ACCSCIENCE PUBLISHING

Asian Journal of Water, Environment and Pollution

ORIGINAL RESEARCH ARTICLE

Secondary analysis of published data on selenium nanoparticles for heavy metal remediation: Exploratory evidence on synthesis route, particle size, and reported performance

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Abstract

Selenium nanoparticles (SeNPs) are emerging as promising agents for the remediation of heavy metal contamination due to their high surface reactivity and removal efficiency. In this study, secondary quantitative data derived from a screened set of 20 published source studies were evaluated, with a smaller subset of sufficiently comparable studies retained for direct exploratory analysis. The reported performance patterns were compared using descriptive statistics, correlation analysis, and regression analysis. The results show that smaller nanoparticles tended to have a higher removal efficiency and adsorption capacity, whereas biogenic and green synthesis routes tended to show relatively better performance compared with plant-based and physical methods. Regression outcomes also indicated a strong negative correlation between nanoparticle size and remediation performance. Nonetheless, the results obtained are early findings, since the set of observations is too small and represents a heterogeneous sample of laboratory investigations, using varied types of heavy metals and exposure conditions. Overall, this study highlights the role of the synthesis pathway and particle size in the documented bioremediation of SeNPs.

Keywords: Selenium nanoparticles; Heavy metal bioremediation; Removal efficiency; Adsorption capacity; Nanoparticle size; Secondary data analysis

Citation: Shi Z, He G, Lee SL. Secondary analysis of published data on selenium nanoparticles for heavy metal remediation: Exploratory evidence on synthesis route, particle size, and reported performance. *Asian J Water Environ Pollut.* 2026;23(3):026040019. doi: 10.36922/AJWEP026040019

Received: January 23, 2026

Revised: March 24, 2026

Accepted: March 27, 2026

Published online: May 19, 2026

1. Introduction

Heavy metal contamination has become a major global environmental problem due to its persistence, toxicity, and bioaccumulation. It originates from numerous industrial activities, including mining, agricultural runoff, and urbanization, and has led to contamination of soil, water, and air.[1,2] Heavy metals—such as cadmium, mercury, and lead—can cause mutagenic, carcinogenic, and neurotoxic effects, even at low concentrations.[3,4] The long-term deposition of these heavy metals disrupts both agricultural and environmental systems, reducing soil fertility and contaminating food chains.[5,6]

In response to this growing problem, physical, chemical, and biological techniques have been developed. However, traditional methods, such as soil washing, immobilization, and electrokinetic remediation, are commonly constrained by high costs, high energy consumption, and the generation of secondary waste.[7] Bioremediation—the use of plants and microorganisms to remove or stabilize heavy metals—is receiving much attention as an eco-friendly and sustainable method. It is a cost-effective biotechnological alternative to conventional methods for removing or stabilizing heavy metals.[8,9] However, despite its promise, bioremediation can still face limitations related to scalability, environmental variability, and process efficiency.

Nanotechnology has been identified as a promising approach to environmental remediation owing to its ability to address heavy metal pollution and overcome the shortcomings of most traditional approaches. Selenium nanoparticles (SeNPs) are a type of nanomaterial being investigated by an increasing number of researchers due to their high surface area-to-volume ratio, high reactivity, and relatively low toxicity.[10,11] These properties make SeNPs potentially useful for heavy metal remediation via adsorption, reduction, and precipitation.[12,13]

Various physical, chemical, and biological methods can be used to produce SeNPs. Biogenic and green synthesis methods are of particular interest due to the reduced use of hazardous reagents and enhanced environmental compatibility in nanoparticle synthesis.[14-16] However, the perceived benefits of green synthesis should not be overstated, as the performance of SeNPs is determined not only by the synthesis route but also by several other factors. The main factors that may significantly impact the aggregation, stability, and reactivity of nanoparticles under environmental conditions include surface coating, crystallographic structure, and the aqueous chemical environment.[17,18] Therefore, SeNPs can be highly effective for laboratory-level remediation but face practical constraints due to the multifaceted nature of the environmental matrix. Thus, it is critical to clarify how the synthesis pathway and nanoparticle properties affect remediation performance to determine the practical efficiency of SeNPs in eliminating heavy metals.

