Materials International
Open Access Journal (ISSN: 2668-5728)

Review
Volume 6, Issue 2, 2024, 15
https://doi.org/10.33263/Materials62.015

Application of Nanotechnological Compounds in the Removal of Heavy Metals

Antônio Rony da Silva Pereira Rodrigues [1,*]

[1] State University of Ceará - UECE, Centro de Ciências e Tecnologia – CCT, Fortaleza, Ceará, Brazil
* Correspondence: ronny346silva@gmail.com
Scopus Author ID N/A

Received: 1.01.2024; Accepted: 30.01.2024; Published: 10.06.2024

Abstract: Contamination by heavy metals poses a risk to human and environmental health, as it causes contamination of soil, water, food, and living organisms. The application of nanotechnologies for this purpose has emerged in the need to seek technologies that facilitate the removal of heavy metals and their ions. The present study aimed to evaluate relevant studies in the literature on the application of nanotechnologies in the removal of heavy metals. The study is a systematic review that analyzed articles published in the Scopus, Embase, ScienceDirect, and Web of Science databases between 2019 and the present. 19 articles were included in the review, which were selected after careful application of selective methods. The studies included in the review describe nanomaterials associated or not with other compounds, such as membranes and organic structures, in the removal of heavy metals, with emphasis on metals such as Cd, Pb, Mg, and Cu and their ions. The studies reveal that the nanomaterials used to remove heavy metals have high adsorption activity, as reported for the Hg^{2+} ion, which obtained 99.9% removal with the use of Hg-selective magnetic composite nanomaterial.

Keywords: adsorption technologies; adsorption kinetics; nanotechnologies in the removal of metal ions; heavy metals; environmental decontamination; nanocomposites.

1. Introduction

Heavy metals are disposed of in the environment, acting as natural agents or coming from industrial, chemical, and agricultural environments. Being non-degradable and therefore requiring their removal, heavy metals in high dosages act with a harmful effect on living organisms, especially cadmium (Cd), lead (Pb), and copper (Cu) [1]. Heavy metals can contaminate agricultural chains, being incorporated into the food chain through leaching into groundwater or bioaccumulation in the human body, which can cause neurotoxicity, nephrotoxicity, and hepatotoxicity [2].

Among the existing heavy metal removal methods, adsorption stands out because it allows the removal of trace contaminants, is considered a simplified operating process, enables the regeneration and reuse of the adsorbent, has high efficiency, and does not produce harmful intermediate compounds [3].

When choosing an efficient adsorbent, several characteristics must be considered. The physicochemical and mechanical properties directly influence the adsorption coefficient. Efficient adsorbents must exhibit recyclability, porosity, low cost, availability, fast kinetics, high regeneration potential, thermal and chemical stability, large specific surface area, and excellent removal efficiency [4,5].

Different compounds have been studied as adsorbent agents of heavy metals, the use of electrospun fibers [6], zeolitic compounds [7], several biomasses such as *Ulva flexuosa* [8], *Leucaena leucocephala* [9], *Moringa oleifera* [10, 11] and *Cocos nucifera* [12], are evaluated and have relevant adsorption capacity, but new compounds are being studied for the removal of heavy metals applying the use of nanotechnological products and nanocomposites.

Nanocomposites are lightweight, high-strength structural materials with functionalities to detect, restore, transform, repair, and adapt, being products of natural or synthetic origin with combinations that allow unique mechanical properties that enable a wide range of applications [13].

Nanocomposites are described as emerging technologies that can be applied in the most diverse fields of science. The use of this technology is already described as a possibility for the treatment of breast cancer through the application of nanocomposites based on carbohydrate polymers [14], heterostructured nanocomposites doped with lanthanides are studied for information storage [15], and nanocomposites based on terbium, carbon and oxygen nanostructures are already evaluated as photocatalysts under UV/Visible light for the removal of organic pollutant compounds in water [16].

