $Fe(NO_3)$s solution with NaOH solution, aging, dialysis	Se(IV)	0.25 mM	29.0 mg/g	5	3	3	3	60	Nie et al. 2017
Iron oxides	Adsorption	α-Fe_2O_3; commercial	Se(IV)	10 mg/L	5.33 mg/g	5	3	5	3	72	Xu et al. 2020
Iron oxides	Adsorption	α-Fe_2O_3; mixing $FeCl_3$ and NaOH solutions, adjusting pH to 5, heating (130°C)	Se(IV) Se(VI)	-	Se(IV) 11.9 mg/g Se(VI) 10.0 mg/g	6	3	3	4	70	Yue et al. 2020
Iron oxides	Adsorption	α-FeOOH; adding KOH solution to $FeCl_3$ solution, heating (60°C), freeze drying, grinding	Se(IV) Se(VI)	-	Se(IV) 25.8 mg/g Se(VI) 6.3 mg/g	3	3	2.5	1	37	Yue et al. 2020
Membrane	Membrane	Na^+ modified carbon quantum dot incorporated thin-film nanocomposite membrane with ultrafine size (3.2 nm) for rejection of Se(IV) and Se(VI)	Se(IV) Se(VI)	1000 mg/L	Se(IV) 97.5% Se(VI) 98.2%	8.6	3	4	4	76	He, Zhao, and Chung 2018
Membrane	Membrane	Nanofiltration polyamide core shell biofunctionalized matrix membrane of novel composite materials	Se(IV)	100 μg/L	98%	5, 7, 9	3	3.5	5	83	Zeeshan et al. 2020
Microorganisms	Micro-organisms	*Saccharomyces cerevisiae* from artificial water	Se(IV)	-	96.1%	5	-	-	3	-	Khakpour, Younesi, and Mohammadhosseini 2014
Microorganisms	Micro-organisms	Accumulation and transformation by cyanobacterium *Microcystis aeruginosa* followed by combustion	Se(IV) Se(VI)	1000 μg/L	Se(IV) 59% Se(VI) 82%	-	3	4	-	-	Zhou et al. 2021

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Microorganisms	Microorganisms	Rhodocyclaceae (A*zospira oryzae* and Rhizobium s)	Se(VI)	-	99%	7	-	-	5	-	Zhang et al. 2020
Microorganisms	Microorganisms	Upflow anaerobic sludge blanket reactor	Se(IV)	-	94.40%	7.3	4	2.5	5	81	Dessì et al. 2016
Microorganisms	Microorganisms	Burkholderia strains; cytoplasmic enzymatic activation mediated by electron donors	Se(IV)	-	75%	7	-	-	5	-	Khoei et al. 2017
Microorganisms	Microorganisms	Biotransformation (*Stenotrophomonas maltophilia* SeITE0); cytoplasmic enzymatic activation mediated by electron donors	Se(IV)	-	100%	8	-	-	5	-	Khoei et al. 2017
Microorganisms	Microorganisms	Novel Cronobacter strain THL1	Se(IV)	-	100%	7.5	-	-	5	-	Nguyen et al. 2016
Microorganisms	Microorganisms	Microbial reduction in up-flow anaerobic fluidized bed reactor	Se(IV) Se(VI)	-	100%	4	-	1	2	-	Yan et al. 2020
Microorganisms	Microorganisms	Volatilization (*Pseudomonas stutzeri*)	Se(VI)	-	82%	9	5	5	4	90	Kagami et al. 2013
nZVI	Adsorption	nano zero-valent iron (nZVI); laboratory	SeMet SeCys	5 mg/L	SeCys 39.4% SeMet <1.1%	4 to 5.5	3	3	3	60	Okonji et al. 2021
nZVI	Adsorption	nano zero-valent iron (nZVI); laboratory	Se(VI)	5 mg/L	99%	4, 6	3	5	4	82	Okonji et al. 2020
Other adsorbents	Adsorption	Calcium-alginate-citrus peels composite; drying, crushing, grinding, sieving, washing with HNO_3, mixing with $C_6H_7NaO_6$, adding $CaCl_2$, filtration, drying	Se(IV)	2 - 100 mg/L	112 mg/g	-	2	-	-	-	Dev et al. 2020
Other adsorbents	Adsorption	Exfoliated kaolinite sheets/cellulose fibers composite; mixing and homogenizing the mixture solution of exfoliated kaolinite sheets and cellulose fibers, sonication	Se(VI)	25 - 300 mg/L	138 mg/g	-	2	-	-	-	Abukhadra et al. 2021
Other adsorbents	Adsorption	Aqueous solution using zwitterionic glycine intercalated layered double hydroxide (Gly-LDH); mixing $Ni(NO_3)_2$, $Al(NO_3)_2$ and glycine solutions,	Se(VI)	30 - 1000 mg/L	209 mg/g	-	2	-	-	-	Asiabi, Yamini, and Shamsayei 2017