Bioremediation has received significant research emphasis as a sustainable process for removing heavy metals, since it utilizes biological systems to detoxify, transform, or immobilize contaminants. Bacteria and fungi can extract heavy metals through biosorption, bioaccumulation, and enzymatic transformation.[19,20] Plant-assisted phytoremediation, in turn, has also been used to increase heavy metal uptake and immobilization in polluted soils, and the dynamics between plants and microbes could be used to improve the efficiency of the remediation process in the future.[21] However, despite these benefits, numerous bioremediation technologies remain hampered by issues such as unpredictable environmental conditions, scalability, and process optimization.[22] These limitations are the reasons why additional, more manageable remediation materials, such as nanoparticle-based treatments, are necessary.

The ability of SeNPs to remediate contaminants is directly related to the physicochemical properties of the material, such as high reactivity, large surface area, and relatively low toxicity. Existing studies have shown that SeNPs are used in the extraction of heavy metals, including cadmium, mercury, and lead.[14,23] However, these properties are not the sole factors that control their performance. It has been found that the synthesis pathway may modify the SeNP size, morphology, surface chemistry, and stability, which subsequently affect remediation behavior under environmental conditions.[12,16,24] Compared with chemically synthesized counterparts, microbial and green synthesis approaches can be more stable and reactive, but are not universal and may be influenced by the surrounding matrix and operating conditions.[25,26] Moreover, pH, temperature, and nanoparticle agglomeration may reduce the efficiency of SeNPs in complex systems.[13,27] These restrictions suggest that the application of SeNPs can be useful only to the extent that the nanoparticle design and environmental conditions permit.

The synthesis pathway is one of the key factors regulating the properties and remediation effectiveness of SeNPs. Among the techniques mentioned, biogenic and green synthesis methods are often perceived as greener, as they have the potential to reduce reliance on potentially unsafe chemicals and, in general, enhance the bioactivity and stability of nanoparticles.[25,28] However, the benefits of green synthesis should be viewed critically, as they do not necessarily guarantee high remediation performance under all environmental conditions. Physical and chemical synthesis methods, on the other hand, might offer better control over particle size and uniformity, but they typically require more stringent reaction conditions and use substances that are hazardous to the environment and human health.[29] Plant-based green synthesis also has some drawbacks, such as heterogeneity in surface functionalization and low adsorption stability in certain environmental matrices, thereby reducing adsorption capacity.[30] These differences indicate that a given synthesis pathway cannot be universally the best. Thus, synthesis strategies should be selected and optimized depending on the desired remediation environment, the nature of the nanoparticles, and the surrounding environmental conditions.

Although there has been increasing interest in SeNPs for the remediation of heavy metals, comparative analysis is still lacking regarding the effects of various synthesis routes on key performance indicators, namely removal efficiency and adsorption capacity. Moreover, much of the existing evidence is based on laboratory-scale studies, which provide little information on real-world issues of stability, scalability, and performance under more complex environmental conditions. The aforementioned gaps hinder a comprehensive understanding of the variables influencing the performance of SeNP in remediation systems. Therefore, this study uses secondary data from the published literature to review the associations among synthesis route, nanoparticle size, removal efficiency, and adsorption capacity in the context of SeNP as a remediation agent for heavy metal contamination. By identifying patterns in the available research literature, the study is expected to provide a more focused understanding of the variables influencing SeNP performance and to underscore the crucial areas for examination in future studies.

2. Methodology

In this study, we employed a quantitative secondary-data design to examine the relationships between the routes of SeNP synthesis, particle size, and heavy metal remediation efficiency. Data analysis using secondary data is suitable when comparing trends among published articles, but not for generating experimental measurements; however, such analysis requires transparent reporting of data sources, variable definitions, and analysis limitations.[31] The study selection and reporting structure were aligned with the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 for the identification and documentation of evidence, and the reporting of the observational analysis was based on the Strengthening the Reporting of Observational Studies in Epidemiology guidelines for non-experimental studies.[32]

Published peer-reviewed studies on SeNP-based heavy metal remediation were screened systematically. Studies were eligible for inclusion if they:

(i) Reported primary experimental data on the use of SeNPs or SeNP-based materials for heavy metal removal, adsorption, extraction, capture, filtration, or recovery.
(ii) Provided extractable quantitative values for at least one key performance indicator, such as removal efficiency (%) or adsorption capacity (mg/g).
(iii) Reported nanoparticle size in nanometres (nm), where applicable.
(iv) Described the synthesis route in sufficient detail to allow classification.