Nanostructured compounds in removing pollutants and organic contaminants in water have been shown to be efficient. The catalytic reduction of nitroaromatic compounds in wastewater by means of nanostructured materials is a promising process; the use of hybrid $NiCo_2S^{4-}$ (Fe, Co, Ni) 9S8 nanosheets has been shown to be efficient in reducing 4-nitrophenol to 4-aminophenol [17].

Nanostructured materials are also proving to be an emerging technology for inorganic compounds, such as heavy metals. Nanostructured Au/TiO_2 and Y_2 membranes have been presented as an alternative arsenic in aqueous medium. In addition to removal, nanocomposites can be used to identify pollutants. The use of a copolyester called poly(butylene adipate-co-terephthalate) (PBAT) and carbon nitrite dots (CNDs), which combines aliphatic and aromatic structures, having thermal and mechanical properties that works as a biodegradable electrochemical sensor, being able to detect copper and cadmium, with electrochemical activity with sensitivity of $(3.79 \pm 0.21) \times 10^{-5}$ (mA cm^{-2}) (M)$^{-1}$ for cadmium and $(2.06 \pm 0.14) \times 10^{-5}$ (mA cm^{-2}) (M)$^{-1}$ for copper, considered excellent [18,19].

Because of the above, the present systematic review aims to investigate the applicability of nanotechnologies, such as nanocomposites, nanocomposites, associated or dissociated nanostructured materials in the adsorption of heavy metals, through the analysis of relevant studies on the subject. The study elucidates the different aspects that involve the adsorbent capacity of nanotechnologies, among them the influence of physicochemical characteristics, mechanical properties, and the influence of the medium, such as pH and concentration in the adsorption capacity and isotherms. Finally, an analysis describes the challenges and future perspectives for applying nanotechnologies in the adsorption of heavy metals.

2. Materials and Methods

The present study is a systematic literature review based on the study by Pagani et al. (2015) [20]. The study is a qualitative approach with objectives classified as exploratory. The systematic review aims to answer a scientific question through the search and systematic synthesis of the available literature on the theme addressed and critical analysis of the studies using methods pre-established by the researcher [21]. The systematic review allows the complete analysis of a topic with the literature as a data source, providing a means for future investigations on the topic [22].

The potential studies to compose the systematic review were identified through a comprehensive strategy. First, the electronic databases Scopus, Web of Science, ScienceDirect, and Embase were selected. The search for articles took place between October and November 2023.

In a second moment, the descriptors used for the search were defined considering English, Spanish and Portuguese, together with the Boolean operator "AND", which resulted in the following crossings: 1) Adsorption AND heavy metals AND nanomaterials AND nanocomposites AND adsorptive nanotechnologies; 2) Adsorção AND metais pesados AND nanomateriais AND nanocompósitos AND nanotecnologias adsortivas; 3) Adsorción NAD metales pesados AND nanomateriales AND nanocompuestos AND nanotecnologías adsorbentes.

Thirdly, inclusion and exclusion criteria were defined, and articles for inclusion were defined as studies published between 2019 and the present moment, available in full, studies within the theme addressed in the research and studies in Portuguese, English, and Spanish, studies available in full, original experimental articles, were included. Studies that were not available in full, outside the time frame and language proposed, review articles, editorials, reports, monographs, dissertations, theses, abstracts, books, and book chapters were excluded.

In the last moment, the selection process was defined, and 4 stages were established: 1) analysis and selection through the reading of titles; 2) analysis and selection through the reading of abstracts; 3) analysis and selection through the reading of the texts in full; 4) analysis of the quality and classification of the articles selected by the checklist for a systematic review of the Critical Appraisal Skills Programme (CASP) [23].

The Critical Appraisal Skills Programme classifies studies into two categories, namely: Category A) study with low risk of bias and meets at least 9 of the 10 items proposed, with studies classified as relevant, with good methodological design, reasoned analysis, and clear objectives; Category B) studies with moderate risk of bias and meets at least 5 of the 10 items proposed.

