Environmental Quality Management

WILEY

REVIEW ARTICLE OPEN ACCESS

A Structured Review of Selenium Pollution in Global Aquatic Environments: Sources, Levels, and Co-Pollutants

Jorge Enrique Ascencio-Damian | Daisuke Inoue | Michihiko Ike

Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, The University of Osaka, Suita, Osaka, Japan

Correspondence: Michihiko Ike (ike@see.eng.osaka-u.ac.jp)

Received: 7 October 2025 | **Revised:** 10 April 2026 | **Accepted:** 30 April 2026

Keywords: aquatic environments | co-contamination | contamination sources | groundwater | pollution index | selenium

ABSTRACT

Despite its nutritional and industrial significance, selenium (Se) is considered a pollutant in aquatic environments owing to its toxicity at elevated concentrations, which potentially cause environmental degradation and adverse health effects in humans and local biota. We conducted a structured review of studies published between 2015 and 2024 to identify Se sources, contamination levels, and co-occurring inorganic pollutants in surface water and groundwater impacted with Se pollution. We found that anthropogenic activities, particularly mining, are the predominant sources of Se pollution, accounting for over 71% of all cases. Industrial and agricultural activities also contribute to a lesser extent. Geogenic processes, including mineral oxidation, weathering, and seawater intrusion, also cause excessive Se accumulation predominantly in groundwater. In most freshwater sources, Se concentrations range from 100 to 1000 μg/L ($n = 59$ of 116 water bodies); however, values from anthropogenic sources can be significantly higher, reaching up to 7640 μg/L. Se pollution is frequently associated with several co-pollutants across all sources, including anions such as chloride and phosphate, as well as metals such as cadmium, lead, and nickel, but arsenic is consistently the most prevalent, with concentrations generally ranging between 10 and 100 μg/L. Other significant co-pollutants, including aluminum, chromium, mercury, manganese, uranium, vanadium, and antimony, are source-specific. This structured review provides essential insights for addressing sources and concentration ranges of Se pollution and highlights the necessity for developing simultaneous removal strategies of Se and its co-pollutants from global aquatic environments and groundwater sources.

1 | Introduction

Aquatic environments are of particular importance due to their capacity to provide ecosystem services essential for human activities and inhabit various aquatic species, including fish, algae, and aquatic plants that serve as cost-effective sources of nutrients (Irfan and Alatawi 2019; Kennedy et al. 2023). In addition, groundwater stored in aquifers is considered a vital water resource, supplying wells, springs, and rivers used for human consumption, agriculture, and industrial applications (United States Geological Survey 2025).

Trace elements such as copper, manganese, selenium (Se), and zinc play an important role in the aquatic ecosystem for normal metabolic and physiological functions of fishes and humans (Bagheri et al. 2024; Rekha 2023). Particularly, Se at low doses in the form of selenoproteins is a micronutrient that plays important roles in multiple physiological processes, including immune functions, redox homeostasis, reproduction, and thyroid hormone production, in humans and animals (Au et al. 2023; Tinggi and Perkins 2022; Xia et al. 2021). Similarly, a previous study indicated that Se enhances photosynthetic activity, growth, and protein content in plants (Saleem and Fariduddin 2022).

However, several-fold increases in its concentration can have negative effects on flora, fauna, humans, and the environment. For example, exposure to Se levels > 2000 μg/L can cause oxidative stress, chlorosis, and cell damage in terrestrial and aquatic plants (Mechora et al. 2015; Saleem and Fariduddin 2022). In addition, the threshold between deficiency (< 40 μg/day) and toxicity (> 400 μg/day) in humans and animals is narrow, exhibiting the fragile balance required for Se homeostasis (Fordyce 2013). Chronic Se toxicity in humans can manifest as selenosis, whereas acute toxicity can produce symptoms such as hyper-salivation, vomiting, diarrhea, and muscle spasms (Bai et al. 2025; Lombeck et al. 1987). Furthermore, chronic Se exposure in animals has been shown to induce oxidative stress, behavioral alterations, and impaired growth and reproduction, which have been linked to the disappearance of fish species in the United States of America (USA) (Uddin et al. 2024).

> *"Se contamination in aquatic environments, including groundwater, is a significant concern because of its potential for bioaccumulation, biomagnification, and toxicity to aquatic life and humans."*

Se contamination in aquatic environments, including groundwater, is a significant concern because of its potential for bioaccumulation, biomagnification, and toxicity to aquatic life and humans (Khamkhash et al. 2017; Li et al. 2024). In particular, Se in its +4 and +6 oxidation states (i.e., selenite [Se(IV); SeO_3^{2-}] and selenate [Se(VI); SeO_4^{2-}], respectively) poses a high risk due to their high mobility and solubility (Stewart et al. 2010). Although Se naturally occurs in minerals and soils, anthropogenic activities such as coal and metal mining, agriculture, coal combustion, and industrial processes in the medical, electronics, and manufacturing sectors also release Se-containing wastewater, increasing Se levels in surface water and groundwater (Khamkhash et al. 2017; Tan et al. 2016). The global demand for Se has increased significantly from 2300 tons per year in 1999 to 3600 tons in 2023, potentially exacerbating Se contamination (Haug et al. 2007; United States Geological Survey 2024).

Previous reviews have examined Se pollution, its potential sources, and the associated treatment/cleanup technologies (He et al. 2018; Li, Xu, et al. 2022; Lichtfouse et al. 2022, 2021). However, the reviews did not describe the overall spectrum of Se concentration levels in polluted sites affected by differentiated sources. In addition, the occurrence of Se co-contaminants in the aquatic environment remains largely unexplored, though they can significantly affect the performance of Se cleanup technologies. For example, it has been reported that certain anionic co-pollutants can either enhance or inhibit the removal of Se using different technologies (Ascencio-Damian et al. 2025; Tan 2018). Furthermore, the removal of other potentially hazardous toxic metals and metalloids that co-occur with Se is important for achieving healthy and safe aquatic environments for humans and aquatic biota. To address these gaps, the objectives of this structured review were to quantify source-specific Se contamination and concentrations in Se-polluted sites and to evaluate inorganic co-pollutants in both surface water and groundwater systems, based on international Se guidelines (Environmental Protection Agency 1999; World Health Organization 2022).

2 | Literature Screening and Analysis

For the purposes of this review, we adopted a structured literature review methodology to facilitate a comprehensive analysis of Se contamination in global aquatic environments. The approach comprised the following three stages: (1) a two-phase search using different combinations of keywords, (2) a relevance-based screening process to filter results based on environmental standards, and (3) an extraction and qualitative assessment of data from the identified literatures. However, although this structured approach contributes to ensuring that the findings are transparent and reproducible, given the vast nature of the subject, it is unlikely to account for all the relevant information (Villar 2022).

At the identification stage, we adopted a two-phase procedure to ensure a rigorous selection of the recent literatures. The search encompassed academic articles, reports, and theses published in English between 2015 and 2024. This 10-year timeframe was selected to identify contemporary cases of Se contamination. In the initial phase, we conducted a manual search of the Scopus and Google Scholar databases between December 2023 and March 2024 for published papers, using the keywords "selenium," "water," "pollution," "contamination," "heavy metals," "surface water," "groundwater," "estuarine water," "coastal water," and "health," to enable a preliminary identification of the relevant literatures. To ensure a comprehensive review, this search was supplemented by a backward/forward snowballing approach for additional relevant literature. This phase yielded 143 records describing Se concentrations in natural water. In the second phase, conducted between December 3 and December 8, 2025, we carried out a structured manual search of the Google Scholar database using specific Boolean operations and keyword combinations (**Exhibit 1**) to confirm previous findings and to identify studies published after the period covered in the first phase. The search covered the first 300 results per search string, established as a relevance-based threshold. The titles and abstracts were manually inspected for relevance (i.e., the reporting of Se in natural waters) (Exhibit 1), which resulted in the selection of a further 229 records.

In the screening stage, the combined records from both phases (n = 372) were independently and sequentially evaluated to determine whether they described the occurrence of significant Se contamination in the respective areas of study. Specifically, an area was classified as contaminated if the maximum reported Se concentration exceeded the guideline values established by the World Health Organization (WHO) for freshwater ecosystems or the United States Environmental Protection Agency (USEPA) for coastal and estuarine waters, as WHO guidelines were unavailable for saltwater systems. The guideline concentrations used for reference screening are listed in **Exhibit 2**. For studies with available raw pollutant data, only values exceeding the guidelines were recorded to avoid reporting bias. The screening stage yielded 56 and 59 records from the first and second phases, respectively, describing the detection of significant Se contamination in aquatic environments. Subsequent to this analysis, we conducted a duplicate check, which resulted in the removal of 28 records, leaving 87 records for consideration of full-text analysis.

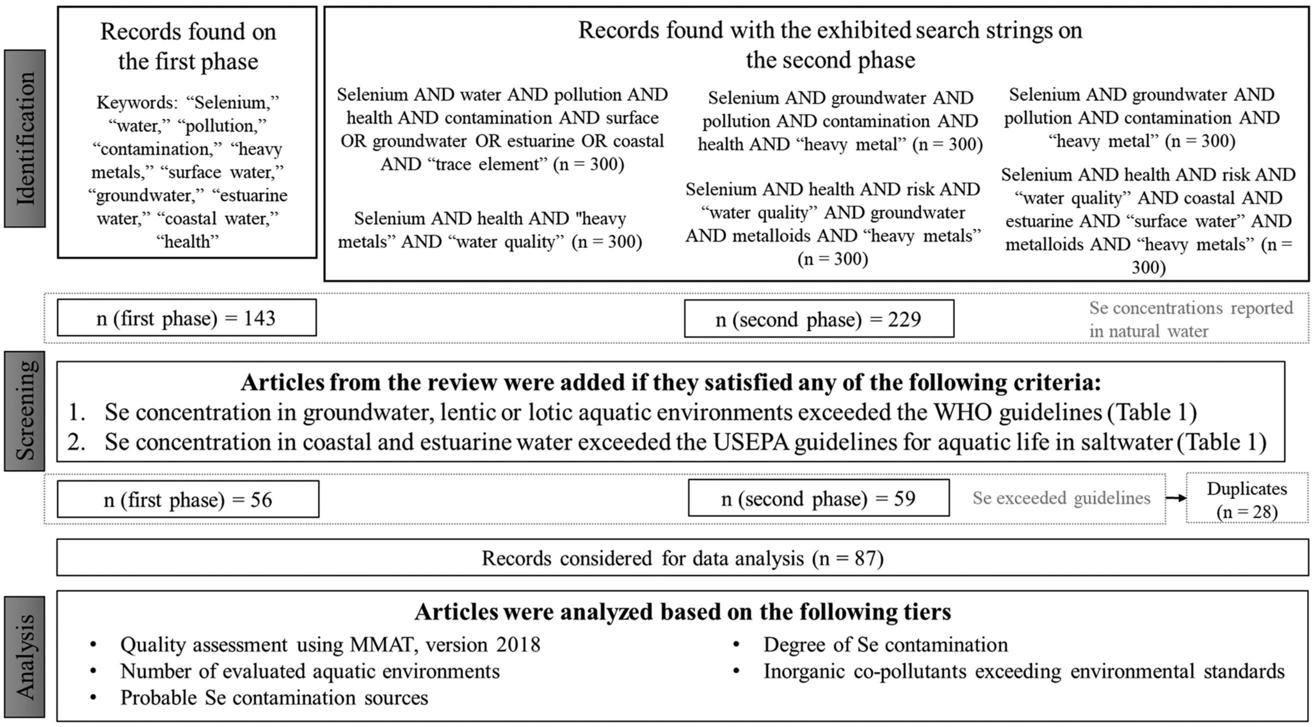

EXHIBIT 1 | Design of the structured literature review.

EXHIBIT 2 | Se environmental standards for drinking water and aquatic life used for screening during the literature review in this study.

	Se guideline value (μg/L)	Target water bodies	Reference of the Se guideline values
WHO provisional guideline value of Se in drinking water	40	Groundwater Lotic Lentic	World Health Organization (2022)
USEPA guidelines for aquatic life in saltwater (chronic)	71	Coastal and estuarine	Environmental Protection Agency (1999)

Analysis entailed a detailed two-step examination of the 87 records for quality assessment and data extraction. To ensure the reliability of the findings, quality assessment was performed using the Mixed Methods Appraisal Tool (MMAT, Version 2018) for quantitative descriptive studies (Hong et al. 2018). Specifically, five questions from the original MMAT (Q1–Q5) were modified to align with the focus of this review. The quality of each record was assessed as follows: Q1 for sample relevance, Q2 for sample representativeness, Q3 for quality assurance (QA) and quality control (QC), Q4 for data display, and Q5 for statistical analyses. Details of the assessment criteria and scoring outcomes are provided in Tables S1.1 and S2.1, respectively. The majority of the studies exhibited high quality. Those failing to satisfy the stipulated quality criteria were still included in the analysis, based on a reasonable overall appraisal and the fact that they successfully addressed core questions. Following this assessment, structured data extraction was conducted to identify the number and type of investigated water bodies, Se contamination level, possible sources of pollution, and the occurrence and concentrations of inorganic co-pollutants (i.e., anions, heavy metals, and metalloids). In detail, occurrence and concentration data for 23 co-pollutants, including six major anions: chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}–P), and sulfate (SO_4^{2-}), 15 metals: aluminum (Al), antimony (Sb), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), silver (Ag), uranium (U), vanadium (V), and zinc (Zn), and two metalloids: arsenic (As) and boron (B) were noted and analyzed. To ensure toxicological relevance, the occurrence of co-pollutants was evaluated in a manner similar to that used for Se, by determining whether the respective maximum concentrations exceeded the guideline values provided by the WHO. However, in instances for which the WHO criteria were unavailable, guidelines from the USEPA or other recognized environmental agencies were applied. For contaminants that have not been assessed by these regulatory institutions, or those primarily associated with ecological rather than direct health risks (i.e., PO_4^{3-}–P), threshold values were derived from peer-reviewed scientific papers (Tables S1.2–S1.4). In this review, the evaluation of contamination occurrence only considered the maximum concentrations of Se and the co-pollutants, irrespective of the correlation between them. Studies reporting concentration

EXHIBIT 3 | Summary of sources of Se contamination in groundwater and surface water.

Source		Groundwater	Surface water			Total cases per source
			Lentic	Lotic	Estuarine and coastal	
Natural		14 (21.2%)	1 (4.2%)	N.R.	N.R.	15 (10.6%)
Anthropogenic	Mining	21 (31.8%)	8 (33.3%)	11 (23.9%)	N.R.	40 (28.1%)
	Industry	13 (19.7%)	6 (25.0%)	17 (37.0%)	1 (16.7%)	37 (26.0%)
	Agriculture	6 (9.1%)	4 (16.7%)	13 (28.3%)	1 (16.7%)	24 (16.9%)
Natural and anthropogenic		7 (10.6%)	3 (12.5%)	3 (6.5%)	N.R.	13 (9.2%)
Unknown		5 (7.6%)	2 (8.3%)	2 (4.3%)	4 (66.6%)	13 (9.2%)
Total cases per water body		66	24	46	6	142

Note: Percentages indicate the ratio of reported cases in each water body or in the total count.
Abbreviation: N.R., not reported.

ranges from multiple sampling points and several time periods within the same water body were classified as polluted based on the maximum reported pollutant concentration or to the most recent year, unless stated otherwise. This conservative, risk-based approach was adopted to avoid "false negative" cases and potential underestimation of contamination levels, thereby ensuring that assessments reflected the maximum potential burden on the ecosystem. Detailed information of the dataset, including study location, specific sources, Se and co-pollutant concentration ranges, measuring instruments, sampling dates, and correlation matrix of Se was compiled and can be found in the Supplementary Materials (Tables S2.2–S2.5). It should be noted that in the case of some studies presenting statistical summaries for multiple water bodies or with indistinguishable water bodies (i.e., without an appropriate description), these were treated as records for single water bodies, even if they assessed multiple sources.