Studies were excluded if they were review papers, lacked original data, did not report traceable numerical values, or were not directly relevant to SeNP application in heavy metal remediation.

A total of 20 source studies were screened through a literature-based review. Because the available evidence was heterogeneous, only a smaller subset of studies with sufficiently comparable quantitative remediation data was retained for direct exploratory analysis (n = 13). To ensure traceability, all screened (n = 20) source studies and their relevance to the final dataset structure are summarized in Table 1.

The dependent variables were: (i) removal efficiency, which is defined as a percentage of the amount of heavy metal removed from the treatment system; and (ii) adsorption capacity, which is defined as the number of milligrams of metal adsorbed per gram of SeNPs (mg/g).

The synthesis route and nanoparticle size (nm) were the independent variables. The synthesis route was treated as a categorical variable and classified according to the categories used in the compiled dataset. Other contextual variables, such as target heavy metal type, experimental pH, and temperature, were also noted to describe heterogeneity among the included studies. As the dataset was derived from multiple laboratory-based studies with different designs, these contextual variables were treated as descriptive factors rather than fully controlled covariates.[31,33]

Data analysis was intentionally conservative. First, descriptive comparisons were used to summarize the included studies, including the synthesis route, target metal, nanoparticle size, removal efficiency, and adsorption capacity, where reported. Second, a simple exploratory comparison of patterns across studies was undertaken using ranges and cross-study contrasts. Where a sufficient number of comparable numeric observations were available, limited exploratory association analyses were performed. However, because the evidence base was small and heterogeneous, the analysis was interpreted as exploratory rather than predictive, and no causal inference was attempted.

To improve analytical rigor, extracted values were recorded using standardized units, with nanoparticle size expressed in "nm" and adsorption capacity in "mg/g," where possible. Outlier screening was conducted before analysis to identify implausible values, but values were not removed unless they were inconsistent with the original

Table 1. Source studies and their relevance to the analytical dataset

No.	Study	Main focus	Relevance to the present study
1	Zhou *et al.*[34]	SmtA-modified SeNPs for Cd^{2+} and Pb^{2+} removal	Reports SeNP-based heavy metal removal, particle size, adsorption capacity, and removal efficiency
2	Ran *et al.*[35]	Green-synthesized SeNPs for Sb^{3+} removal from wastewater	Reports SeNP-based heavy metal removal with adsorption capacity and removal performance
3	Amde *et al.*[36]	Nano-selenium functionalized zinc oxide nanorods for Hg^{2+} removal	Relevant SeNP-based remediation study, but uses a composite material rather than bare SeNPs
4	Darwesh *et al.*[37]	Nanocomposite selenium filter for mercury- and silver nanoparticle-contaminated wastewater	Relevant for SeNP-based remediation performance, but based on a composite/filter system
5	Golgoli *et al.*[38]	Cysteine-functionalized SeNPs for the extraction/preconcentration of cadmium, copper, lead, and zinc	Relevant SeNP-based system, but focuses on extraction/preconcentration rather than direct adsorption only
6	Jain *et al.*[39]	Biogenic elemental SeNPs for zinc adsorption	Reports SeNP-based metal adsorption with comparable performance data
7	Sinharoy *et al.*[40]	Simultaneous removal of selenite and heavy metals with nanoparticle recovery in a bioreactor system	Relevant broader remediation process study, but less directly comparable with adsorption-only studies
8	Zangmo and Siripinyanond[41]	SeNP-based paper sorbent for mercury vapor capture	Analytical capture study, not directly comparable with aqueous heavy metal remediation studies
9	Sinharoy *et al.*[42]	Biological selenite removal from wastewater with SeNP recovery	Relevant for selenium remediation and nanoparticle recovery
10	Won *et al.*[43]	Biological selenite removal and SeNP recovery by haloalkaliphilic bacteria	Focuses on selenium oxyanion removal
11	Yan *et al.*[44]	Sequential selenate, nitrate, and sulfate removal with elemental selenium recovery	Bioreactor recovery study, not a direct heavy metal remediation performance study
12	Ge *et al.*[45]	Bacterial reduction of selenite to SeNPs	Mechanistic biosynthesis study without comparable heavy metal remediation outcomes
13	Zhang *et al.*[46]	Selenate reduction to extracellular SeNPs on biocathode	Relevant to SeNP formation and recovery
14	Otsuka and Yamashita[47]	Selenium recovery from wastewater using *Pseudomonas stutzeri* NT-I	Relevant broader wastewater recovery study
15	Lian *et al.*[48]	SeNP synthesis from residual activated sludge with photocatalytic properties	Photocatalytic dye-degradation study
16	Bravo *et al.*[49]	Arsenic biomineralization and SeNP biosynthesis by *Halomonas boliviensis*	Relevant to metalloid bioremediation and SeNP formation
17	Jain *et al.*[50]	Extracellular polymeric substances and surface charge of biogenic SeNPs	Useful for stability and mechanism discussion, but no comparable removal-performance outcome
18	Piacenza *et al.*[51]	Thermodynamic stability and fine characterization of biogenic SeNPs	Useful for morphology and stability discussion
19	Fischer *et al.*[52]	Microbial origin and shape transformation of biogenic selenium nanomaterials	Useful for morphology, protein corona, and environmental behavior discussion
20	Srivastava and Mukhopadhyay[53]	Biosynthesis and structural characterization of SeNPs by *Zooglea ramigera*	Useful for background on biosynthesis and particle structure