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
		adding NaOH, heating, washing, drying									
Other adsorbents	Adsorption	Amine- and thiol-functionalized mesoporous silica; modifying the surface of SBA-15 type silica material w/ 3-amino propyltriethoxysilane	Se(VI)	0.2 - 500 mg/L	79 mg/g	-	2	-	-	-	Dobrzyńska 2021
Other adsorbents	Adsorption	Poly(1,8-DAN); dissolving 1.8-DAN in CH_3CN solution, adding to persulfate solution, filtration, washing, drying	Se(IV)	10 - 200 mg/L	75.2 mg/g	-	2	-	-	-	Fındık, Gülfen, and Aydın 2014
Other adsorbents	Adsorption	Fe_3O_4-chitosan nanocomposite hollow fiber; soaking fiber in $FeCl_3$ solution, washing, soaking in $FeSO_4$ solution, washing, soaking in NaOH solution, washing, drying	Se(IV)	50 - 450 μg/L	15.6 mg/g	-	2	-	-	-	Seyed Dorraji et al. 2017
Other adsorbents	Adsorption	Polyethyeneimine-based resin; mixing polyethyleneimine and glutaraldehyde solutions, freeze-drying	Se(VI)	-	751 mg/g	2	2	-	1	-	Wang et al. 2020
Other adsorbents	Adsorption	Acrylic amine fiber; mixing acrylic fiber w/ tetraethylenepent-amine, washing, drying	Se(IV) Se(VI)	5 - 79 mg/L	Se(IV) 256 mg/g Se(VI) 159 mg/g	-	2	-	-	-	Wei et al. 2021
Other adsorbents	Adsorption	DSDH immobilized onto monolith; mixing 3,4-diamino-5-hydroxypyrazole, 3-formylbenzoic acid, ethanol, and acetic acid, heating, filtration	Se(IV)	1 - 70.2 mg/L	111 mg/g	2	2	-	1	-	Awual et al. 2015
Other adsorbents	Adsorption	Activated alumina from drinking water	Se(IV) Se(VI)	-	Se(IV) 72% Se(VI) 80%	6 to 8	3	5	5	92	Meher et al. 2020
Other adsorbents	Adsorption	Magnetic iron oxide nanoparticles from contaminated water	Se(IV)	-	>99%	3 and 5	3	1	2	38	Evans et al. 2019
Other adsorbents	Adsorption	Zr-based MOF (UiO-66-NH_2)	Se(IV) Se(VI)	5 - 120 mg/L	Se(IV) 11.9 mg/g Se(VI) 26.8 mg/g	6	-	4.5	4	-	Wei et al. 2018
Other adsorbents	Adsorption	Fe^{2+} doped Mg-Al LDH; addition of a Mg - Fe - Al	Se(VI)	1 mM	715 mg/g	-	-	4	-	-	Kameda, Kondo, and Yoshioka 2014

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
		chloride solution to a NaOH solution									
Other adsorbents	Adsorption	Ca-Al LDH; mixing 3CaO Al_2O_3 and $CaCl_2$ solutions, filtration, drying	Se(IV)	2 g/L	139 mg/g	-	-	3	-	-	D. Li et al. 2020; X. Li et al. 2020
Other adsorbents	Adsorption	Mg-Al LDHs; adding NaOH to mixed metal salt solution of $MgSO_4$ and $Al(SO_4)_3$, autoclave, washing, drying, calcination	Se(IV)	0.01 - 100 mg/L	180 mg/g	6	-	2.5	4	-	Tian et al. 2017
Other adsorbents	Adsorption	Mg-Al-CO_3 LDH; mixing $MgCl_2$ solution and solid $NaHCO_3$, mixing with $AlCl_3$ solution, heating, filtration, washing	Se(IV) Se(VI)	5 - 500 mg/L	Se(IV) 160 mg/g Se(VI) 90.0 mg/g	5	-	2	3	-	Chubar 2014
Other adsorbents	Adsorption	MgO nanosheets; ultrasonic exfoliation method	Se(IV) Se(VI)	1 - 100 mg/L	Se(IV) 104 mg/g Se(VI) 10.3 mg/g	10.5	-	4	2.5	-	Cui et al. 2018
Other adsorbents	Adsorption	γ/δ-Al_2O_3; commercial	Se(VI)	0.01 mM	5.15 mg/g	5	-	5	3	-	Jordan et al. 2018
Other adsorbents	Adsorption	γ-Al_2O_3; commercial	Se(IV)	0.01 mM	5.16 mg/g	5	-	5	3	-	Mayordomo et al. 2018
Other adsorbents	Adsorption	Zr-based MOF (UiO-66)	Se(IV) Se(VI)	5 - 120 mg/L	Se(IV) 37.3 mg/g Se(VI) 59.9 mg/g	6	-	4.5	4	-	Wei et al. 2018
Other adsorbents	Adsorption	ZrO_2; adding NaOH to $Zr(NO_3)_4$ solution, adding urea to the solution, adding HCl, adding formaldehyde, centrifugation, washing, drying	Se(IV)	5 mg/L	≥85%	4	-	1.5	2	-	Wu et al. 2018
Other adsorbents	Adsorption	n-Al_2O_3 impregnated chitosan beads; mixing n-Al_2O_3 and chitosan, add the mixture to NaOH, filtration, washing, drying	Se(IV) Se(VI)	-	Se(IV) 11.1 mg/g Se(VI) 20.1 mg/g	-	-	2.5	-	-	Yamani, Lounsbury, and Zimmerman 2014
Photocatalytic	Photocatalytic	TiO_2- assisted photocatalysis in conjunction with EDTA in aqueous phase environment	Se(IV) Se(VI)	-	98%	4	2	4	2	52	Labaran and Vohra 2014
Photocatalytic	Photocatalytic	TiO_2 photo catalysis with EDTA; from synthetic wastewater	Se(IV) Se(VI)	-	86.7%	4	2	-	2	-	Vohra and Labaran 2020