3 | Se Contamination Sources

Attribution of the possible sources of Se contamination (**Exhibit 3**) followed a classification based on the level of evidence provided in the reviewed literature. Sources were categorized as "natural," "anthropogenic," or "natural and anthropogenic," according to the criteria of direct author attribution or inference from the area in which the study was conducted. Among the anthropogenic sources, we established the three sub-categories "mining activities," "industrial activities," and "agricultural activities," as these have previously been reported to be predominant anthropogenic sources of Se in different environments (El-Ramady et al. 2014; Saha et al. 2017). Specifically, sources were attributed directly when the study explicitly identified a primary pollution driver, as was the case for all natural sources and certain anthropogenic sources. In the absence of an explicit statement, sources were inferred by evaluating the site descriptions for specific geographical indicators (e.g., industrial zones or mining areas), although we acknowledge that this approach could potentially lead to misclassification. In ambiguous cases, for which no source was mentioned, and site descriptions were insufficient to make a reasonable assignment, the source was categorized as "unknown" to minimize classification bias. For water bodies affected by multiple sources of pollution, each source was counted individually.

3.1 | Natural Sources

Se pollution from natural sources alone was identified in approximately 10.6% of the reported contamination cases (n = 15 of 142 cases), predominantly in groundwater, while 9.2% were linked to both natural and anthropogenic origins (n = 13 of 142 cases) (Exhibit 3). Although not consistently reported, several significant sources of natural Se pollution were identified as geological formations and seawater intrusion.

3.1.1 | Geological Formations

Se occurs naturally in different geological formations, including sedimentary rocks such as black shales, coals, and phosphatic deposits associated with sulfide minerals. Upon weathering, Se is primarily mobilized as water-soluble species Se(IV) and Se(VI) (Fordyce 2013; Mehdi et al. 2013), which have high potential for migration through infiltration and runoff into aquatic environments. For instance, the oxidation of sulfides and weathering of sulfate-evaporites such as gypsum and anhydrite have been reported as the main cause of mobilization of Se together with SO_4^{2-}, causing the contamination of groundwater in Mexico (Mora et al. 2021), whereas Se pollution originating from Mancos Shale weathering, efflorescent salt dissolution, and redox processes has been reported in the USA (Linard et al. 2017). In addition, Se-containing sediments and rocks have been attributed as the main causes of groundwater pollution in India (Kumar et al. 2020). Similarly, natural pollution in surface water and groundwater was reported to originate from weathering of clastic and carbonate rocks in China (Hao et al. 2022; Luo et al. 2024).

Weathering of parent rocks is also a primary factor in the formation of seleniferous soils (Saha et al. 2017). Seleniferous soils are abundant in the USA, Russia, India, and China, where soils have reportedly exhibited elevated Se levels (Kieliszek 2019; Saha et al. 2017). In fact, in India, mobilization from such soils has been reported to elevate Se concentration in groundwater (Lapworth et al. 2017). It should be noted that depositions from eruptions and volcanic plumes typically contribute to an enrichment of soils with Se (Fordyce 2013; Saha et al. 2017), as observed in the volcanic soil of the Gulf Basalt in Djibouti, which in turn has led to Se contamination in regional groundwater sources (Ahmed et al. 2017).

3.1.2 | Seawater Intrusion

> "*The landward incursion of seawater introduces competing anions, such as PO_4^{3-}, NO_3^-, and SO_4^{2-}, modifying the hydrochemistry of coastal aquifers, which leads to ion exchange processes that enhance the desorption of Se(IV) and Se(VI) and promote the weathering of different carbonate, silicate, and sodium-magnesium-sulfate minerals.*"

Seawater intrusion (SI) is a natural process caused by the density difference between seawater and freshwater, which leads to the natural inland movement of seawater until equilibrium is achieved. This process is governed by dispersive mixing, tidal effects, and density effects, often enhanced by anthropogenic activities (e.g., an excessive abstraction of groundwater and climate change) (Werner et al. 2013). The landward incursion of seawater introduces competing anions, such as PO_4^{3-}, NO_3^-, and SO_4^{2-}, modifying the hydrochemistry of coastal aquifers, which leads to ion exchange processes that enhance the desorption of Se(IV) and Se(VI) and promote the weathering of different carbonate, silicate, and sodium-magnesium-sulfate minerals (Ahmed et al. 2017; Chen et al. 2019; Mora et al. 2020), thereby mobilizing Se, with subsequent entry into groundwater. Furthermore, SI has been suggested to be an important mechanism underlying Se contamination in coastal aquifers in Djibouti, India, and Saudi Arabia (Ahmed et al. 2017; Alshehri et al. 2021; Kumar et al. 2024), whereas in Egypt, storms have been reported to transport seawater inland via outlets and across coastal ridges, causing the pollution of an adjacent lake (Al-Agroudy and Elmorsi 2022).

3.2 | Anthropogenic Sources

As shown in Exhibit 3, most reported Se pollution in surface and groundwater can be attributed to anthropogenic activities. Nearly 71% (n = 93 of 142 cases) of the total excess Se was linked to anthropogenic sources, although the contribution of each source subcategory varied across different water bodies.

3.2.1 | Mining Activities

Mining activities bring Se-enriched deposits to the surface (USEPA 2018) and account for approximately 28.1% of reported pollution cases (n = 40 of 142 cases), representing the highest occurrence among the anthropogenic sources evaluated in this review (Exhibit 3). This observation highlights their predominant role in Se pollution of both surface water and groundwater.

Se is mainly recovered as a by-product of copper mining, which, consequently, can lead to elevated Se concentrations in mine waste, as observed in the Iberian Pyrite Belt, posing a potential risk of Se pollution to aquatic environments (Figueiredo et al. 2014; Haug et al. 2007). In addition, copper and iron mining are primary contamination sources of surface water and groundwater in India and Iran (Gharaat et al. 2020; Kazemi et al. 2022; Prasad et al. 2020). Other Se-containing mine waste, such as dzharkenite and Se-substituted pyrite in a phosphate patch in the USA have been reported to generate leachate from backfilled pits and overburden storage piles, causing Se to leach into groundwater (Hay et al. 2016; Ryser et al. 2005). Other metal mining sources of Se pollution included rare earth mining in China (Hao et al. 2016), uranium mining in Mongolia (Ariunbileg et al. 2016), gold mining in Cameroon (Mambou Ngueyep et al. 2021), and salt, lead, and zinc mining in Nigeria, where environmental pollution is worse due to illegal mining (Egbueri and Enyigwe 2020; Obasi et al. 2024; Obasi and Akudinobi 2020). Notably, abandoned mines represent important pollution sources as demonstrated in surface waters in China (Jiao et al. 2023), although active mines present a higher risk (Obasi and Akudinobi 2020).

Coal mining was identified as another significant source of Se pollution. Elevated Se content in coal has increased the hazardous risk to the aquatic environments in several regions in China and Canada (Lemly 2009; Wang et al. 2010). Particularly, in Elk Valley, Canada, Se is present in coal waste dumps with various minerals, including pyrite, sphalerite, and chalcopyrite, which could be responsible for surface water pollution at concentrations exceeding ecological safety thresholds (Hendry et al. 2015; Teck Coal Limited 2023). Similarly, a closed coal mine in Canada was shown to be a continuous Se pollution source in a lake below the mine spoil pile (Cooke et al. 2024). In India, Se contamination of surface water and groundwater was attributed to open-cast coal mining (Prathap and Chakraborty 2019; Sahoo and Sahu 2022).

3.2.2 | Industrial Activities

Industrial activities as a Se pollution source was highlighted during the COVID-19 lockdown in India. The suspension of industrial operations led to a significant reduction in Se concentrations in groundwater compared to pre-lockdown levels (Selvam et al. 2020). Although Se pollution from industrial activities is widely mentioned in previous studies and is considered the second major anthropogenic source of Se pollution (Exhibit 3) (26%, n = 37 of 142 cases), specific sources were scarcely or not clearly identified. However, some potential sources of Se pollution, such as metal smelting, the semiconductor industry, and oil-refining and coal-fired plants (Lichtfouse et al. 2021) are considered contamination sources via emission of gaseous Se into the atmosphere and Se-containing wastewater.

Metallurgical activities, specifically metal smelters, are recognized as major Se pollution sources (Maret and Skinner 2000), as Se is a byproduct of metal smelting, particularly during the smelting of Cu and Ni. These smelting processes mobilize Se into the atmosphere, which can settle on surface waters (Dudka and Adriano 1997; USEPA 2018). In addition, during Cu smelting, a significant proportion of Se is lost in the slag, which, when discarded, can increase Se concentrations in the waste effluent (Desai et al. 2016; Kenzhaliyev et al. 2018).

Se is considered a useful raw material for semiconductor production in several industrial applications such as solar cells and X-ray flat-panel detectors (Liu et al. 2024; Qi et al. 2022). However, the semiconductor industry has generated significant amounts of Se-containing wastewater, likely increasing the risk to the environment (Gilles and Loehr 1994).

Se pollution from oil refining occurs primarily through the discharge of Se-laden wastewater, a byproduct of the refining process (Wang et al. 2024). Throughout the refining process, Se is introduced into wastewater in various chemical forms that could cause environmental concerns (Staicu et al. 2017). This issue is particularly prominent in San Francisco Bay, where Se pollution from oil refining has been confirmed (Hansen et al. 1998).

The high Se emissions from coal-fired power plants could also pose a threat to aquatic ecosystems (Brandt et al. 2017; Tian et al. 2011). Although volatilized Se generated in the coal-fired plants is captured in flue gas treatment systems, significant amounts of Se could enter wastewater streams (Ma et al. 2022).

3.2.3 | Agricultural Activities

Seleniferous agricultural drainage wastewater is a major source of Se pollution worldwide (Kharaka et al. 1996), whereas the number of pollution reports in aquatic environments from agricultural activities was less than that of mining and industrial activities in the literature (16.9%, $n = 24$ of 142 cases) (Exhibit 3).

Since Se is considered an essential nutrient for plants and helps mitigate heavy metal toxicity and against pests, it is often applied in fertilizer, which could lead to Se contamination in aquatic environments (Feng et al. 2021; Mechora 2019; Saleem and Fariduddin 2022). Fertilizers heavily applied to various cultivation fields are the main source of Se contamination in tributaries of the Mahaweli River (Diyabalanage et al. 2016), as well as in the Bizana and Mthatha Rivers in South Africa (Madikizela et al. 2023). Other mechanisms involve the mobilization of Se from seleniferous soils through agricultural irrigation for crop production (Linard et al. 2017) and the exposure of Se-bearing sedimentary deposits caused by the construction of open drainage channels in agricultural areas, which have been implicated in surface water contamination in the USA (USEPA 2018).

4 | Se Contamination Levels

It is crucial to understand the extent and origin of Se pollution in global aquatic environments for effective remediation, particularly through selecting the appropriate cleanup techniques and implementing appropriate prevention and mitigation strategies. The single-factor pollution index (P_i, dimensionless) was used to categorize Se environmental contamination levels reported in the literature (Dey et al. 2021). P_i was calculated using the following Equation (1):

$$P_i = \frac{C_{max}}{C_{standard}} \tag{1}$$

where C_{max} is the measured maximum concentration, and $C_{standard}$ is the Se environmental standard criterion ($C_{standard}$ (freshwater) = 40 μg/L; $C_{standard}$ (saltwater) = 71 μg/L) (Exhibit 2). Herein, pollution levels in freshwater sources were categorized based on P_i and corresponding C_{max} values as: $1 \leq P_i \leq 2.5$ (40 μg/L $\leq C_{max} \leq$ 100 μg/L), which indicated low pollution level; $2.5 < P_i \leq 25$ (100 μg/L $< C_{max} \leq$ 1000 μg/L), which indicated moderate pollution level; and $P_i > 25$ ($C_{max} >$ 1000 μg/L), which indicated high pollution level. For estuarine and coastal waters, the same P_i categories were applied, but with different corresponding C_{max} values based on their specific standard criterion (Exhibit 2): 71 $\leq C_{max} \leq$ 177.5 μg/L for low pollution level; 177.5 $< C_{max} \leq$ 1775 μg/L for moderate pollution level; and $C_{max} >$ 1775 μg/L for high pollution level. The upper and lower concentration values in freshwater were selected based on previous toxicological reports on aquatic plants. For example, an aquatic plant grown in simulated freshwater systems exposed to Se at concentrations up to 1000 μg/L showed no apparent Se-induced toxicity, whereas exposure to higher concentrations resulted in pronounced necrosis (Ascencio-Damian et al. 2025). Conversely, low Se concentrations, even > 40 μg/L have been indicated to enhance growth and antioxidant activities of an aquatic plant (Zhong and Cheng 2016). Having calculated P_i values for freshwater systems, for the purposes of standardization, these values were similarly applied to estuarine and coastal waters. To ensure the robustness of the results, we also calculated P_i values relative to the mean values for a subset of studies in groundwater, owing to their marked heterogeneity, thereby confirming that the use of maximum concentrations enabled us to identify all areas of concern without indicating unrealistic scenarios, with the exception of certain cases characterized by low levels of pollution (Table S1.5). All the reviewed studies described distinguishable freshwater (groundwater and surface water) or saltwater (estuarine and coastal) environments, and thus, no water bodies were evaluated with reference to multiple guideline values.

To summarize the levels of Se contamination among the compiled dataset and source types, we conducted a descriptive analysis, which exhibited notable differences in Se pollution levels among different source types, water bodies, and geographical regions (**Exhibits 4–6**). This analysis revealed that in all water bodies except estuarine and coastal waters, moderate levels of Se pollution (100–1000 μg/L) were more frequently found than either high or low levels ($n = 59$, 50.9%). This suggests that global cleanup and remediation efforts, particularly in drinking water sources, should prioritize Se concentrations within this range. Furthermore, anthropogenic sources reportedly generated all levels of Se pollution (from low to high), while natural sources mainly caused moderate and low pollution levels.