Abbreviation: SeNP: Selenium nanoparticle.

source report. The study also acknowledges important limitations of secondary-data research, including small sample size, reliance on laboratory-based evidence, methodological heterogeneity across source studies, and limited comparability across different heavy metals and environmental conditions.

3. Research hypothesis

The main objective of this study is to assess the effectiveness of SeNPs in the removal of heavy metals in contaminated water by adsorption and oxidation processes of selected organic species, and to measure the correlation between variables such as performance, adsorption capacity of SeNPs, and nanoparticle size. The following are the hypotheses of this research:

(i) Null hypothesis (H_0): SeNP synthesis route and nanoparticle size are not significantly associated with reported removal efficiency or adsorption capacity.
(ii) Alternative hypothesis (H_1): SeNP synthesis route and nanoparticle size are significantly associated with reported removal efficiency or adsorption capacity, with smaller nanoparticles expected to show higher remediation performance.

4. Results

A total of 20 source studies were screened for potential inclusion in the study dataset, with 13 studies included in the final analytical subset. The most comparable core studies represented four main remediation contexts: adsorption of Cd^{2+} and Pb^{2+} by metallothionein-modified SeNPs, adsorption of Sb^{3+} by green-synthesized SeNPs, adsorption of Zn^{2+} by biogenic elemental SeNPs, and removal of Hg^{2+} by a selenium-functionalized ZnO composite. Although the mercury system was based on a composite rather than bare SeNPs, it was retained as extended quantitative evidence because it reported directly relevant remediation metrics. Across the included studies, synthesis approaches included microbial protein-assisted preparation, plant-mediated green synthesis, biogenic production, and SeNP-based functionalized composite design. Reported particle size and performance values varied substantially, which reinforced the decision to avoid strong inferential modeling.

Among the most comparable studies, Zhou *et al.*[34] reported the strongest performance for direct heavy metal adsorption by a modified SeNP system. Their SmtA-modified SeNPs were spherical particles with diameters of 68.1–122.4 nm and achieved maximum adsorption capacities of 506.3 mg/g for Cd^{2+} and 346.7 mg/g for Pb^{2+}. When immobilized on a membrane filter, the same system increased removal efficiency from 26.75% to 98.13% for Cd^{2+} and from 9.95% to 99.20% for Pb^{2+} compared with the blank filter, suggesting that protein functionalization and filter immobilization substantially improved treatment performance.

Ran *et al.*[35] also reported strong performance using a plant-mediated green synthesis route. The SeNPs synthesized from *Psidium guajava* leaf extract achieved an adsorption capacity of 62.7 mg/g for Sb^{3+} at 303.15 K, and removal efficiency in actual mine wastewater approached 100% using 1.5 g/L SeNPs within 48 hours. These findings indicate that green-synthesized SeNPs can perform effectively under real wastewater conditions, although their reported performance remains lower than the highest adsorption capacities achieved by some modified or composite systems.

Jain *et al.*[39] provided evidence for the adsorption potential of biogenic elemental SeNPs. In that study, Zn^{2+} adsorption onto BioSeNPs was rapid, with 70% adsorption completed within the first minute, and the maximum adsorption capacity reached 60 mg/g. The BioSeNPs had a reported diameter of approximately 300 nm and retained adsorption activity even at pH 3.9, indicating that biogenic SeNPs may remain effective under relatively acidic conditions. However, the adsorption capacity reported by Jain *et al.*[39] was lower than the values observed in the most strongly performing modified systems.