3. Results and Discussion

3.1. Result of the analysis and selection of articles.

A total of 2,124 articles were found in the databases. By filtering by inclusion and removing duplicates, 1,759 articles were excluded, and 365 articles were chosen for reading titles. After reading the titles, 130 studies were selected for reading abstracts, where 94 articles were excluded, and 36 studies were chosen to be read in full. With the analysis of the full text of the articles, 19 articles were considered eligible to compose the systematic review, and 17 studies were excluded because they described other adsorption methods, were not nanotechnologies, or removed compounds that were not heavy metals. After quality analysis using the CASP checklist, the 19 articles were analyzed, and the final review version was made. Figure 1 shows the steps for selecting the articles that make up the review.

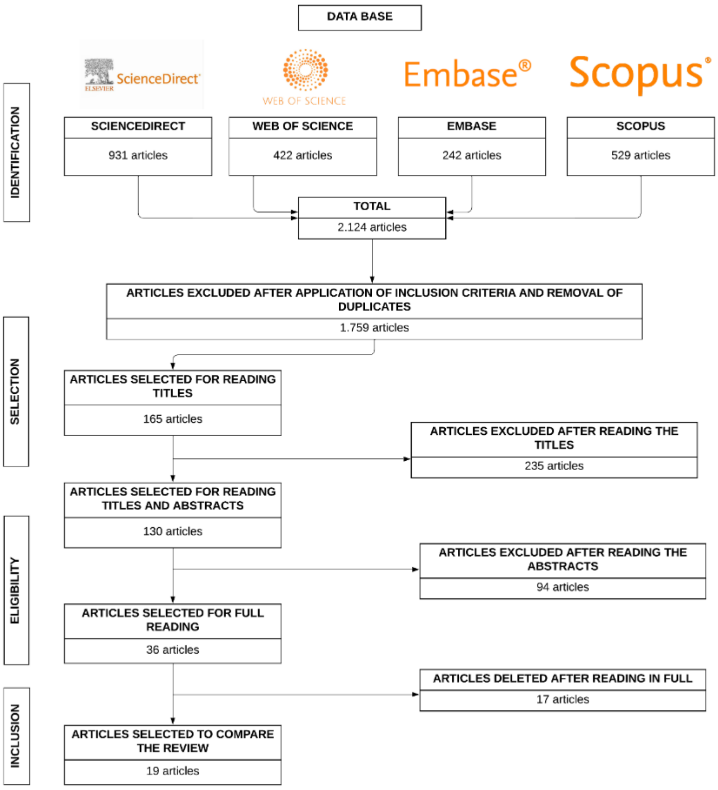

Figure 1. Flow chart Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) selection of the articles that comprise the systematic review.

The articles included in the review were classified according to the year of publication, according to data from Scopus, Embase, ScienceDirect, and Web of Science. The prevalence of studies published in 2023 was evident with 31.59% of the studies (6 articles), followed by 2019 and 2021 with 21.05% of the studies (4 studies each). The data according to year of publication is shown in Table 1:

Table 1. Number of articles included per year of publication (2019-2023).

Year of publication	Quantity	% of 19
2019	4	21.05
2020	2	10.52
2021	4	21.05
2022	3	15.78
2023	6	31.59

Table 2 shows the characterization of the studies that make up the systematic review in terms of article title, author/reference, and year of publication.

Table 2. Characterization of the study in terms of title, reference, and year of publication.

Title	Author	Year
Mesoporous nanomaterials based on manganese with different interlayer alkali cations: An efficient approach for the removal of Pb(II) and Cd(II) from aqueous medium	[24]	2021
Adsorption and desorption of phenanthrene by magnetic graphene nanomaterials from water: Roles of pH, heavy metal ions, and natural organic matter	[25]	2019
A facile synthesis of ibandronate modified hydroxyapatite renewable nanomaterials for simultaneous removal of Cu^{2+}/Pb^{2+} and chlortetracycline: Experimental design and adsorption mechanism study	[26]	2022
Facile synthesis of bismuth and iron co-doped hydroxyapatite nanomaterials for high-performance fluoride ions adsorption	[27]	2023
Synthesis of amine functionalization carbon nanotube-low symmetry porphyrin derivatives conjugates toward dye and metal ions removal	[28]	2021
Assessing sustainable Lutetium(III) ions adsorption and recovery using novel composite hybrid nanomaterials	[29]	2023