Moderate to high levels of Se pollution have direct implications for sustainable development goal (SDG) 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water). These elevated concentrations not only threaten the security of freshwater resources for human consumption but also the health of aquatic

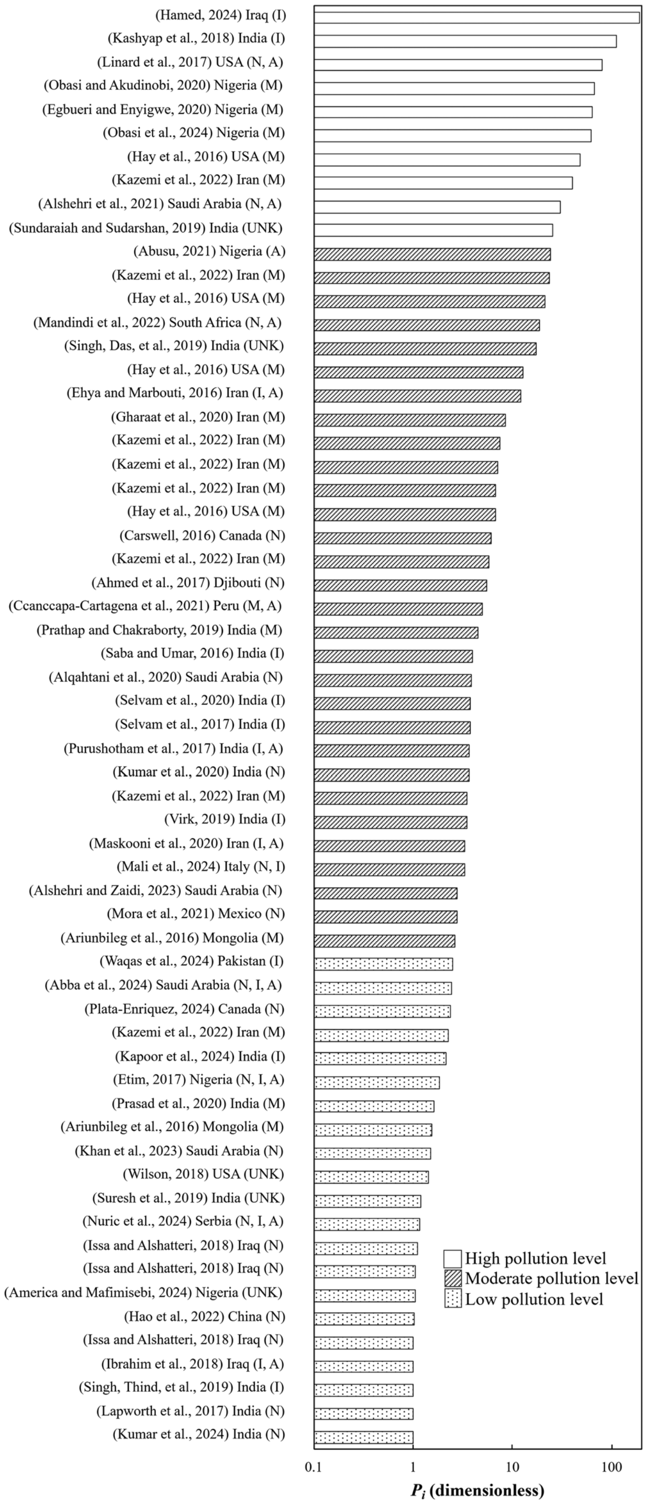

EXHIBIT 4 | Single-factor pollution indices of Se (P_i) calculated for groundwater worldwide. $P_i = C_{max}/C_{standard}$ (dimensionless). Letters in parentheses indicate the possible source of origin: N, natural; A, agriculture; M, mining; I, industrial activities; UNK, unknown. The data are shown in order of highest to lowest contamination levels. Low pollution level ($n = 21$): $1 \le P_i \le 2.5$ (40 μg/L $\le C_{max} \le$ 100 μg/L); moderate pollution level ($n = 30$): $2.5 < P_i \le 25$ (100 μg/L $< C_{max} \le$ 1000 μg/L); high pollution level ($n = 10$): $P_i > 25$ ($C_{max} >$ 1000 μg/L). Total sample size is 61.

ecosystems, potentially having detrimental effects on both marine and riverine biodiversity. Furthermore, even at low levels of pollution, the persistence of Se facilitates the bioaccumulation and biomagnification of this element within food webs, thereby posing potential long-term risks to human health and thus jeopardizing the achievement of SDG 3 (Good health and well-being).

4.1 | Groundwater Contamination

The Se contamination cases in groundwater are illustrated in **Exhibit 4** to compare the contamination levels with their respective source, the corresponding detailed data for which are presented in Table S2.2. Among 61 pollution cases observed in groundwater, ten cases (16.4%) exhibited high pollution levels (> 1000 μg/L), and were predominantly attributed to mining activities (n = 5) (Egbueri and Enyigwe 2020; Hay et al. 2016; Kazemi et al. 2022; Obasi et al. 2024; Obasi and Akudinobi 2020). Other, less frequently reported sources of high pollution levels include industrial discharges, which produced Se concentrations up to 7640 μg/L (Hamed 2024; Kashyap et al. 2018), and a combination of geogenic and agricultural processes, which generated concentrations as high as 3220 μg/L (Alshehri et al. 2021; Linard et al. 2017). An unknown source also produced a concentration of 1011 μg/L (Sundaraiah and Sudarshan 2019). Overall, these findings suggest mining as the predominant source of high Se pollution in groundwater.

Similarly, moderate Se pollution levels in groundwater (100–1000 μg/L) (n = 30, 49.2%) were predominantly linked to mining activities (n = 12) (Ccanccapa-Cartagena et al. 2021; Hay et al. 2016; Kazemi et al. 2022; Prathap and Chakraborty 2019), accounting for 40% of the reported moderate cases. Industrial and agricultural sources contributed to moderate pollution levels to a lower degree (Abusu 2021; Ccanccapa-Cartagena et al. 2021; Ehya and Marbouti 2016; Mali et al. 2024; Mandindi et al. 2022; Maskooni et al. 2020; Purushotham et al. 2017; Saba and Umar 2016; Selvam et al. 2017, 2020; Virk 2019). In contrast, moderate pollution from solely natural sources was observed only in six sites (Ahmed et al. 2017; Alqahtani et al. 2020; Alshehri and Zaidi 2023; Carswell 2016; Kumar et al. 2020; Mora et al. 2021), whereas one pollution case was generated from an unknown source (Singh, Das, et al. 2019).

The number of low-level pollution cases (< 100 μg/L) was higher than that of high-level cases in terms of the contribution of anthropogenic and natural sources (n = 21, 34.4%). In contrast to high and moderate pollution cases, natural sources individually or in combination predominantly generated low-level Se pollution (n = 11, 52.4%) (Abba et al. 2024; Etim 2017; Hao et al. 2022; Issa and Alshatteri 2018; Khan et al. 2023; Kumar et al. 2024; Lapworth et al. 2017; Nurić et al. 2024; Plata-Enriquez 2024). In addition, anthropogenic sources, particularly industrial and mining activities, caused low-level groundwater pollution, though to a lesser extent (Ariunbileg et al. 2016; Ibrahim et al. 2018; Kapoor et al. 2024; Kazemi et al. 2022; Prasad et al. 2020; Singh, Thind, et al. 2019). Some areas were impacted by unknown sources producing Se concentrations between 42 and 57 μg/L (America and Mafimisebi 2024; Suresh et al. 2019; Wilson 2018).

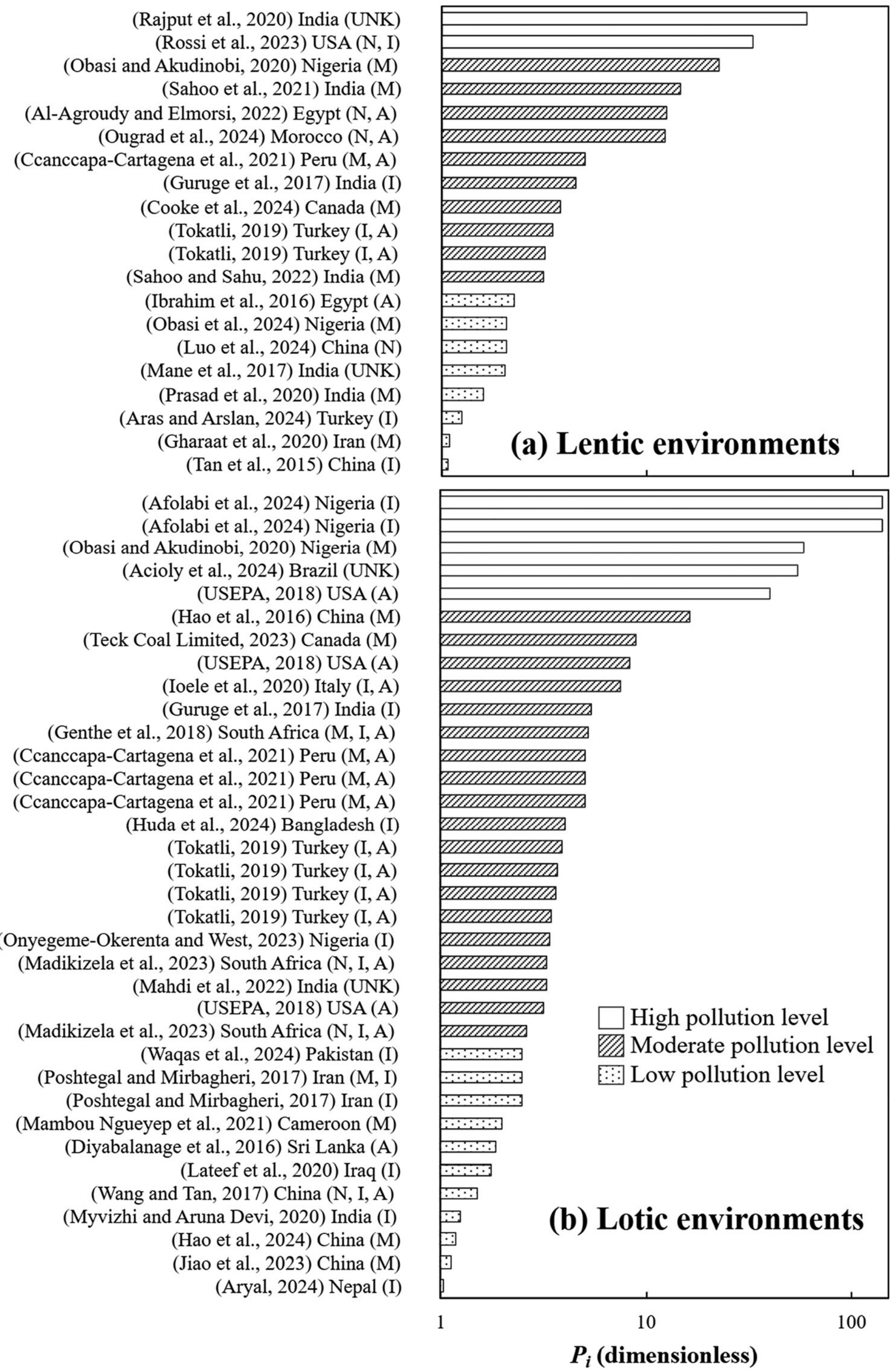

EXHIBIT 5 | Single-factor pollution indices of Se (P_i) calculated for surface freshwater sources worldwide. (a) Lentic environments and (b) lotic environments. $P_i = C_{max}/C_{standard}$ (dimensionless). Letters in parentheses indicate the possible source of origin. N, natural; A, agriculture; M, mining; I, industrial activities; UNK, unknown. The data are shown in order of highest to lowest contamination levels. Low pollution level ($n = 8$ (lentic) and $n = 11$ (lotic)): $1 \leq P_i \leq 2.5$ (40 μg/L $\leq C_{max} \leq$ 100 μg/L); moderate pollution level ($n = 10$ (lentic) and $n = 19$ (lotic)): $2.5 < P_i \leq 25$ (100 μg/L $< C_{max} \leq$ 1000 μg/L); high pollution level ($n = 2$ (lentic) and $n = 5$ (lotic)): $P_i > 25$ ($C_{max} >$ 1000 μg/L). Total sample size is 20 and 35 for lentic and lotic environments, respectively.

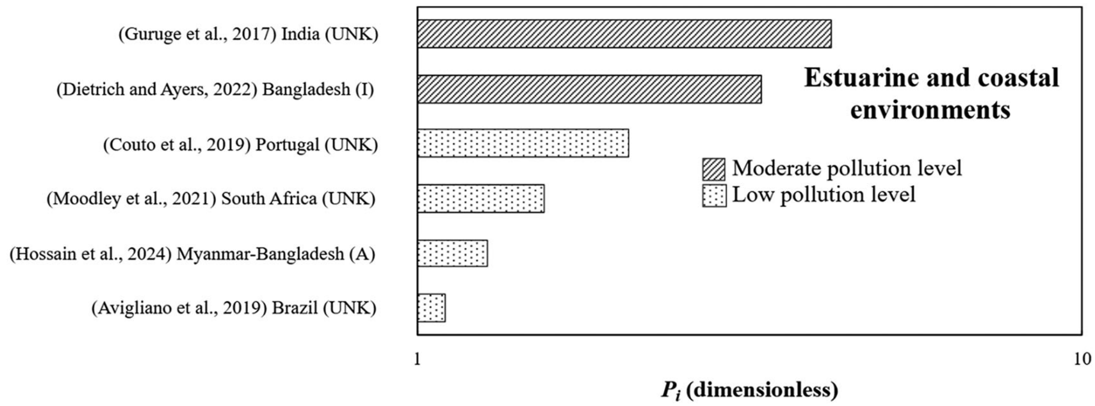

EXHIBIT 6 | Single-factor pollution indices of Se (P_i) calculated for estuarine and coastal water worldwide. $P_i = C_{max}/C_{standard}$ (dimensionless). Letters in parentheses indicate the source of origin. A, agriculture; I, industrial activities; UNK, unknown. The data are shown in order of highest to lowest contamination levels. Low pollution level ($n = 4$): $1 \leq P_i \leq 2.5$ (71 μg/L $\leq C_{max} \leq$ 177.5 μg/L); moderate pollution level ($n = 2$): $2.5 < P_i \leq 25$ (177.5 μg/L $< C_{max} \leq$ 1775 μg/L). Total sample size is 6.

4.2 | Surface Water Contamination

Se contamination in surface water was analyzed across freshwater (lentic and lotic) (**Exhibit 5**, Tables S2.3 and S2.4) and estuarine and coastal waters (**Exhibit 6**, Table S2.5). Reports of high Se pollution (> 1000 μg/L) in surface water were less frequent than those in groundwater ($n = 7$, 12.7%). Within these environments, lotic waters exhibit a higher vulnerability to high Se enrichment than lentic waters, a trend primarily driven by anthropogenic sources. Instances of concentrations reaching 5600 μg/L (Afolabi et al. 2024) suggest that while the effects are greater on groundwater than on surface water, anthropogenic sources can exert a heavy environmental burden, causing high Se pollution (> 1000 μg/L) across surface waters. For instance, pollution cases in lentic waters generated from unknown sources, and natural and industrial activities, reached Se concentrations of 2383 μg/L (Rajput et al. 2020) and 1300 μg/L (Rossi et al. 2023), respectively (Exhibit 5a). Similarly, anthropogenic processes in lotic waters resulted in Se concentrations of 5600 μg/L (Afolabi et al. 2024), 2330 μg/L (Obasi and Akudinobi 2020), and 1591 μg/L (USEPA 2018) (Exhibit 5b). A high initial Se concentration (2170 μg/L) was observed in a lotic environment originating from an unknown source, followed by a gradual decline over the subsequent months, though consistently above environmental criteria (Acioly et al. 2024). This suggests that although concentrations may peak at a specific time, pollution levels can remain elevated over prolonged periods.