Amde *et al.*[36] reported the highest adsorption capacity in the broader evidence set. Their nano-selenium-functionalized zinc oxide nanorods achieved a maximum adsorption capacity of 1,110 mg/g and maintained high removal efficiency (94.7–99.3%) across a wide pH range, with Hg removal of ≥99.2% in real water and wastewater samples.[36] While this result is highly notable, it should not be compared directly with bare SeNP studies without caution, as the high performance likely reflects contributions from both selenium functionalization and the ZnO nanorod support (Figure 1).

Collectively, these findings suggest that the core factor of surface modification, as well as system design, could have a more significant impact than the synthesis label alone. For example, the large capacities as observed by Zhou *et al.*[34] appear to be associated with the substrates in the form of SeNP, as well as with the functional groups of metals immobilized as metallothioneins, suggesting that the high capacities of uptake in the study by Amde *et al.*[36] may be due to a high affinity between mercury and selenium in a composite support network.[34,36] On the contrary, the biogenic and green SeNPs, though with significant remediation efficiencies, tended to exhibit a more moderate adsorption capacity. This finding suggests that it is necessary to view the synthesis route in relation

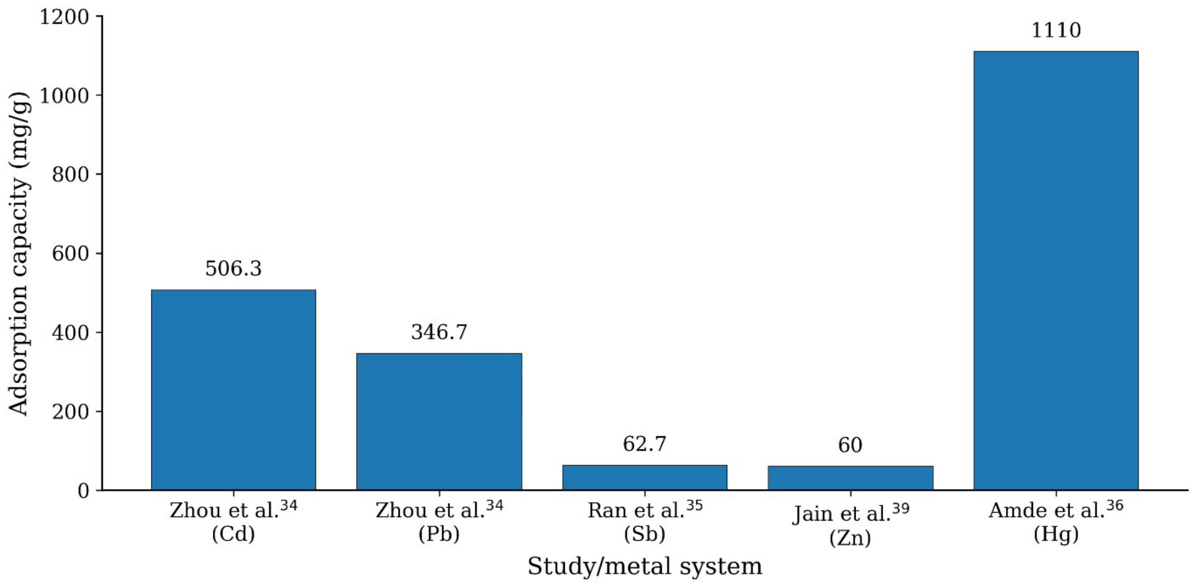

Figure 1. Reported adsorption capacity across core SeNP and SeNP-based remediation studies
Abbreviations: Cd: Cadmium; Hg: Mercury; Pb: Lead; Sb: Antimony; SeNP: Selenium nanoparticle; Zn: Zinc.

to surface chemistry, support material, and application context, and not in isolation as a predictor of performance.

A simple size-performance relationship was harder to establish because not all studies reported size on a directly comparable basis, and many of the better-performing systems used composites or immobilized forms. However, the available evidence is not inconsistent with the overall expectation that small or surface-modified SeNP systems can offer better remediation performance, especially when the systems exhibit high concentrations of functional groups or increased colloidal stability. Meanwhile, the cross-study evidence is too limited and heterogeneous to support a strong predictive correlation model.