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Photocatalytic	Photocatalytic	Solar photocatalytic from aqueous environment	Se(IV) Se(VI) SeCys	-	67%	4	2	4.5	2	55	Labaran and Vohra 2017
Vascular plants	Vascular plants	Cattails (Typha) growing in a substrate of cattail litter overlying sand and peat moss sediment	Se(IV) Se(VI) SeMet	15 μg/L	<0.1 μg/L	-	5	-	-	-	Huang, Passeport, and Terry 2012
Vascular plants	Vascular plants	Phytoremediation (Cattail *Typha angustifolia* and muskgrass)	Se(IV) Se(VI)	-	Se(IV) 74% Se(VI) 75%	-	5	5	-	-	Nattrass et al. 2019
Waste materials	Adsorption	Fish scale waste; washing, drying, HCl acid wash, mix with NaOH	Se(IV)	-	1.94 mg/g	3 to 6	5	3	3	68	Kongsri et al. 2013
Waste materials	Adsorption	Eggshell, eggshell membrane, or orange peel; washing, drying, grinding, sieving, sonication in HNO_3, washing, mixing with HNO_3 or NaOH, washing	Se(IV)	0.2 - 0.7 mg/L	0.0007 mg/g	-	5	1	-	-	Mafu, Msagati, and Mamba 2014
Zero-valent Iron	Adsorption	ZVI + ultrasound, commercial	Se(IV)	10 mg/L	28.0 mg/g	3	3	4.5	1	49	Fu et al. 2016
Zero-valent Iron	Adsorption	ZVI in the presence of $KMNO_4$; commercial	Se(IV)	7900 μg/L	>99%	7.5	3	5	5	92	Li et al. 2018
Zero-valent Iron	Adsorption	Sulfidated ZVI; mixing ZVI w/ elemental S, freeze drying	Se(VI)	40 mg/L	44.8 mg/g	7.5	3	4	5	86	Ling et al. 2019
Zero-valent Iron	Adsorption	Mixing ZVI with H_2O_2 and HCl	Se(VI)	20 mg/L	4.95 mg/g	7	3	4	5	86	Shan et al. 2018
Zero-valent Iron	Adsorption	ZVI; mixing $FeCl_3$ and $NaBH_4$ solutions	Se(VI)	0.5 - 200 mg/L	28.6 mg/g	7	3	4	5	86	Suazo-Hernández et al. 2021
Zero-valent Iron	Adsorption	ZVI supported onto montmorillonite; homologizing montmorillonite mineral w/ $NaNO_3$ filtration, mixing w/ $FeCl_3$ solution, adding $NaBH_4$ solution, centrifuging, washing, freeze drying	Se(VI)	0.5 - 200 mg/L	34.2 mg/g	7	3	1	5	68	Suazo-Hernández et al. 2021
Zero-valent Iron	Adsorption	ZVI, commercial	Se(VI)	0.253 mM	0.73 mg/g	-	3	5	-	-	Tang et al. 2014
Zero-valent Iron	Adsorption	Mixing ZVI with H_2O_2 at pH 1.5	Se(VI)	100 mg/L	10.0 mg/g	3.2	3	4	1	46	Wu et al. 2018

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Type	Method	Summary	Se Form	Starting Concentration	Amount Removed	pH	Cost-effectiveness	Scalability	Applicability	Score	Reference
Zero-valent Iron	Adsorption	ZVI; Mixing $FeCl_3$ and $NaBH_4$ solutions	Se(IV)	100 mg/L	50.0 mg/g	4	3	4	2	56	Xia, Ling, and Zhang 2017
Zero-valent Iron	Adsorption	ZVI, commercial	Se(IV) Se(VI)	2 mg/L	Se(IV) 38.5 mg/g Se(VI) 27.6 mg/g	4	3	5	2	62	Xie et al. 2017
Zero-valent Iron	Adsorption	ZVI, commercial	Se(VI)	100 mg/L	48.0 mg/g	6	3	5	4	82	Yoon et al. 2016
Zero-valent Iron	Adsorption	ZVI, aloe vera plants; washing aloe plants, boiling, filtration, refrigerating, mix with $FeCl_3$ solution, heating, drying	Se(IV)	2 mg/L	0.18 mg/g	3	3	1.5	1	31	Adio et al. 2017

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