Primary sources of moderate Se pollution (100–1000 μg/L) varied among lentic and lotic environments ($n = 29$, 52.7%). Mining activities alone (Cooke et al. 2024; Obasi and Akudinobi 2020; Sahoo et al. 2021; Sahoo and Sahu 2022), and together with agriculture (Ccanccapa-Cartagena et al. 2021) were predominant sources of moderate Se pollution in lentic environments ($n = 5$), while agriculture (Al-Agroudy and Elmorsi 2022; Ougrad et al. 2024) and industrial activities (Guruge et al. 2017) also generated moderate Se pollution (Tokatli 2019). Conversely, in lotic environments, agriculture was the major source of moderate Se pollution either alone (USEPA 2018), or combined with other sources ($n = 10$) (Ccanccapa-Cartagena et al. 2021; Genthe et al. 2018; Ioele et al. 2020; Madikizela et al. 2023; Tokatli 2019). Mining (Hao et al. 2016; Teck Coal Limited 2023) and industrial discharges (Guruge et al. 2017; Huda et al. 2024; Onyegeme-Okerenta and West 2023) have been reported to be associated with moderate levels of pollution, and one case originated from an undetermined source (Mahdi et al. 2022).

Low Se pollution cases (< 100 μg/L) were less frequent than those of moderate levels ($n = 19$, 34.6%). Mining and industrial activities were the dominant sources of low Se pollution in both lentic and lotic environments ($n = 16$ in total) (Aras and Arslan 2024; Aryal 2024; Gharaat et al. 2020; Jiao et al. 2023; Lateef et al. 2020; Mambou Ngueyep et al. 2021; Myvizhi and Aruna Devi 2020; Obasi et al. 2024; Poshtegal and Mirbagheri 2017; Prasad et al. 2020; Tan et al. 2015; Waqas et al. 2024), whereas agricultural activities had a lower impact (Diyabalanage et al. 2016; Ibrahim et al. 2016). Natural sources alone, or together with anthropogenic sources, also produced low pollution levels both in lentic and lotic environments, but at lower frequency (Luo et al. 2024; Wang and Tan 2017). In addition, one case was impacted by an unknown source (Mane et al. 2017).

Reports of Se pollution in coastal and estuarine waters were much less frequent than those in surface water or groundwater ($n = 6$), with reports only exhibiting low to moderate pollution levels (Avigliano et al. 2019; Couto et al. 2019; Guruge et al. 2017; Moodley et al. 2021) (Exhibit 6). The pollution sources were identified in two cases in Bangladesh (Dietrich and Ayers 2022; Hossain et al. 2024), but the highest Se concentration (298 μg/L) originated from an unknown source (Guruge et al. 2017).

4.3 | Spatial and Temporal Variations in Se Contamination

Se pollution exhibits a wide spatial variation globally. Although Se is mainly produced in China, Germany, Japan, and Russia (United States Geological Survey 2024), severe pollution in aquatic environments is rarely reported in these nations, with the notable exceptions of China (Hao et al. 2024, 2022, 2016; Jiao et al. 2023; Luo et al. 2024; Tan et al. 2015; Wang and Tan 2017). This exception is likely due to improper wastewater management in areas with industrial Se production. The highest frequency of Se exceedances in both surface water and groundwater has been reported in Asia outside China and Japan, primarily in India and Iran, with low to high levels of pollution, influenced by both anthropogenic and geogenic sources, with Africa, predominantly Nigeria, identified as the second most affected region. On the basis of our analysis of relevant records, groundwater and fresh surface water contamination appears to be regularly reported in India ($n = 16$ for groundwater and $n = 9$ for surface water), whereas reports from Bangladesh were slightly more frequent for estuarine and coastal water pollution ($n = 2$). This distribution provides evidence to indicate that although industrial production is localized, Se pollution is a widespread concern, particularly in Asian and African countries.

Temporal variations in Se concentrations show distinct regional patterns, which in Asian and African countries, such as China, India, Iran, and Nigeria, are typically influenced by seasonal monsoon rains. For example, with respect to groundwater, the heightened levels of precipitation during monsoon periods appear to have a dilution effect, resulting in a general trend of lower Se concentrations post-monsoon compared with those prior to the onset of the monsoon season (Kumar et al. 2020; Obasi and Akudinobi 2020; Saba and Umar 2016; Singh, Thind, et al. 2019). In contrast, Se contamination in surface waters tends to increase during and after the monsoon period (Obasi and Akudinobi 2020; Sahoo et al. 2021), thereby suggesting that an intensification of weathering and runoff processes, driven by the high volumes and frequency of precipitation, enhance the mobilization and release of Se into surface aquatic systems, although this pattern was not clearly discerned in the study conducted by Sahoo and Sahu (2022). Furthermore, this phenomenon suggests a potential hydrogeological coupling, in which the displacement of Se-contaminated groundwater to surface water occurs during periods of high groundwater recharge, thereby elevating levels of surface contamination.

5 | Co-Pollutants Associated With Se Contamination

Natural aquatic ecosystems contaminated with Se often exhibit excessive amounts of several anions, metals, and metalloids. Therefore, it is important to understand the prevalence and origin of each co-pollutant for implementing effective environmental cleanup, mitigation, and remediation solutions. The highest concentration data for six anions and 17 metals and metalloids reported in the literature were evaluated to describe their co-occurrence with Se pollution. The dataset employed for analysis included three variables: (i) type of co-pollutant, (ii) source of contamination, and (iii) criteria for contamination assessment (Tables S1.2–S1.4), which were classified as "over standard,", "not over standard," or "not determined (N.D.)," based on their comparison with environmental standards (Tables S2.2–S2.5). Co-pollutants with fewer than three total reports or with unspecified sources were excluded from further analysis. Elements with two or more cited sources were regarded as originating from each respective source. The exceedance (%) for each co-pollutant across its correspondent source was calculated using Equation (2):

$$Exceedance\ (\%) = \left(\frac{N_{exceed}}{N_{total}}\right) \times 100 \qquad (2)$$

where N_{exceed} is the number of cases reported as "over standard" for a specific co-pollutant and N_{total} is the total number of cases reported for that specific co-pollutant (i.e., "over standards" and "not over standards"). The exceedance score was categorized as follows: scores > 70% were classified as "high occurrence" (+++), between 30% and 70% as "moderate occurrence" (++), between 5% and 30% as "low occurrence" (+), and < 5% as "rare" (−); "N.D." denoted undetermined cases due to inapplicability or insufficient data.

5.1 | Anions

Although some anions are essential for aquatic life, in some cases, their elevated concentrations can pose a threat to them and humans and lead to eutrophication and oxygen depletion (Table S1.2). The co-occurrence frequency (exceedance) of anionic pollutants with Se is presented in **Exhibit 7**. Most anions evaluated, except NO_2^- and PO_4^{3-}, exhibited moderate to high co-occurrence in groundwater, but varied in surface waters depending on the origin.

Anions including Cl^-, F^-, NO_3^-, and SO_4^{2-} released by geogenic processes surpassed environmental standards in groundwater with moderate and high co-occurrences with Se pollution. This observation suggests that weathering, oxidation of geological formations, and seawater intrusion that increase Se concentrations also mobilize these anions, leading to their enrichment in groundwater.

Anthropogenic sources caused different degrees of anionic co-pollution in groundwater and surface waters. For instance, Cl^- exceedance, reaching up to 23208 mg/L, was attributed to all anthropogenic sources in groundwater, whereas its release from industrial and agricultural activities primarily affected surface water. This observation is consistent with a previous study identifying industrial effluents as a primary Cl^- source in water (Li, Yang, et al. 2022). Similarly, all anthropogenic sources frequently led to moderate SO_4^{2-} co-pollution of groundwater, while its contamination of surface water predominantly originated from mining and industrial activities. Elevated SO_4^{2-} levels in surface water (as high as 10200 mg/L) can be attributed to Se-enriched leachate from SO_4^{2-} and sulfide minerals and mining drainage, as well as wastewater from coal combustion and metallurgy (Staicu et al. 2020; Yadav and Ghosh 2024). As a significant pollutant with eutrophication potential, particularly in lentic environments (Dodds et al. 2009), PO_4^{3-} was also frequently observed across all sources in surface water at concentrations < 2 mg/L, indicating a strong association with Se pollution. In contrast, F^- and NO_3^- exceedances in groundwater mainly originated from geogenic, industrial, and agricultural activities, whereas their exceedances in surface water were rare for F^-, or limited to mining processes for NO_3^-.

The presence of anionic co-pollutants, particularly SO_4^{2-}, in Se-contaminated environments can have certain antagonistic

EXHIBIT 7 | Qualitative analysis of ions exceeding the environmental standards for drinking water co-occurring with Se.

		Source				
Anion	**Water body**	**Geogenic**	**Mining**	**Industrial activities**	**Agriculture**	**All sources**
Cl^-	Groundwater	++	+++	+++	+++	+++
	Lentic	N.D.	–	+++	+++	+++
	Lotic	N.D.	–	+	+	+
F^-	Groundwater	++	–*	++	++	++
	Lentic	N.D.	–*	–	–	–
	Lotic	N.D.	–	–	–	–
NO_3^-	Groundwater	+++	–*	++	++	++
	Lentic	–*	–	+	–	+
	Lotic	N.D.	++	–	–	+
NO_2^-	Groundwater	N.D.	N.D.	N.D.	N.D.	N.D.
	Lentic	–*	N.D.	–	–	–
	Lotic	N.D.	–*	–	–	–
PO_4^{3-}**	Groundwater	N.D.	N.D.	N.D.	N.D.	N.D.
	Lentic	–*	+++*	++	+	++
	Lotic	N.D.	++	++	++	++
SO_4^{2-}	Groundwater	++	++	++	++	++
	Lentic	N.D.	++	+	–	+
	Lotic	N.D.	+++	+	–*	+

Note: Exceedance scores were categorized as high (+++), moderate (++), low (+), and rare (–), based on the percentage of reported cases exceeding standards. N.D., indicates undetermined cases.
Cl^-, chloride; F^-, fluoride; NO_3^-, nitrate; NO_2^- nitrite, PO_4^{3-}, phosphate; SO_4^{2-}, sulfate.
* Based on a single case
** PO_4^{3-}-P was not evaluated on groundwater and reports showing only phosphorus concentrations were assumed to be PO_4^{3-} and evaluated based on P concentrations

effects on the bioaccumulation of Se. For example, SO_4^{2-} can contribute to a significant mitigation of Se(VI) toxicity in aquatic flora and fauna, possibly due to their similar uptake mechanisms (Ascencio-Damian et al. 2025; Forsythe and Klaine 1994). Conversely, the influence of SO_4^{2-} on Se(IV) uptake is less pronounced, with only a slight mitigative effect observed in aquatic plants and algal species (Ascencio-Damian et al. 2025; Ponton et al. 2020).

5.2 | Metals and Metalloids

Excesses of metals and metalloids in aquatic environments are concerning because of their toxic effects on natural biota and humans (Tables S1.3 and S1.4). The co-occurrence frequency (exceedance) of 15 metals and two metalloids, sorted by source, in groundwater and surface water, is presented in **Exhibit 8**. Due to the scarcity of specific sources reported for Se pollution in coastal and estuarine waters, the occurrence of co-pollutants in these environments could not be analyzed. Similar to Se, most metals and metalloids are mobilized into aquatic environments through common anthropogenic sources, including mining, metal processing, industrial fabrication, fossil fuel burning, the application of pesticides and fertilizers, and irrigation (Saravanan et al. 2024). Geogenic processes also contribute to the mobilization of some of these elements as evidenced by recurrent exceedances primarily in groundwater.

Several metals and metalloids consistently demonstrated overall or source-specific high-frequency co-occurrence with Se in aquatic environments. For example, As had a high frequency and broad distribution across all sources and aquatic environments with exceedances of up to almost 81% among 83 water bodies reporting As concentrations, strongly suggesting its relevance as a co-pollutant with Se. While As concentrations were as high as 11930 µg/L, most concentrations ranged from above the environmental criteria limit of 10 to 100 µg/L. Cd also displayed a high frequency of co-occurrence with Se in groundwater regardless of contamination source, with approximately 66% of exceedances within all reports (n = 70). While mining activities significantly released Cd into surface waters, reaching a peak concentration of over 15000 µg/L, most concentrations were between 3.3 and 70.3 µg/L. Similarly, Pb and Ni co-occurred with Se across all aquatic environments, primarily associated with mining and industrial activities, with concentrations from industrial activities as high as 61300 µg/L for Pb and 43900 µg/L for Ni, respectively. Pb exceedances accounted for 65% of the reported cases (n = 75), with most concentrations ranging from 28 to 3580 µg/L, whereas the

EXHIBIT 8 | Qualitative analysis of metals and metalloids exceeding the environmental criteria co-occurring with Se in drinking water sources.

Metal/metalloid	Water body	Source				All sources
		Geogenic	Mining	Industrial activities	Agriculture	
Al	Groundwater	+	++	+++	+++	++
	Lentic	+++*	++	+++	++	++
	Lotic	–	++	++	+	++
Sb	Groundwater	++	+	++	+++	++
	Lentic	–*	N.D.	–*	–*	–
	Lotic	N.D.	++	++	+++*	++
As	Groundwater	++	+++	+++	+++	+++
	Lentic	++	+++	+++	+++	+++
	Lotic	N.D.	+++	+++	+++	+++
B	Groundwater	+	+++*	++	++	++
	Lentic	–*	++	++	+	+
	Lotic	–	–	+	+	+
Cd	Groundwater	++	+++	+++	+++	++
	Lentic	++	+++	+	++	++
	Lotic	+++	++	++	++	++
Cr	Groundwater	+	++	+++	+++	++
	Lentic	–	++	++	++	+
	Lotic	–	++	++	+	++
Cu	Groundwater	–	–	–	–	–
	Lentic	–	–	–	–	–
	Lotic	–	+	+	–	+
Fe	Groundwater	++	++	++	++	++
	Lentic	–*	+	++	++	+
	Lotic	–	++	++	+	++
Pb	Groundwater	++	+++	+++	+++	+++
	Lentic	+++	++	++	+++	+++
	Lotic	+++	++	++	++	++
Mn	Groundwater	++	+++	+++	+++	+++
	Lentic	++	++	+++*	++	++
	Lotic	–*	++	+++	+	++
Hg	Groundwater	+	+++	++	+++	++
	Lentic	N.D.	++	+++*	N.D.	+++
	Lotic	N.D.	+++	+++	+++	+++
Mo	Groundwater	+	++	++	++	++
	Lentic	–*	++	–*	++	++
	Lotic	N.D.	++	++	++	++
Ni	Groundwater	+	+++	+++	+++	++
	Lentic	–	++	+++	++	++
	Lotic	–	++	+++	++	++
Ag	Groundwater	–	–	–	N.D.	–
	Lentic	+++*	++	–*	+++*	++
	Lotic	N.D.	N.D.	N.D.	N.D.	N.D.