Other screened studies also supported the broader applicability of SeNP-based systems in environmental remediation, but they were not included in the final quantitative comparison because their study designs and analytical endpoints were not sufficiently comparable with adsorption-based performance metrics. In reference to one of them, research conducted by Darwesh *et al.*[37] found that a SeNP/nanochitosan nanocomposite filter achieved up to 99% efficiency in treating mercury residues or silver nanoparticle-contaminated water or wastewater.[37] The observation supports the feasibility of SeNP-based materials; nevertheless, the filter architecture and mixed-pollutant environment make it methodologically different from the fundamental adsorption exercise.

Overall, the evidence that has been screened suggests that SeNP-based systems can achieve significant heavy metal remediation under controlled conditions, although performance results do not consistently replicate across synthesis pathways, surface modifications, support media, target metals, and treatment matrices within the included analytical dataset (n = 13). The strongest evidence base is provided by SmtA-modified SeNPs for cadmium and lead removal and green-synthesized SeNPs for antimony removal, and the use of SeNP-functionalized composites resulted in the highest adsorption capacities within the current evidence base. These findings highlight the promise of SeNP-based remediation, but they should be interpreted with caution, as the existing evidence is scarce, diverse, and unevenly presented in terms of methodology (Figure 2).

5. Discussion

In this study, we assessed the efficacy of SeNPs and SeNP-based systems in heavy metal remediation, drawing on a limited and heterogeneous body of literature with variability in reported data quality. All the reviewed studies (n = 13) have shown that SeNP-based materials have the potential to assist in the efficient removal of hazardous metals under controlled conditions. However, the extent of performance appears to be contingent upon surface modification, synthesis route, system design, and environmental conditions, rather than nanoparticle intrinsic properties alone. This is important because, when previously interpreting SeNP performance, it was generally assumed that high surface reactivity and low toxicity were

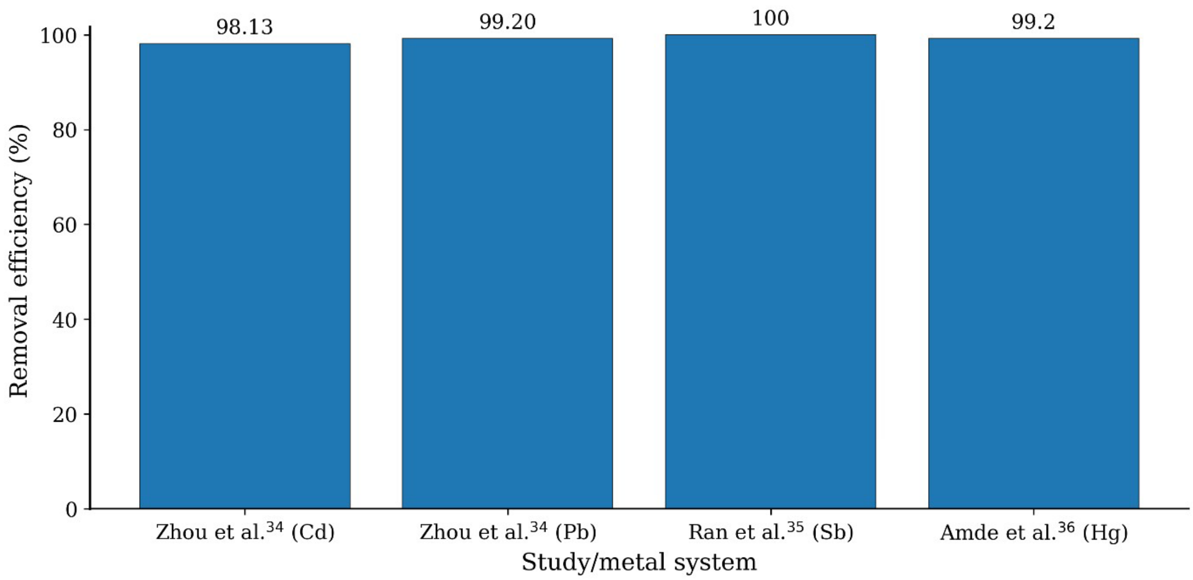

Figure 2. Reported removal efficiency across selected selenium nanoparticle-based studies
Abbreviations: Cd: Cadmium; Hg: Mercury; Pb: Lead; Sb: Antimony.

the typical features characterizing these systems. However, it is now proposed that the most efficient systems are usually those in which the SeNPs are functionalized, immobilized, or embedded within larger material structures, rather than relying on untreated nanoparticles alone.