Title	Author	Year
Removal of cu(Ii), pb(ii), mg(ii), and fe(ii) by adsorption onto alginate/nanocellulose beads as bio-sorbent	[30]	2021
Copper-doped ZIF-8 nanomaterials as an adsorbent for the efficient removal of As(V) from wastewater	[31]	2023
Fe-based ceramic nanocomposite membranes were via e-spinning and vacuum filtration to remove $Cd2^{+}$ ions	[32]	2019
Stripping of Cu ion from aquatic media by means of MgY2O4@g-C3N4 nanomaterials	[33]	2023
Application of response surface methodology for simultaneous removal of major cations from seawater using metal oxide nanostructures	[34]	2020
A poly ethanolamine nano dendrimer as a magnetic hybrid material for fast adsorption of heavy metal contaminants	[35]	2022
Silver nanoclusters encapsulated into metal-organic frameworks for rapid removal of heavy metal ions from water	[36]	2019
Mesoporous silica/iron phthalocyanine light-driven nanomaterials for efficient removal of Pb^{2+} Ions from wastewater	[37]	2023
Removal of thallium(I) from aqueous solutions using titanate nanomaterials: The performance and the influence of morphology	[38]	2020
Facile adsorption-electroflotation method for the removal of heavy metal ions from water using carbon nanomaterials	[39]	2023
Macrocyclic host appended carbon nanotubes for selective adsorption of metal ions: Combined experimental, DFT and MD studies	[40]	2019
Synthesis and application of titania nanotubes and hydrous manganese oxide in heavy metal removal from aqueous solution: characterization, comparative study, and adsorption kinetics	[41]	2021
Synthesis of magnetic CuS composite nanomaterial and its specific adsorption of Hg(II) in water	[42]	2020

Analyzing the studies that are part of the review, it was possible to notice that studies carried out in the Asian continent stand out of the 19 selected articles, 14 were carried out in countries of the Asian continent, representing 73.68% of the articles that make up the review. Studies carried out in China (36.86%), Saudi Arabia (10.52%), India (10.52%) and Iran (10.52%) stand out. There was a dissipation of studies about the scientific journal of publication, with no studies published in the same journal. When analyzing the 19 articles through the CASP checklist, all of them were classified as the maximum quality level (Level A), as they answered at least 9 of the 10 items proposed. The characterization of the journal, study location, and quality level can be seen in Table 3.

Table 3. Characterization of the studies in terms of journal, study location, and CASP quality level.

Author	Journal	Study location	Quality level CASP
[24]	Journal of Water Process Engineering	Morocco	A
[25]	Chemical Engineering Journal	China	A
[26]	Journal of Cleaner Production	China	A
[27]	Journal of Environmental Chemical Engineering	Ethiopia	A
[28]	Journal of Molecular Liquids	Saudi Arabia	A
[29]	Journal of Molecular Structure	Bangladesh	A
[30]	Journal of Renewable Materials	Egypt	A
[31]	Journal of Physics and Chemistry of Solids	China	A
[32]	Chemosphere	United States	A
[33]	Water (Switzerland)	Saudi Arabia	A
[34]	Water SA	South Africa	A
[35]	Journal of Materials Science: Materials in Electronics	Iran	A
[36]	Molecules	China	A
[37]	ACS Applied Nano Materials	China	A
[38]	Science of the Total Environment	China	A
[39]	Environmental Science and Pollution Research	India	A
[40]	Molecular Systems Design and Engineering	India	A
[41]	Theoretical Foundations of Chemical Engineering	Iran	A
[42]	Chinese Journal of Applied Chemistry	China	A

As can be seen, authors from several countries have studied and pointed out the use of nanotechnologies as a trend for heavy metal adsorption. The next section presents the main results from the studies selected to be part of the systematic review, presenting a synthesis based on the authors' discussions on the theme.