(Continues)

Metal/metalloid	Water body	Source				All sources
		Geogenic	Mining	Industrial activities	Agriculture	
U	Groundwater	+++	++	++	+++*	+++
	Lentic	N.D.	N.D.	N.D.	N.D.	N.D.
	Lotic	N.D.	++	+++*	+++*	+++
V	Groundwater	++	++	+++	+++	++
	Lentic	++	++	–*	++	++
	Lotic	N.D.	++	++	++	++
Zn	Groundwater	–	+	++	+	+
	Lentic	–	+	+	+	+
	Lotic	–	+	+	+	+

Note: Exceedance scores were categorized as high (+++), moderate (++), low (+), and rare (–), based on the percentage of reported cases exceeding standards. N.D., indicates undetermined cases.

Al, aluminum; Sb, antimony; As, arsenic; B, boron; Cd, cadmium; Cr, chromium; Cu, copper; Fe, iron; Pb, lead; Mn, manganese; Hg, mercury; Mo, molybdenum; Ni, nickel; Ag, silver; U, uranium; V, vanadium; Zn, zinc

* Based on a single case.

reported occurrence of Ni was slightly lower with 58% of polluted water bodies being found to have elevated Ni concentrations (*n* = 66), the majority of which were at levels between 193 and 1900 µg/L.

Other elements showed more source-specific co-pollution with Se. Al and Cr were predominantly associated with contamination from industrial effluents, with Al concentrations reaching 25000 µg/L and Cr concentrations primarily ranging from 50 to 847 µg/L, and reaching up to 91200 µg/L. Mining activities specifically induced Hg co-pollution with Se in both surface water and groundwater reaching concentrations as high as 4130 µg/L. Mn co-occurred with Se mainly in groundwater, with less source-dependency, at levels ranging from 290–63800 µg/L. U originates from geogenic processes and primarily affects groundwater sources, although the highest concentration (200 µg/L) was found to be derived from an unknown source; V primarily originated from industrial and agricultural activities, reaching concentrations up to 630 µg/L; and Sb primarily originated from agricultural sources, although the highest concentrations (up to 15000 µg/L) have been reported from mining sources, as Se co-contaminants.

The co-occurrence of hazardous heavy metals and metalloids together with Se contamination poses potential health risks via the intake of contaminated water or fish products. However, the co-bioaccumulation of Se and specific heavy metals has been suggested to have antagonistic effects, which could result in an apparent mitigation of the toxicological effects on flora and fauna, particularly in environments characterized by low levels of Se pollution. For example, at Se-to-metal ratios of > 1, Se has been shown to effectively reduce the accumulation of Cd and Pb in marine fish (Zhao et al. 2024). Similarly, different species of Se have been pointed out to effectively reduce the bioaccumulation of As and Hg in both freshwater and marine fish, with 4- to 6-fold reductions in As-related growth inhibition, and 2- to 4-fold reductions of Hg bioaccumulation (Dang and Wang 2011; Ferreira et al. 2024). The role of Se in heavy metal detoxification in fish is largely attributed to its influence on selenoproteins with antioxidant enzymatic activity such as glutathione peroxidase, catalase, and superoxide dismutase. These enzymes mitigate malondialdehyde levels and lipid peroxidation during exposure to toxic heavy metals (Zhao et al. 2024). An alternative mechanism involves the sequestration of heavy metals, such as As and Hg, into inert Se-complexes; however, this pathway has only been demonstrated in humans and other mammals (Dang and Wang 2011; Ferreira et al. 2024). However, despite these protective benefits, assessments of toxicological parameters, such as half maximum effective and inhibitory concentrations (i.e., EC_{50} and IC_{50}, respectively) for local flora and fauna, will be necessary to determine the threshold between Se-mediated detoxification and Se-induced toxicity.

Metals and metalloids exhibiting moderate to low co-occurrence with Se pollution included B, Cu, Fe, Mo, Ag, and Zn. Among them, Fe and Mo showed moderate co-occurrences across all evaluated sources, B is primarily associated with industrial and agricultural activities, whereas Zn is generally derived from industrial sources. Given that certain metals such as Cu and Zn serve as essential micronutrients, their presence at concentrations below regulatory thresholds could play a beneficial biological role via the enhancement of antioxidant production, thereby maintaining detoxification pathways, as observed in fish (Bagheri et al. 2024). Consequently, these elements may enhance the physiological resilience of aquatic biota and mitigate the human health risks associated with Se pollution.

6 | Limitations and Future Research

Although in this review, we present a comprehensive insight into the global Se pollution status and co-pollutants, certain methodological limitations should be acknowledged. Notably, the heterogeneity of the concentration metrics for Se and co-occurring pollutants, specifically between total and dissolved concentrations, as evidenced by the lack of appropriate preservation methods observed in some studies, requires cautious data aggregation and comparison. The precision of reported concentrations is further influenced by the disparities in analytical instrumentation, detection limits, and calibration protocols among the included studies. In addition, the disproportionate reporting of co-pollutants in the literature may bias co-occurrence patterns, particularly regarding source-specific classifications, as several hazardous co-pollutants (e.g., B, Hg, Mo, U, V, and Ag) remain largely unevaluated despite their relatively high abundance and toxicological relevance. Furthermore, differences in the formats in which the concentration data are presented (e.g., raw data versus descriptive statistics) preclude uniform standardization. The dependence on maximum concentration values for datasets lacking raw values may inadvertently over-represent contaminated sites or amplify the influence of statistical outliers, whereas the number of sampling points mainly observed in studies lacking representativeness could also bias the detection of extreme concentrations. Moreover, the current literatures may be subject to publication bias, with a disproportionate focus on highly contaminated sites, and, consequently, future research should prioritize systematic monitoring of diverse aquatic environments to establish pollution trends more accurately.

On the basis of our literature search, we have described the extent of Se contamination, its spatial distribution, and the typical co-pollutants. The findings obtained are useful for selecting remedial technologies to cleanup Se-contaminated water bodies and for determining future technical development directions. Although certain available technologies are based on the adsorption of soluble Se and specific co-pollutants, such as As (Wei et al. 2021; He et al. 2016), and anaerobic microbial systems which have certain potentials for removing Se, SO_4^{2-} and NO_3^- (Tan, 2018), the relevant studies are limited to wastewater treatment, which are typically characterized by vastly elevated concentrations of Se compared with natural environments, but are not effective or suitable for the remediation of contaminated water bodies. Also, they are generally high-cost technologies, which may not be adopted by Asian and African countries, which are considered as low- and middle-income regions by the World Bank (Metreau et al. 2024). Conversely, phytoremediation offers a promising solution, given the capacity of aquatic plants to simultaneously remove a range of pollutants, as well as being eco-friendly and cost-efficient (Kafle et al. 2022). Phytoremediation also possesses an advantageous feature for the cleanup of Se contamination with co-pollutants in that aquatic plants have certain potential to simultaneously remove various pollutants in addition to Se. For example, phytoremediation by aquatic plants has demonstrated efficient removal of both Se and Ni from diluted mining effluents at concentrations comparable to those identified in this review (Miranda et al. 2014). However, the findings of our previous study revealed that SO_4^{2-}, a further typical Se co-pollutant, severely impairs the removal of Se(VI) by duckweeds, due to uptake competition. Furthermore, Se concentrations > 4000 μg/L have been found to induce severe phytotoxicity in duckweed species, thereby jeopardizing their phytoremediation capacity (Ascencio-Damian et al. 2025). These observations thus indicate that whereas phytoremediation can serve as an effective strategy for addressing low to moderate levels of Se pollution, preferably under conditions of low SO_4^{2-} concentrations, its efficacy in the presence of co-pollutants, such as As, Cd, Pb, and Mn, remains largely unassessed. Accordingly, future research should also focus on the development of effective technologies applicable to the removal of high Se pollution levels (as high as 7640 μg/L) in natural environments.

Our synthesis of data for the purposes of this review enabled us to identify certain key research gaps requiring urgent attention. Although we identified Asia, particularly India, as a region with a high incidence of Se-polluted environments, this may reflect a geographical reporting bias rather than a lack of contamination elsewhere. Consequently, further evaluations are required in under-studied regions, such as North America, South America, and Africa, in which coal and metal mining are prevalent activities, or areas with reported seleniferous soils or with Se-intensive industries. A further potential gap concerns that the adequate speciation of Se found in the contaminated water bodies has rarely been reported. Although we found that a majority of the reviewed studies reported total Se concentrations, the efficiency of remediation technologies differs markedly with respect to different Se species, and, consequently, chemical speciation is viewed as a necessary step for effective global Se pollution management. In addition, although temporal patterns have been examined in multiple areas, particularly those affected by climatological events (e.g., monsoons), a majority of the reviewed studies did not include long-term monitoring that would effectively reflect temporal variability, which will also be a vital step for proper management of Se pollution. A further limitation of this review is that the human health risk associated with Se contamination could not be comprehensively assessed, as these risks are determined by a diverse range of factors.

7 | Conclusion

While previous reviews have documented Se pollution in aquatic environments, this review addresses a critical knowledge gap by providing the first detailed analysis of source-based Se concentrations and quantifying the global impact of various anthropogenic and natural pollution sources. In addition, this review offers the first comprehensive evaluation of inorganic co-pollutants, a requirement for developing effective remediation technologies for real-world aquatic environments. Furthermore, this review identified several under-researched areas that should be addressed in future research, including periodical analyses of Se contamination, monitoring in under-evaluated regions, Se speciation at contaminated sites, and the targeted assessment of the risk to human health and local biota.

This review demonstrates that global aquatic environments affected by Se exhibit different degrees of contamination. High pollution levels > 1000 μg/L primarily generated by anthropogenic sources, were observed in groundwater, and with less frequency, in surface water, reaching as high as 7640 μg/L. Notably, this review revealed that moderate pollution levels, ranging from 100–1000 μg/L, are the most prevalent across all natural and anthropogenic sources and freshwater environments (n = 59 out of 116 water bodies). This indicates that remediation and cleanup efforts and future research should prioritize the development of technologies optimized for these specific sources and moderate-to-high concentration ranges. Such advancements are essential for achieving SDGs, particularly in regions with middle and low income where cost-effective solutions for these pollution levels are most critical.

This review reveals that Se contamination often co-occurs with other pollutants. While previous research has focused on Se as a standalone target or on the removal of Se and certain co-pollutants in wastewater, our findings reveal a global co-occurrence of inorganic pollutants within aquatic environments. For instance, common co-pollutants include the anions Cl^-, which was prevalent across all environments, and PO_4^{3-}, which was mainly observed in lentic surface water. Co-occurrence of metals and metalloids such as As, Cd, Pb, and Ni was prevalent regardless of the contamination source, whereas the presence of other elements such as Al, Cr, Hg, Mn, U, V, and Sb was mainly source-dependent. The widespread co-occurrence of these pollutants at varying concentrations underscores the need for effective Se remediation technologies that can be applied to co-occurring pollutants in real-world aquatic matrices.

Acknowledgments

Jorge Enrique Ascencio-Damian gratefully acknowledges the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan, for the PhD scholarship. We would also like to thank Editage (www.editage.com) for English language editing throughout the work. During the preparation of this work, the authors used Gemini 3 to improve clarity and readability in the abstract and main text. After using this tool, the authors carefully reviewed, verified, and edited the content, and they take full responsibility for the content of the publication.

Funding

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data are presented in the manuscript and supplementary materials.

References

Abba, S. I., M. A. Yassin, S. M. H. Shah, et al. 2024. "Trace Element Pollution Tracking in the Complex Multi-Aquifer Groundwater System of Al-Hassa Oasis (Saudi Arabia) Using Spatial, Chemometric and Index-based Techniques." *Environmental Research* 249: 118320. https://doi.org/10.1016/j.envres.2024.118320.

Abusu, C. O. 2021. "Groundwater Heavy Metal Pollution and human Health Risk Assessment in Shendam Area, North central Nigeria." *Savanna Journal of Basic and Applied Sciences* 3, no. 1: 43–52.

Acioly, T. M. d. S., M. F. da Silva, L. A. Barbosa, J. Iannacone, and D. C. Viana. 2024. "Levels of Potentially Toxic and Essential Elements in Water and Estimation of human Health Risks in a River Located at the Interface of Brazilian Savanna and Amazon Biomes (Tocantins River)." *Toxics* 12, no. 7. https://doi.org/10.3390/toxics12070444.

Afolabi, O. O., P. B. Okwori, O. I. T. Yemi-Jonathan, et al. 2024. "Ecotoxicological Status, Source Apportionment and human Health Risk Assessment of Potential Toxic Element in Surface Water and Sediments of Creeks Along Bonny River, Nigeria." *Watershed Ecology and the Environment* 6: 105–113. https://doi.org/10.1016/j.wsee.2024.06.001.

Ahmed, A. H., W. E. Rayaleh, A. Zghibi, and B. Ouddane. 2017. "Assessment of Chemical Quality of Groundwater in Coastal Volcano-sedimentary Aquifer of Djibouti, Horn of Africa." *Journal of African Earth Sciences* 131: 284–300. https://doi.org/10.1016/j.jafrearsci.2017.04.010.

Al-Agroudy, N., and R. Elmorsi. 2022. "Progressive Improvement of the Water Quality Criteria of Lake Manzala, Egypt." *Egyptian Journal of Aquatic Biology and Fisheries* 26, no. 3: 31–43. https://doi.org/10.21608/ejabf.2022.235089.

Alqahtani, F. Z., S. Y. Daifallah, Y. F. Alaryan, A. M. Elkhaleefa, and E. I. Brima. 2020. "Assessment of Major and Trace Elements in Drinking Groundwater in Bisha Area, Saudi Arabia." *Journal of Chemistry* 2020: 5265634. https://doi.org/10.1155/2020/5265634.

Alshehri, F., and F. K. Zaidi. 2023. "Hydrochemical Assessment of Groundwater From the Harrat Khyber Flood Basalts, Northwest Saudi Arabia." *ACS Omega* 8, no. 45: 42186–42196. https://doi.org/10.1021/acsomega.3c04008.

Alshehri, F., S. Almadani, A. S. El-Sorogy, E. Alwaqdani, H. J. Alfaifi, and T. Alharbi. 2021. "Influence of Seawater Intrusion and Heavy Metals Contamination on Groundwater Quality, Red Sea Coast, Saudi Arabia." *Marine Pollution Bulletin* 165: 112094. https://doi.org/10.1016/j.marpolbul.2021.112094.

America, A., and P. Mafimisebi. 2024. "Assessment of Heavy Metal Concentration in Water Around the Ijokodo Catchment Area in Ibadan, Oyo State, Nigeria." *International Journal of Trendy Research in Engineering and Technology* 8, no. 6: 01–07. https://doi.org/10.54473/IJTRET.2024.8601.

Aras, S., and N. Arslan. 2024. "The Effect of Water Quality on the Structure and Distribution of Benthic Community and Evaluation of the Lake's Water With some Water Quality Indices: a Case Study of Büyük Akgöl Lake." *Biology Bulletin* 51, no. 3: 746–760. https://doi.org/10.1134/S1062359023603324.

Ariunbileg, S., O. Gaskova, A. Vladimirov, A. Battushig, and E. Moroz. 2016. "Spatial Distribution of Uranium and Metalloids in Groundwater near Sandstone-type Uranium Deposits, Southern Mongolia." *Geochemical Journal* 50, no. 5: 393–401. https://doi.org/10.2343/geochemj.2.0434.

Aryal, M. 2024. "An Analysis of Drinking Water Quality Parameters to Achieve Sustainable Development Goals in Rural and Urban Areas of Besisahar, Lamjung, Nepal." *World Water Policy* 10, no. 1: 297–323. https://doi.org/10.1002/wwp2.12073.