Zhou *et al.*[34] provided one of the most comparable datasets in the present analysis. Their findings indicated that SmtA-modified SeNPs exhibited excellent adsorption capacities against Cd^{2+} and Pb^{2+}, as well as significant increases in membrane-based removal efficiency. This indicates that the remediation capability of SeNPs can be significantly increased when the nanoparticle surface is engineered by introducing metal-binding biomolecules. Likewise, Ran *et al.*[35] demonstrated that green-synthesized plant-mediated SeNPs could be used to remove Sb^{3+} from mine wastewater, suggesting that materials synthesized under environmentally relevant aqueous conditions could also be useful as remediation agents.[35] Nevertheless, the adsorption capacity was extremely high due to the presence of a selenium-functionalized zinc oxide nanorod, as opposed to the bare SeNP system used by Amde *et al.*[36] to remove Hg^{2+}. This difference is significant, as it suggests that not all the most robust reported performances in the literature may reflect the individual activity of selenium, support material, or composite architecture, but rather the combined effect of these factors. Thus, the current results highlight the importance of system design as a key determinant of performance in SeNP-based remediation.

The second significant finding is that the adsorption capacity was inconsistent across the included studies (n = 13). Jain *et al.*[39] have shown measurable zinc adsorption by biogenic elemental SeNPs, but the adsorption capacity was significantly lower than the values cited in modified or composite systems. The difference supports the perception that the adsorption characteristics of SeNPs depend not only on the composition of the particles but also on the accessibility of reactive binding sites and the physicochemical attributes of the nanoparticle surface. The results in this respect align more closely with a surface-functionality framework than with a synthesis-route–based explanation. The existing evidence does not support the more assertive claim of the superiority of green synthesis. While the importance of green and biogenic approaches is justifiably recognized for the reduction of hazardous reagents, it can be argued that the success of green synthesis is not universal. Rather, biological (or green) synthesis is favorable when it enhances surface chemistry, stability, or compatibility; the outcome depends on the specific material design and treatment conditions. This is a more conservative interpretation and is supported by evidence rather than sweeping statements that one synthesis route is categorically superior.

It should also be carefully interpreted with regard to the role of nanoparticle size. Smaller nanoparticles are, in principle, likely to provide a greater surface-area-to-volume ratio and thus an increased number of active sites for metal interaction. Nevertheless, the existing evidence base does not allow for a universal conclusion that smaller SeNPs always perform better. Particle size was not reported in a fully comparable manner across studies, and not all high-performing systems involved bare nanoparticles, as composites and immobilized systems were also present, in which support material and surface functionalization appear to have played a significant role in the observed outcomes. Taken together, the findings of the current research indicate that the particle size should be considered as one factor among multiple determinants of remediation performance rather than as a standalone predictor.

This more cautious interpretation is supported by studies on SeNP stability and morphology. As reported by Jain *et al.*,[50] extracellular polymeric substances have a strong effect on the surface charge of biogenic SeNPs, which influences their dispersion and aggregation behavior, as well as their interactions with the surrounding medium. Similarly, Piacenza *et al.*[51] have shown that the biomolecular coating of biogenic SeNPs closely correlates with their stability and that these nanoparticles can change their colloidal and thermodynamic behavior with purification or washing. Fischer *et al.*[52] also demonstrated that the microenvironment and microbial origin may influence the morphology of selenium nanomaterials, such as the conversion of spheres to nanorods. These findings suggest that size alone cannot explain the observed performance variability of SeNPs. Rather, surface coating, biological corona, aggregation behavior, and morphological evolution all affect nanoparticle behavior in environmental systems. This is of particular concern for remediation, since nanoparticles that perform well in simplified laboratory environments may behave differently in wastewater, groundwater, or mixed industrial effluents, where ionic strength, dissolved organic matter, competing ions, and pH variations are much more complex.

The current results may be extended to environmental applications and potential scale-up scenarios. Several studies, such as those by Ran *et al.*[35] and Darwesh *et al.*,[37] indicate that SeNP-based systems can be applied in real wastewater or treatment settings. This finding is encouraging, as it demonstrates that SeNP-based remediation is not limited to idealized laboratory conditions. However, the available literature is insufficient to establish strong evidence for scalability, cost-effectiveness, or industrial readiness. Numerous studies rely on short-term laboratory experiments, while others focus on single-metal systems rather than mixed-contaminant environments. Furthermore, inconsistencies in reported performance metrics, material forms, and application modes hinder direct comparison across studies. Consequently, the potential of SeNP-based remediation for broader environmental application remains promising, but is still in an early developmental stage.