Ascencio-Damian, J. E., D. Inoue, and M. Ike. 2025. "Screening of Selenium-tolerant Duckweeds and Evaluation of Their Selenium Removal Capability." *Environmental Technology & Innovation* 40: 104486. https://doi.org/10.1016/j.eti.2025.104486.

Au, A., A. Mojadadi, J. Y. Shao, G. Ahmad, and P. K. Witting. 2023. "Physiological Benefits of Novel Selenium Delivery via Nanoparticles." *International Journal of Molecular Sciences* 24, no. 7: 6068. https://doi.org/10.3390/ijms24076068.

Avigliano, E., B. Maichak de Carvalho, R. Invernizzi, M. Olmedo, R. Jasan, and A. V. Volpedo. 2019. "Arsenic, Selenium, and Metals in a Commercial and Vulnerable Fish From Southwestern Atlantic Estuaries: distribution in Water and Tissues and Public Health Risk Assessment." *Environmental Science and Pollution Research* 26, no. 8: 7994–8006. https://doi.org/10.1007/s11356-019-04258-3.

Bagheri, S., A. Gholamhosseini, S. Hoseinifar, and M. Banaee. 2024. "Investigation of the Effects of Heavy Metals (copper, cobalt, manganese, selenium, and zinc) on Fish Immune Systems—An Overview." *Annals of Animal Science* 24, no. 4: 1025–1035. https://doi.org/10.2478/aoas-2024-0017.

Bai, S., M. Zhang, S. Tang, et al. 2025. "Effects and Impact of Selenium on Human Health, a Review." *Molecules* 30, no. 1: 50. https://doi.org/10.3390/molecules30010050.

Brandt, J. E., E. S. Bernhardt, G. S. Dwyer, and R. T. Di Giulio. 2017. "Selenium Ecotoxicology in Freshwater Lakes Receiving Coal Combustion Residual Effluents: a North Carolina Example." *Environmental*

Science and Technology 51, no. 4: 2418–2426. https://doi.org/10.1021/acs.est.6b05353.

Carswell, K. 2016. Background Groundwater Concentrations of Dissolved Selenium in the Kamloops, BC Area—Characterization, Spatial Distribution, and Management. Master's Thesis, Royal Roads University.

Ccanccapa-Cartagena, A., B. Paredes, C. Vera, et al. 2021. "Occurrence and Probabilistic Health Risk Assessment (PRA) of Dissolved Metals in Surface Water Sources in Southern Peru." *Environmental Advances* 5: 100102. https://doi.org/10.1016/j.envadv.2021.100102.

Chen, Q., J. C. Wei, C. P. Jia, et al. 2019. "Groundwater Selenium Level and Its Enrichment Dynamics in Seawater Intrusion Area Along the Northern Coastal Zones of Shandong Province, China." *Geochemistry International* 57, no. 11: 1236–1242. https://doi.org/10.1134/S0016702919110065.

Cooke, C. A., C. A. Emmerton, and P. E. Drevnick. 2024. "Legacy Coal Mining Impacts Downstream Ecosystems for Decades in the Canadian Rockies." *Environmental Pollution* 344: 123328. https://doi.org/10.1016/j.envpol.2024.123328.

Couto, C. M. C. M., C. Ribeiro, A. R. Ribeiro, et al. 2019. "Spatiotemporal Distribution and Sources of Trace Elements in Ave River (Portugal) Lower Basin: Estuarine Water, Sediments and Indigenous Flora." *International Journal of Environmental Research* 13, no. 2: 303–318. https://doi.org/10.1007/s41742-019-00174-z.

Dang, F., and W.-X. Wang. 2011. "Antagonistic Interaction of Mercury and Selenium in a Marine Fish Is Dependent on Their Chemical Species." *Environmental Science & Technology* 45, no. 7: 3116–3122. https://doi.org/10.1021/es103705a.

Desai, B., V. Tathavadkar, S. Basu, and K. Vakil. 2016. "Behavior of Selenium in Copper Smelting Slag." In *Advances in Molten Slags, Fluxes, and Salts: Proceedings of the 10th International Conference on Molten Slags, Fluxes and Salts 2016*, edited by R. G. Reddy, P. Chaubal, P. C. Pistorius, and U. Pal, 677–685. Springer International Publishing. https://doi.org/10.1007/978-3-319-48769-4_72.

Dey, M., A. Akter, S. Islam, et al. 2021. "Assessment of Contamination Level, Pollution Risk and Source Apportionment of Heavy Metals in the Halda River Water, Bangladesh." *Heliyon* 7, no. 12: e08625. https://doi.org/10.1016/j.heliyon.2021.e08625.

Dietrich, M., and J. C. Ayers. 2022. "Element Transport and Partitioning Along Tidal Channels in Southwest Bangladesh." *Estuaries and Coasts* 45, no. 7: 1948–1966. https://doi.org/10.1007/s12237-022-01082-w.

Diyabalanage, S., S. Abekoon, I. Watanabe, et al. 2016. "Has Irrigated Water From Mahaweli River Contributed to the Kidney Disease of Uncertain Etiology in the Dry Zone of Sri Lanka?" *Environmental Geochemistry and Health* 38, no. 3: 679–690. https://doi.org/10.1007/s10653-015-9749-1.

Dodds, W. K., W. W. Bouska, J. L. Eitzmann, et al. 2009. "Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages." *Environmental Science and Technology* 43, no. 1: 12–19. https://doi.org/10.1021/es801217q.

Dudka, S., and D. C. Adriano. 1997. "Environmental Impacts of Metal Ore Mining and Processing: a Review." *Journal of Environmental Quality* 26, no. 3: 590–602. https://doi.org/10.2134/jeq1997.00472425002600030003x.

Egbueri, J. C., and M. T. Enyigwe. 2020. "Pollution and Ecological Risk Assessment of Potentially Toxic Elements in Natural Waters From the Ameka Metallogenic District in Southeastern Nigeria." *Analytical Letters* 53, no. 17: 2812–2839. https://doi.org/10.1080/00032719.2020.1759616.

Ehya, F., and Z. Marbouti. 2016. "Hydrochemistry and Contamination of Groundwater Resources in the Behbahan Plain, SW Iran." *Environmental Earth Sciences* 75, no. 6: 455. https://doi.org/10.1007/s12665-016-5320-3.

El-Ramady, H. R., É. Domokos-Szabolcsy, N. A. Abdalla, et al. 2014. "Selenium and Nano-selenium in Agroecosystems." *Environmental Chemistry Letters* 12, no. 4: 495–510. https://doi.org/10.1007/s10311-014-0476-0.

Environmental Protection Agency. 1999. National recommended water quality criteria—Aquatic life criteria table. https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table.

Etim, E. U. 2017. "Occurrence and Distribution of Arsenic, Antimony and Selenium in Shallow Groundwater Systems of Ibadan Metropolis, Southwestern Nigerian." *Journal of Health & Pollution* 7, no. 13: 32–41. https://doi.org/10.5696/2156-9614-7-13.32.

Feng, R. W., P. P. Zhao, Y. M. Zhu, et al. 2021. "Application of Inorganic Selenium to Reduce Accumulation and Toxicity of Heavy Metals (Metalloids) in Plants: the Main Mechanisms, Concerns, and Risks." *Science of the Total Environment* 771: 144776. https://doi.org/10.1016/j.scitotenv.2020.144776.

Ferreira, N. d. S., P. H. d. Costa, Í. P. de Sá, et al. 2024. "Arsenic Bioaccumulation and Biotransformation in Different Tissues of Nile Tilapia (*Oreochromis niloticus*): a Comparative Study Between As(III) and As(V) Exposure and Evaluation of Antagonistic Effects of Selenium." *Chemosphere* 359: 142289. https://doi.org/10.1016/j.chemosphere.2024.142289.

Figueiredo, M. O., T. P. Silva, J. P. Veiga, M.-J. Batista, E. Salas-Colera, and D. P. de Oliveira. 2014. "Selenium Speciation in Waste Materials From an Exhausted iberian Pyrite Belt Mine." *Journal of Materials Science Research* 3, no. 4: 22–30. https://doi.org/10.5539/jmsr.v3n4p22.

Fordyce, F. M. 2013. "Selenium Deficiency and Toxicity in the environment." In *Essentials of Medical Geology*, edited by O. Selinus, 375–416. Springer. https://doi.org/10.1007/978-94-007-4375-5_16.

Forsythe, B. L., and S. J. Klaine. 1994. "The Interaction of Sulfate and Selenate (Se^{+6}) Effects on Brine Shrimp, *Artemia* SPP." *Chemosphere* 29, no. 4: 789–800. https://doi.org/10.1016/0045-6535(94)90047-7.

Genthe, B., T. Kapwata, W. Le Roux, J. Chamier, and C. Y. Wright. 2018. "The Reach of human Health Risks Associated With Metals/Metalloids in Water and Vegetables Along a Contaminated River Catchment: South Africa and Mozambique." *Chemosphere* 199: 1–9. https://doi.org/10.1016/j.chemosphere.2018.01.160.

Gharaat, M. J., Z. Mohammadi, and F. Rezanezhad. 2020. "Distribution and Origin of Potentially Toxic Elements in a Multi-aquifer System." *Environmental Science and Pollution Research* 27, no. 35: 43724–43742. https://doi.org/10.1007/s11356-020-10223-2.

Gilles, D. G., and R. C. Loehr. 1994. "Waste Generation and Minimization in Semiconductor Industry." *Journal of Environmental Engineering* 120, no. 1: 72–86. https://doi.org/10.1061/(ASCE)0733-9372(1994)120:1(72).

Guruge, K. S., P. Goswami, I. Watanabe, et al. 2017. "Trace Element Distribution and Risk Assessment in South Indian Surface Waterways." *International Journal of Environmental Science and Technology* 14, no. 1: 1–18. https://doi.org/10.1007/s13762-016-1129-6.

Hamed, M. H. 2024. "Concentration of Heavy Metals and Heavy Metal Pollution Index Used for Groundwater Quality Assessment in Shamamik Basin in Erbil Governorate, Northern Iraq." *Iraqi National Journal of Earth Science* 24, no. 1: 70–84. https://doi.org/10.33899/earth.2023.140292.1082.

Hansen, D., P. J. Duda, A. Zayed, and N. Terry. 1998. "Selenium Removal by Constructed Wetlands: role of Biological Volatilization." *Environmental Science & Technology* 32, no. 5: 591–597. https://doi.org/10.1021/es970502l.

Hao, L., S. Zhang, and K. Luo. 2022. "Content of Selenium and Other Elements, Water Quality, Health Risks and Utilization Prospect in Natural Water of Southern Qinling-Daba Mountains, Southern Shaanxi, China." *Exposure and Health* 14, no. 1: 29–47. https://doi.org/10.1007/s12403-021-00416-6.

Hao, W., H. Liu, S. Hao, and K. Mao. 2024. "Characterization of Heavy Metal Contamination in Groundwater of Typical Mining Area in Hunan Province." *Scientific Reports* 14: 13054. https://doi.org/10.1038/s41598-024-63460-7.

Hao, X., D. Wang, P. Wang, Y. Wang, and D. Zhou. 2016. "Evaluation of Water Quality in Surface Water and Shallow Groundwater: A Case Study of a Rare Earth Mining Area in Southern Jiangxi Province, China."

Environmental Monitoring and Assessment 188, no. 1: 1–11. https://doi.org/10.1007/s10661-015-5025-1.

Haug, A., R. D. Graham, O. A. Christophersen, and G. H. Lyons. 2007. "How to Use the World's Scarce Selenium Resources Efficiently to Increase the Selenium Concentration in Food." *Microbial Ecology in Health and Disease* 19, no. 4: 209–228. https://doi.org/10.1080/08910600701698986.

Hay, M. B., G. Leone, F. Partey, and B. Wilking. 2016. "Selenium Attenuation via Reductive Precipitation in Unsaturated Waste Rock as a Control on Groundwater Impacts in the Idaho Phosphate Patch." *Applied Geochemistry* 74: 176–193. https://doi.org/10.1016/j.apgeochem.2016.09.008.

He, Y., Y. P. Tang, and T. S. Chung. 2016. "Concurrent Removal of Selenium and Arsenic From Water Using Polyhedral Oligomeric Silsesquioxane (POSS)–Polyamide Thin-film Nanocomposite Nanofiltration Membranes." *Industrial & Engineering Chemistry Research* 55, no. 50: 12929–12938. https://doi.org/10.1021/acs.iecr.6b04272.

He, Y., Y. Xiang, Y. Zhou, et al. 2018. "Selenium Contamination, Consequences and Remediation Techniques in Water and Soils: a Review." *Environmental Research* 164: 288–301. https://doi.org/10.1016/j.envres.2018.02.037.

Hendry, M. J., A. Biswas, J. Essilfie-Dughan, N. Chen, S. J. Day, and S. L. Barbour. 2015. "Reservoirs of Selenium in Coal Waste Rock: Elk Valley, British Columbia, Canada." *Environmental Science and Technology* 49, no. 13: 8228–8236. https://doi.org/10.1021/acs.est.5b01246.

Hong, Q. N., P. Pluye, S. Fàbregues, et al. 2018. Mixed Methods Appraisal Tool (MMAT) version 2018.

Hossain, I., M. K. Ahmed, K. M. A. Chowdhury, M. Moniruzzaman, and M. T. Alim Shampa. 2024. "Ecological Risk Assessment of Oil & Grease (OG) and Heavy Metals in the Surface Water of Naf River, Bangladesh." *Heliyon* 10, no. 9: e30271. https://doi.org/10.1016/j.heliyon.2024.e30271.

Huda, M. N., M. Harun-Ur-Rashid, A. Hosen, et al. 2024. "A Potential Toxicological Risk Assessment of Heavy Metals and Pesticides in Irrigated Rice Cultivars near Industrial Areas of Dhaka, Bangladesh." *Environmental Monitoring and Assessment* 196, no. 9: 794. https://doi.org/10.1007/s10661-024-12927-1.

Ibrahim, A. T., E. T. Wassif, and M. S. Alfons. 2016. "Heavy Metals Assessment in Water, Sediments and Some Organs of *Oreochromis niloticus* Under the Impact of Sewage Water." *Journal of Heavy Metal Toxicity and Diseases* 1, no. 1: 4. https://doi.org/10.21767/2473-6457.100004.

Ibrahim, S. A., B. S. Al-Tawash, and M. F. Abed. 2018. "Environmental Assessment of Heavy Metals in Surface and Groundwater at Samarra City, central Iraq." *Iraqi Journal of Science* 59, no. 3A: 1277–1284. https://doi.org/10.24996/ijs.2018.59.3A.16.

Ioele, G., M. De Luca, F. Grande, et al. 2020. "Assessment of Surface Water Quality Using Multivariate Analysis: case Study of the Crati River, Italy." *Water* 12, no. 8: 2214. https://doi.org/10.3390/w12082214.

Irfan, S., and A. M. M. Alatawi. 2019. "Aquatic Ecosystem and Biodiversity: A Review." *Open Journal of Ecology* 9, no. 1: 1–13. https://doi.org/10.4236/oje.2019.91001.

Issa, H. M., and A. Alshatteri. 2018. "Assessment of Heavy Metals Contamination in Drinking Water of Garmian Region, Iraq." *UHD Journal of Science and Technology* 2, no. 2: 40–53. https://doi.org/10.21928/uhdjst.v2n2y2018.pp40-53.

Jiao, Y., Y. Liu, W. Wang, et al. 2023. "Heavy Metal Distribution Characteristics, Water Quality Evaluation, and Health Risk Evaluation of Surface Water in Abandoned Multi-year Pyrite Mine Area." *Water* 15, no. 17: 3138. https://doi.org/10.3390/w15173138.

Kafle, A., A. Timilsina, A. Gautam, K. Adhikari, A. Bhattarai, and N. Aryal. 2022. "Phytoremediation: mechanisms, Plant Selection and Enhancement by Natural and Synthetic Agents." *Environmental Advances* 8: 100203. https://doi.org/10.1016/j.envadv.2022.100203.

Kapoor, K., S. Kumar, D. K. Vishwakarma, A. J. Obaidullah, and K. K. Yadav. 2024. "Health Risk Assessment of Heavy Metals in Groundwater Sources: Carcinogenic and Non-carcinogenic Evaluation." *Journal of Water and Health* 22, no. 10: 1972–1987. https://doi.org/10.2166/wh.2024.243.

Kashyap, R., K. S. Verma, S. K. Uniyal, and S. K. Bhardwaj. 2018. "Geospatial Distribution of Metal(loid)s and human Health Risk Assessment Due to Intake of Contaminated Groundwater Around an Industrial Hub of northern India." *Environmental Monitoring and Assessment* 190, no. 3: 136. https://doi.org/10.1007/s10661-018-6525-6.

Kazemi, A., M. Esmaeilbeigi, Z. Sahebi, and S. J. Shooshtari. 2022. "Hydrochemical Evaluation of Groundwater Quality and human Health Risk Assessment of Trace Elements in the Largest Mining District of South Khorasan, Eastern Iran." *Environmental Science and Pollution Research* 29, no. 54: 81804–81829. https://doi.org/10.1007/s11356-022-21494-2.

Kennedy, G., M. B. Ahern, L. L. Iannotti, S. Vie, L. Sherburne, and S. H. Thilsted. 2023. "Considering the Food Environment Can Help to Promote the Consumption of Aquatic Foods for Healthy Diets." *Frontiers in Sustainable Food Systems* 7: 1241548. https://doi.org/10.3389/fsufs.2023.1241548.

Kenzhaliyev, B. K., S. A. Trebukhov, V. N. Volodin, A. A. Trebukhov, and F. H. Tuleutay. 2018. "Selenium Extraction out of Metallurgical Production Middlings." *Complex Use of Mineral Resources* 307, no. 4: 56–64. https://doi.org/10.31643/2018/6445.30.

Khamkhash, A., V. Srivastava, T. Ghosh, G. Akdogan, R. Ganguli, and S. Aggarwal. 2017. "Mining-related Selenium Contamination in Alaska, and the state of Current Knowledge." *Minerals* 7, no. 3: 46. https://doi.org/10.3390/min7030046.

Khan, M. Y. A., M. ElKashouty, N. Khan, A. M. Subyani, and F. Tian. 2023. "Spatio-temporal Evaluation of Trace Element Contamination Using Multivariate Statistical Techniques and Health Risk Assessment in Groundwater, Khulais, Saudi Arabia." *Applied Water Science* 13, no. 6: 123. https://doi.org/10.1007/s13201-023-01928-z.

Kharaka, Y. K., G. Ambats, T. S. Presser, and R. A. Davis. 1996. "Removal of Selenium From Contaminated Agricultural Drainage Water by Nanofiltration Membranes." *Applied Geochemistry* 11, no. 6: 797–802. https://doi.org/10.1016/S0883-2927(96)00044-3.

Kieliszek, M. 2019. "Selenium–fascinating Microelement, Properties and Sources in Food." *Molecules* 24, no. 7: 1298. https://doi.org/10.3390/molecules24071298.

Kumar, P., C. A. Vishwakarma, P. Singh, et al. 2024. "Hydrogeochemical Characterization and Water Quality Evaluation for Drinking and Irrigation Purposes of Coastal Aquifers of Middle Andaman." *Discover Applied Sciences* 6, no. 5: 228. https://doi.org/10.1007/s42452-024-05889-z.

Kumar, R., S. Mittal, S. Peechat, P. K. Sahoo, and S. K. Sahoo. 2020. "Quantification of Groundwater–agricultural Soil Quality and Associated Health Risks in the Agri-intensive Sutlej River Basin of Punjab, India." *Environmental Geochemistry and Health* 42, no. 12: 4245–4268. https://doi.org/10.1007/s10653-020-00636-w.

Lapworth, D. J., G. Krishan, A. M. MacDonald, and M. S. Rao. 2017. "Groundwater Quality in the Alluvial Aquifer System of Northwest India: New Evidence of the Extent of Anthropogenic and Geogenic Contamination." *Science of the Total Environment* 599–600: 1433–1444. https://doi.org/10.1016/j.scitotenv.2017.04.223.

Lateef, Z. Q., A. S. T. Al-Madhhachi, and D. E. Sachit. 2020. "Evaluation of Water Quality Parameters in Shatt Al-Arab, Southern Iraq, Using Spatial Analysis." *Hydrology* 7, no. 4: 79. https://doi.org/10.3390/hydrology7040079.

Lemly, D. A. 2009. "Aquatic Hazard of Selenium Pollution From Coal Mining." In *Coal Mining: Research, Technology and Safety*, edited by G. B. Fosdyke, 167–183. Nova Science Publishers, Inc.

Li, T., H. Xu, Y. Zhang, et al. 2022. "Treatment Technologies for Selenium Contaminated Water: A Critical Review." *Environmental Pollution* 299: 118858. https://doi.org/10.1016/j.envpol.2022.118858.

Li, X., Z. Meng, L. Bao, et al. 2024. "Occurrence, Bioaccumulation, and Risk Evaluation of Selenium in Typical Chinese Aquatic Ecosystems." *Journal of Cleaner Production* 435: 140552. https://doi.org/10.1016/j.jclepro.2023.140552.

Li, Y., Z. Yang, K. Yang, et al. 2022. "Removal of Chloride From Water and Wastewater: Removal Mechanisms and Recent Trends." *Science of the Total Environment* 821: 153174. https://doi.org/10.1016/j.scitotenv.2022.153174.

Lichtfouse, E., N. Morin-Crini, C. Bradu, et al. 2022. "Methods for Selenium Removal From Contaminated Waters: A Review." *Environmental Chemistry Letters* 20, no. 3: 2019–2041. https://doi.org/10.1007/s10311-022-01419-8.

Lichtfouse, E., N. Morin-Crini, C. Bradu, et al. 2021. "Technologies to Remove Selenium From Water and Wastewater." In *Chemistry for a Sustainable World*, edited by N. Morin-Crini, E. Lichtfouse, and G. Crini, Vol. 66, 207–304. Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-69090-8_3.

Linard, J. I., P. B. McMahon, L. R. Arnold, and J. C. Thomas. 2017. Response of Selenium Concentrations in Groundwater to Seasonal Canal Leakage, Lower Gunnison River Basin, Colorado, 2013 (version 1.1, January 2017). https://dx.doi.org/10.3133/sir20165047.

Liu, H., L. Chen, Y. Shen, et al. 2024. "Advances in Selenium From Materials to Applications." *Nanotechnology* 35, no. 24: 242003. https://doi.org/10.1088/1361-6528/ad32d3.

Lombeck, I., H. Menzel, and D. Frosch. 1987. "Acute Selenium Poisoning of a 2-Year-Old Child." *European Journal of Pediatrics* 146, no. 3: 308–312. https://doi.org/10.1007/BF00716483.

Luo, Y., T. Li, S. Zhang, L. Hao, and K. Luo. 2024. "Chemical Characteristics and Health Risk Evaluation of Natural Waters in the Du River Source National Nature Reserve: A Case Study in Zhushan County, Hubei Province, China." *Environmental Research* 251: 118656. https://doi.org/10.1016/j.envres.2024.118656.

Ma, S., F. Xu, D. Qiu, et al. 2022. "The Occurrence, Transformation and Control of Selenium in Coal-Fired Power Plants: Status Quo and Development." *Journal of the Air and Waste Management Association* 72, no. 2: 131–146. https://doi.org/10.1080/10962247.2021.2010620.

Madikizela, L. M., L. Chimuka, and S. Ncube. 2023. "Metal Pollution Source Apportionment in Two Important Rivers of Eastern Cape Province, South Africa: a Case Study of Bizana and Mthatha Rivers." *Environmental Forensics* 24, no. 1–2: 71–84. https://doi.org/10.1080/15275922.2021.1940382.

Mahdi, A. J., H. M. Ewadh, S. Satee, J. M. Salman, and P. Brahmaji Rao. 2022. "Comprehensive Study of Heavy Metal Pollution in Surface Water of Guntur Region of Andra Pradesh." *IOP Conference Series: Earth and Environmental Science*, 1088, 012016. https://doi.org/10.1088/1755-1315/1088/1/012016.

Mali, M., M. R. Alfio, G. Balacco, G. Ranieri, V. Specchio, and M. D. Fidelibus. 2024. "Mobility of Trace Elements in a Coastal Contaminated Site Under Groundwater Salinization Dynamics." *Scientific Reports* 14, no. 1: 24859. https://doi.org/10.1038/s41598-024-75974-1.

Mambou Ngueyep, L. L., S. Takougang-Kingni, M. Ayiwouo-Ngounouno, and A. A. Ndi. 2021. "The Impact of Gold Mining Exploitation on the Physicochemical Quality of Water: Case of Batouri (Cameroon)." *International Journal of Energy and Water Resources* 5, no. 2: 159–173. https://doi.org/10.1007/s42108-020-00106-0.

Mandindi, W. Z., L. Nyaba, N. Mketo, and P. N. Nomngongo. 2022. "Seasonal Variation of Drinking Water Quality and human Health Risk Assessment: a Case Study in Rural Village of the Eastern Cape, South Africa." *Water* 14, no. 13: 2013. https://doi.org/10.3390/w14132013.

Mane, P. C., D. D. Kadam, R. D. Chaudhari, et al. 2017. "Evaluation of some Water Quality Parameters With Special Reference to Health—A Case Study of Manikdoh Dam, Junnar, Maharashtra." *World Journal of Pharmacy and Pharmaceutical Sciences* 6, no. 10: 1311–1319. https://doi.org/10.20959/wjpps201710-10261.

Maret, T. R., and K. D. Skinner. 2000. Concentrations of Selected Trace Elements in Fish Tissue and Streambed Sediment in the Clark Fork-Pend Oreille and Spokane River Basins, Washington, Idaho, and Montana, 1998 National Water-Quality Assessment Program Boise, Idaho 2000. https://doi.org/10.3133/wri004159.

Maskooni, E. K., M. Naseri-Rad, R. Berndtsson, and K. Nakagawa. 2020. "Use of Heavy Metal Content and Modified Water Quality Index to Assess Groundwater Quality in a Semiarid Area." *Water* 12, no. 4: 1115. https://doi.org/10.3390/w12041115.

Mechora, Š. 2019. "Selenium as a Protective Agent Against Pests: A Review." *Plants* 8, no. 8: 262. https://doi.org/10.3390/plants8080262.

Mechora, Š., V. Stibilj, and M. Germ. 2015. "Response of Duckweed to Various Concentrations of Selenite." *Environmental Science and Pollution Research* 22, no. 4: 2416–2422. https://doi.org/10.1007/s11356-014-3270-4.

Mehdi, Y., J. L. Hornick, L. Istasse, and I. Dufrasne. 2013. "Selenium in the Environment, Metabolism and Involvement in Body Functions." *Molecules* 18, no. 3: 3292–3311. https://doi.org/10.3390/molecules18033292.

Metreau, E., K. E. Young, and S. G. Eapen. 2024. World Bank country classifications by income level for 2024–2025. https://blogs.worldbank.org/en/opendata/world-bank-country-classifications-by-income-level-for-2024-2025.

Miranda, A. F., N. Muradov, A. Gujar, et al. 2014. "Application of Aquatic Plants for the Treatment of Selenium-Rich Mining Wastewater and Production of Renewable Fuels and Petrochemicals." *Journal of Sustainable Bioenergy Systems* 4, no. 1: 97–112. https://doi.org/10.4236/jsbs.2014.41010.

Moodley, R., N. T. Mahlangeni, and P. Reddy. 2021. "Determination of Heavy Metals in Selected Fish Species and Seawater From the South Durban Industrial Basin, KwaZulu-Natal, South Africa." *Environmental Monitoring and Assessment* 193, no. 4: 206. https://doi.org/10.1007/s10661-021-09014-0.

Mora, A., J. A. Torres-Martínez, C. Moreau, G. Bertrand, and J. Mahlknecht. 2021. "Mapping Salinization and Trace Element Abundance (Including As and Other Metalloids) in the Groundwater of North-Central Mexico Using a Double-Clustering Approach." *Water Research* 205: 117709. https://doi.org/10.1016/j.watres.2021.117709.

Mora, A., J. Mahlknecht, R. Ledesma-Ruiz, W. E. Sanford, and L. E. Lesser. 2020. "Dynamics of Major and Trace Elements During Seawater Intrusion in a Coastal Sedimentary Aquifer Impacted by Anthropogenic Activities." *Journal of Contaminant Hydrology* 232: 103653. https://doi.org/10.1016/j.jconhyd.2020.103653.

Myvizhi, P., and P. Aruna Devi. 2020. "Heavy Metal Contamination in Water of the River Cauvery-A Case Study of Erode, Salem and Namakkal Districts, Tamil Nadu." *Journal of Himalayan Ecology and Sustainable Development* 15: 190–202.

Nurić, A., S. Nurić, and A. Varcaković. 2024. "Heavy Metal Pollution of Water Sources "Šićki Brod" and "Studenac" Due to the Exploitation of Coal." *SAR Journal—Science and Research* 12–18. https://doi.org/10.18421/SAR71-02.

Obasi, P. N., M. O. Eyankware, and E. N. Edene. 2024. "Contamination of Potable Water Supply Sources in the Lead–Zinc Mining Communities of Mkpuma Akpatakpa, Southeastern Nigeria." *International Journal of Energy and Water Resources* 8, no. 2: 225–239. https://doi.org/10.1007/s42108-022-00199-9.

Obasi, P. N., and B. B. Akudinobi. 2020. "Potential Health Risk and Levels of Heavy Metals in Water Resources of Lead–Zinc Mining Communities of Abakaliki, Southeast Nigeria." *Applied Water Science* 10, no. 7: 184. https://doi.org/10.1007/s13201-020-01233-z.

Onyegeme-Okerenta, B. M., and O. L. West. 2023. "Toxicological Evaluation of Contamination by Potentially Toxic Elements (PTEs) and Related Risks in the Surface Waters of Three Tidal Streams of the Niger Delta, Nigeria." *Asian Journal of Environment & Ecology* 20, no. 4: 67–83. https://doi.org/10.9734/ajee/2023/v20i4448.

Ougrad, I., Z. Elassassi, A. Mrabet, et al. 2024. "Health Risk Assessment of Trace Elements in Surface Water From Dayat Roumi Lake, Morocco." *Water* 16, no. 22: 3231. https://doi.org/10.3390/w16223231.