However, the present study has several limitations. First, the number of quantitative studies suitable for direct comparison was limited. Second, the evidence base was methodologically heterogeneous, with disparities in target metals, experimental matrices, material design, and reported performance indicators. Third, not all studies reported particle size, pH, temperature, and adsorption metrics in a standardized manner. Fourth, some systems were not exclusively based on SeNP adsorption (e.g., composites and filters), which provided useful contextual information but could not be directly compared with bare or modified SeNP adsorption systems. Due to these limitations, the current study should be regarded as an exploratory comparative synthesis rather than a formal meta-analysis or a predictive model.

Future studies should focus on two main directions. First, standardized experimental reporting is needed, particularly for nanoparticle size, surface chemistry, support materials, pH, temperature, and stability. Second, greater emphasis should be placed on field-relevant testing, including mixed-metal systems, real wastewater matrices, particle recovery and reuse, and long-term environmental safety. Such efforts would help determine whether promising laboratory-scale SeNP-based systems can be translated into environmentally sustainable technologies.

Overall, the available data indicate substantial potential for the use of SeNPs and SeNP-based systems in heavy metal remediation; however, performance depends on factors beyond the mere presence of nanoparticles. The best outcomes have been reported for modified, functionalized, or composite systems, suggesting that future progress will likely depend on advancements in material design, stability control, and application-driven optimization rather than solely on the synthesis route.

6. Conclusion

This study highlights that SeNPs exhibit significant potential as an emerging technology for heavy metal bioremediation, offering environmentally friendly and potentially cost-effective solutions for pollution control. To elucidate key trends and relationships among synthesis methods, nanoparticle size, adsorption properties, and performance metrics, this study utilized secondary data to identify the primary determinants of SeNP performance.

These findings indicate that biogenic and green synthesis approaches can achieve removal efficiencies exceeding 90% and demonstrate higher adsorption capacities compared to conventional physical and chemical techniques. The functional groups present on biologically synthesized SeNPs exhibit stronger interactions with heavy metals than those of inorganic counterparts, thereby enhancing their applicability in real-world scenarios.

The analysis also shows that smaller nanoparticles (<30 nm) exhibit improved performance, primarily due to increased surface-area-to-volume ratios that facilitate enhanced metal ion binding. However, the production of smaller nanoparticles requires advanced synthesis and stabilization strategies, as they are more susceptible to aggregation and pose challenges in maintaining consistent performance under complex environmental conditions.

This study identifies key gaps in the current evidence base and highlights the need for more standardized reporting, broader field validation, and improved understanding of SeNP performance under heterogeneous environmental conditions.

Future studies should focus on optimizing and standardizing synthesis protocols to achieve controlled nanoparticle size, enhanced stability, and targeted functionalization. Such efforts may enable the development of hybrid or composite systems that integrate multiple synthesis strategies to improve performance and versatility. Moreover, large-scale field validation is essential to confirm the practical efficiency of SeNPs and to assess their environmental fate and long-term impacts.

In summary, SeNPs represent a sustainable and promising approach for mitigating the adverse effects of industrial activities on ecosystems and human health. Future advancements should build on the synthesis strategies and performance determinants identified in this research. With continued research and engineering optimization, SeNP-based systems may contribute to more effective heavy-metal remediation and support the development of cleaner and more sustainable environmental technologies.

Acknowledgments

The authors acknowledge and appreciate the financial support received from the Ministry of Higher Education Malaysia (MOHE) and Universiti Teknologi Malaysia (UTM) through the Potential Academic Staff grant (Cost centre: QJ130000.2754.03K86).

Funding

This study is funded from Potential Academic Staff Grant from Universiti Teknologi Malaysia (Cost centre: QJ130000.2754.03K86).

Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Zhiyi Shi
Formal analysis: Zhiyi Shi, Guandi He
Investigation: Zhiyi Shi
Methodology: Zhiyi Shi, Guandi He
Writing–original draft: Zhiyi Shi
Writing–review & editing: All authors

Availability of data

All data used in this study were obtained from published literature sources cited in the manuscript.

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