Plata-Enriquez, I. C. 2024. Occurrence, Origin, and Fate of Redox-Sensitive Constituents in Groundwater in Alberta. Doctoral Thesis, University of Calgary. https://hdl.handle.net/1880/119029.

Ponton, D. E., S. D. Graves, C. Fortin, D. Janz, M. Amyot, and M. Schiavon. 2020. "Selenium Interactions With Algae: Chemical Processes at Biological Uptake Sites, Bioaccumulation, and Intracellular Metabolism." *Plants* 9, no. 4: 528. https://doi.org/10.3390/plants9040528.

Poshtegal, M. K., and S. A. Mirbagheri. 2017. "Distribution and Assessment of Heavy Metals and Physicochemical Parameters in Riverine Basin." *European Water* 58: 95–102.

Prasad, B., A. K. Soni, A. Vishwakarma, R. Trivedi, and K. K. K. Singh. 2020. "Evaluation of Water Quality near the Malanjhkhand Copper Mines, India, by Use of Multivariate Analysis and a Metal Pollution Index." *Environmental Earth Sciences* 79, no. 11: 259. https://doi.org/10.1007/s12665-020-09002-6.

Prathap, A., and S. Chakraborty. 2019. "Hydro Chemical Characterization and Suitability Analysis of Groundwater for Domestic and Irrigation Uses in Open Cast Coal Mining Areas of Charhi and Kuju, Jharkhand, India." *Groundwater for Sustainable Development* 9: 100244. https://doi.org/10.1016/j.gsd.2019.100244.

Purushotham, D., D. Linga, N. Sagar, et al. 2017. "Groundwater Contamination in Parts of Nalgonda District, Telangana, India as Revealed by Trace Elemental Studies." *Journal of the Geological Society of India* 90, no. 4: 447–458. https://doi.org/10.1007/s12594-017-0738-0.

Qi, F., F. R. Lin, and A. K. Y. Jen. 2022. "Selenium: a Unique Member in the Chalcogen Family for Conjugated Materials Used in Perovskite and Organic Solar Cells." *Solar RRL* 6, no. 7: 2200156. https://doi.org/10.1002/solr.202200156.

Rajput, S., T. Kaur, S. Arora, and R. Kaur. 2020. "Heavy Metal Concentration and Mutagenic Assessment of Pond Water Samples: A Case Study From India." *Polish Journal of Environmental Studies* 29, no. 1: 789–798. https://doi.org/10.15244/pjoes/103449.

Rekha, R. 2023. "Trace Metals in the Aquatic Environment and Its Effect on Aquatic Life and human Body." *International Journal of Science and Research* 12, no. 11: 789–795. https://doi.org/10.21275/sr231111141341.

Rossi, R. J., R. A. Tisherman, J. M. Jaeger, J. Domen, S. B. C. Shonkoff, and D. C. DiGiulio. 2023. "Historic and Contemporary Surface Disposal of Produced Water Likely Inputs Arsenic and Selenium to Surficial Aquifers." *Environmental Science and Technology* 57, no. 19: 7559–7567. https://doi.org/10.1021/acs.est.3c01219.

Ryser, A. L., D. G. Strawn, M. A. Marcus, J. L. Johnson-Maynard, M. E. Gunter, and G. Möller. 2005. "Micro-Spectroscopic Investigation of Selenium-Bearing Minerals From the Western US Phosphate Resource Area." *Geochemical Transactions* 6, no. 1: 1–11. https://doi.org/10.1063/1.1852751.

Saba, N. U., and R. Umar. 2016. "Hydrogeochemical Assessment of Moradabad City, an Important Industrial Town of Uttar Pradesh, India." *Sustainable Water Resources Management* 2, no. 3: 217–236. https://doi.org/10.1007/s40899-016-0053-8.

Saha, U., A. Fayiga, and L. Sonon. 2017. "Selenium in the Soil-Plant Environment: A Review." *International Journal of Applied Agricultural Sciences* 3, no. 1: 1–18. https://doi.org/10.11648/j.ijaas.20170301.11.

Sahoo, B. P., and H. B. Sahu. 2022. "Assessment of Metal Pollution in Surface Water Using Pollution Indices and Multivariate Statistics: A Case Study of Talcher coalfield Area, India." *Applied Water Science* 12, no. 9: 223. https://doi.org/10.1007/s13201-022-01743-y.

Sahoo, B. P., H. B. Sahu, and D. S. Pradhan. 2021. "Hydrogeochemistry and Surface Water Quality Assessment of IB Valley Coalfield Area, India." *Applied Water Science* 11, no. 9: 153. https://doi.org/10.1007/s13201-021-01433-1.

Saleem, M., and Q. Fariduddin. 2022. "Novel Mechanistic Insights of Selenium Induced Microscopic, Histochemical and Physio-biochemical Changes in Tomato (*Solanum lycopersicum* L.) Plant. An Account of Beneficiality or Toxicity." *Journal of Hazardous Materials* 434: 128830. https://doi.org/10.1016/j.jhazmat.2022.128830.

Saravanan, P., V. Saravanan, R. Rajeshkannan, et al. 2024. "Comprehensive Review on Toxic Heavy Metals in the Aquatic System: Sources, Identification, Treatment Strategies, and Health Risk Assessment." *Environmental Research* 258: 119440. https://doi.org/10.1016/j.envres.2024.119440.

Selvam, S., K. Jesuraja, S. Venkatramanan, et al. 2020. "Imprints of Pandemic Lockdown on Subsurface Water Quality in the Coastal Industrial City of Tuticorin, South India: a Revival Perspective." *Science of the Total Environment* 738: 139848. https://doi.org/10.1016/j.scitotenv.2020.139848.

Selvam, S., A. Antony Ravindran, S. Venkatramanan, and C. Singaraja. 2017. "Assessment of Heavy Metal and Bacterial Pollution in Coastal Aquifers From SIPCOT Industrial Zones, Gulf of Mannar, South Coast of Tamil Nadu, India." *Applied Water Science* 7, no. 2: 897–913. https://doi.org/10.1007/s13201-015-0301-3.

Singh, A. K., S. Das, S. Singh, et al. 2019. "Physicochemical Parameters and Alarming Coliform Count of the Potable Water of Eastern Himalayan state Sikkim: an Indication of Severe Fecal Contamination and Immediate Health Risk." *Frontiers in Public Health* 7: 174. https://doi.org/10.3389/fpubh.2019.00174.

Singh, D. D., P. S. Thind, M. Sharma, S. Sahoo, and S. John. 2019. "Environmentally Sensitive Elements in Groundwater of an Industrial Town in India: spatial Distribution and human Health Risk." *Water* 11, no. 11: 2350. https://doi.org/10.3390/w11112350.

Staicu, L. C., T. Bajda, L. Drewniak, and L. Charlet. 2020. "Power Generation: feedstock for High-value Sulfate Minerals." *Minerals* 10, no. 2: 188. https://doi.org/10.3390/min10020188.

Staicu, L. C., E. D. Van Hullebusch, B. E. Rittmann, and P. N. L. Lens. 2017. "Industrial Selenium Pollution: Sources and Biological Treatment technologies." In *Bioremediation of Selenium Contaminated Wastewater*, edited by E. van Hullebusch, 75–101. Springer. https://doi.org/10.1007/978-3-319-57831-6_4.

Stewart, A. R., M. Grosell, D. B. Buchwalter, et al. 2010. "Bioaccumulation and Trophic Transfer of Selenium." In *Ecological Assessment of Selenium in the Aquatic Environment*, edited by H. M. Ohlendorf, T. S. Presser, and P. Shaw, 93–139. CRC. http://pubs.er.usgs.gov/publication/70198596.

Sundaraiah, R., and V. Sudarshan. 2019. "Water Quality Index of Trace and Heavy Metal Contamination in Groundwater of Kalwakurthy Area, Telangana State of South India." *Pollution Research* 38: 84–99.

Suresh, P., B. A. Ramesh, N. Sharmila, and V. K. Ch. 2019. "ICP-OES Determination of Trace Metals in Groundwater of Proddatur Area, YSR Kadapa dist., AP-India." *Caribbean Journal of Sciences and Technology* 7, no. 1: 1–7.

Tan, L. C. 2018. *Anaerobic Treatment of Mine Wastewater for the Removal of Selenate and Its Co-Contaminants*, 1st ed. CRC Press. https://doi.org/10.1201/9780429448676.

Tan, L. C., Y. V. Nancharaiah, E. D. van Hullebusch, and P. N. L. Lens. 2016. "Selenium: Environmental Significance, Pollution, and Biological Treatment Technologies." *Biotechnology Advances* 34, no. 5: 886–907. https://doi.org/10.1016/j.biotechadv.2016.05.005.

Tan, X., X. L. Xia, S. Y. Li, and Q. F. Zhang. 2015. "Water Quality Characteristics and Integrated Assessment Based on Multistep Correlation Analysis in the Danjiangkou Reservoir, China." *Journal of Environmental Informatics* 25, no. 1: 60–70. https://doi.org/10.3808/jei.201500296.

Teck Coal Limited. 2023. Permit 107517 surface water quality monitoring 2022 annual report. https://www.glencore.ca/.rest/api/v1/documents/4ea0ec5d6251b40524595799f326c65d/Surface-Water-Quality-Monitoring-2022.pdf.

Tian, H., Y. Wang, Z. Xue, Y. Qu, F. Chai, and J. Hao. 2011. "Atmospheric Emissions Estimation of Hg, As, and Se From Coal-Fired Power Plants in China, 2007." *Science of the Total Environment* 409, no. 16: 3078–3081. https://doi.org/10.1016/j.scitotenv.2011.04.039.

Tinggi, U., and A. V. Perkins. 2022. "Selenium Status: Its Interactions With Dietary Mercury Exposure and Implications in Human Health." *Nutrients* 14, no. 24: 5308. https://doi.org/10.3390/nu14245308.

Tokatli, C. 2019. "Water and Sediment Quality Assessment of the Lifeblood of Thrace Region (Turkey): Meriç River Basin." *Fresenius Environmental Bulletin* 28, no. 5: 4131–4140. https://www.researchgate.net/publication/333080227.

Uddin, M. H., J. R. Ritu, S. K. Putnala, M. Rachamalla, D. P. Chivers, and S. Niyogi. 2024. "Selenium Toxicity in Fishes: A Current Perspective." *Chemosphere* 364: 143214. https://doi.org/10.1016/j.chemosphere.2024.143214.

United States Geological Survey. 2024. *Selenium*. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-selenium.pdf.

United States Geological Survey. 2025. How Important Is Groundwater?. https://www.usgs.gov/faqs/how-important-groundwater.

USEPA. 2018. Aquatic Life and Aquatic-Dependent Wildlife Selenium Water Quality Criterion for Freshwaters of California. https://www.epa.gov/sites/default/files/2019-03/documents/ca_statewide_se_tsd_508_compliant.pdf.

Villar, P. F. 2022. Structured Literature Reviews: Building Transparency and Trust in Standards of Reporting Evidence. IEG Methods and Evaluation Capacity Development Working Paper Series. World Bank. https://doi.org/10.1596/IEG178547.

Virk, H. S. 2019. "Selenium Contamination of Groundwater of Malwa Belt of Punjab, India." *Research & Reviews: A Journal of Toxicology* 9, no. 1: 13–20.

Wang, F., J. Zhang, L. Xu, et al. 2024. "Selenium Volatilization in Plants, Microalgae, and Microorganisms." *Heliyon* 10, no. 4: e26023. https://doi.org/10.1016/j.heliyon.2024.e26023.

Wang, L., Y. Ju, G. Liu, C. L. Chou, L. Zheng, and C. Qi. 2010. "Selenium in Chinese Coals: distribution, Occurrence, and Health Impact." *Environmental Earth Sciences* 60, no. 8: 1641–1651. https://doi.org/10.1007/s12665-009-0298-8.

Wang, X., and X. Tan. 2017. "Macroinvertebrate Community in Relation to Water Quality and Riparian Land Use in a Substropical Mountain Stream, China." *Environmental Science and Pollution Research* 24, no. 17: 14682–14689. https://doi.org/10.1007/s11356-017-9042-1.

Waqas, M., K. Ashraf, M. Mohiuddin, et al. 2024. "Accumulation of Phytotoxic Metals and Metalloids in Vegetable Continuum Subjected to Different Irrigation Streams: a Threat towards Nutritional Security." *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 52, no. 1: 13516. https://doi.org/10.15835/nbha52113516.

Wei, J., B. Shen, G. Ye, et al. 2021. "Selenium and Arsenic Removal From Water Using Amine Sorbent, Competitive Adsorption and Regeneration." *Environmental Pollution* 274: 115866. https://doi.org/10.1016/j.envpol.2020.115866.

Werner, A. D., M. Bakker, V. E. A. Post, et al. 2013. "Seawater Intrusion Processes, Investigation and Management: Recent Advances and Future Challenges." *Advances in Water Resources* 51: 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004.

Wilson, D. C. 2018. "Potential Urban Runoff Impacts and Contaminant Distributions in Shoreline and Reservoir Environments of Lake Havasu, Southwestern United States." *Science of the Total Environment* 621: 95–107. https://doi.org/10.1016/j.scitotenv.2017.11.223.

World Health Organization. 2022. Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda. https://iris.who.int/bitstream/handle/10665/352532/9789240045064-eng.pdf?sequence=1.

Xia, X., X. Zhang, M. Liu, et al. 2021. "Toward Improved Human Health: Efficacy of Dietary Selenium on Immunity at the Cellular Level." *Food and Function* 12, no. 3: 976–989. https://doi.org/10.1039/d0fo03067h.

Yadav, G. S., and P. K. Ghosh. 2024. "Bioremediation of Sulfate in Water Environment: An Overview of Removal Pathways and Influencing Factors." *The Journal of Solid Waste Technology and Management* 50, no. 1: 430–440. https://doi.org/10.5276/jswtm/iswmaw/501/2024.430.

Zhao, B., D. Tu, B. Kong, et al. 2024. "Antagonistic Effects, Sources, and Distribution of Selenium and Toxic Metals in Fish From Selenium-Rich and High Cadmium Areas, Dashan Region, China." *Biological Trace Element Research* 202, no. 12: 5690–5696. https://doi.org/10.1007/s12011-024-04092-w.

Zhong, Y., and J. Cheng. 2016. "Effects of Selenium on Biological and Physiological Properties of the Duckweed *Landoltia Punctata*." *Plant Biology* 18, no. 5: 797–804. https://doi.org/10.1111/plb.12479.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting Table S1.1. Quality assessment questions for selected papers performed during the analysis stage based on the Mixed Methods Appraisal Tool (MMAT, Version 2018). **Supporting Table S1.2**. Criteria for anions considered as pollutants in drinking water sources. **Supporting Table S1.3**. Criteria for metals and metalloids considered as pollutants in drinking water sources (groundwater, lentic and lotic). **Supporting Table S1.4**. Criteria for metals and metalloids considered as pollutants for aquatic life in coastal and estuarine water bodies. **Supporting Table S1.5**. Evaluation of the single-factor pollution index (P_i) values of selenium for a subset of studies representing low to high pollution levels in groundwater. **Supporting Information**: tqem70366-sup-0002-SuppMat.xlsx