3.2. Application of nanotechnologies in the adsorption of metal ions.

Amarray *et al.* (2021) sought to synthesize nanomaterials based on manganese oxide called K-MnO_2 and H-MnO_2 and evaluate the adsorption capacity of 2^+ ions of the heavy metals lead (Pb) and cadmium (Cd) in aqueous medium. The synthesis of K-MnO_2 was based on a hydrothermal process of hydrochloric acid (HCl) solution and potassium permanganate ($KMnO_4$) solution. The H-MnO_2 nanomaterial was elaborated by exchanging K^+ ions inserted into K-MnO_2 with H^+ ions and treated with a nitric acid solution (HNO_3). The nanomaterials K-MnO_2 and H-MnO_2 showed high affinity for Pb(II) ions; with 5 minutes of treatment, the removal efficiency rates reached 98.67% and 97.6% for K-MnO_2 and H-MnO_2. For Cd(II) ions, after 15 minutes of treatment, the efficiency rates were 95.45% and 73.96% for K-MnO_2 and H-MnO_2, respectively, demonstrating the highest removal efficiency for the K-MnO_2 nanomaterial [24].

The HA nanomaterial co-doped bismuth (Bi) and iron (Fe), $Ca_{10-(x+y)}$ Bi_x $Fe_y(PO_4)_6(OH)_2$, where x and y = 0.3, 0.4, 0.5 and 0.6, and x + y = 0.9, were prepared using a co-precipitation method, taking into account the atomic ratio (Ca + Bi +Fe)/P of approximately 1.67. The nanomaterial was evaluated as an adsorbent against fluoride ion (F^-). The pH change was identified as an influencing factor on the F- adsorption rate, according to which the pH increased from 3 to 11, and the efficiency rate varied from 96.87% to 76.6%. In the pH variation from 3 to 7, the efficiency rate varied from 96.87% to 91.17% and 90.36% to 76.6% as the pH varied from 8 to 11. It is revealed that the Bi-Fe-HA nanomaterial has excellent F- adsorption capacity; it is still noticeable that the surface of Bi-Fe-HA is positively charged, but due to the extra charges and excess OH, the surface to be negatively charged, causing the process of removing F- ions to repel each other, making the Bi-Fe-HA unstable at pH below 3 [27].

Nanomaterial MgY_2O_4@g-C_3N_4 evaluated as an adsorbent of copper ion (Cu^{2+}) in an aqueous medium was proposed by Modwi *et al.* (2023). The tests were carried out in experimental batches in glasses of 0.025 L and 10 mg of MgY_2O_4@g-C_3N_4, and the addition of Cu(II) at concentrations of 5 to 200 ppm. The number of adsorbed ions and the equilibrium magnitude *qt* were calculated using equations (1) and (2):

$$q_t = \frac{1}{m}(C_0 - C_t)\,V \qquad (1)$$

$$q_e = \frac{1}{m}(C_0 - C_e)\,V \qquad (2)$$

Where *V*, C_0, C_e, and *Ct* are the volume of the solution (L), initial concentration, equilibrium concentration, and concentration at time t of Cu(II) metal ions (mg/L) in solution, and *m* is the mass of the adsorbent (g). Analyzing the effect of Cu(II) concentration in the concentration range 5 to 200 mg/L, with 10 mg of MgY_2O_4@g-C_3N_4, it was observed that when the Cu(II) concentration increases, the amount of adsorbed ions also increases continuously from 9.85 to 250 mg/g [33]. Different parameters applied to equilibrium isothermal constants for Cu(II) adsorption by the nanomaterial MgY_2O_4@g-C_3N_4 can be seen in Table 4:

Table 4. Different equilibrium isothermal constants for Cu(II) adsorption of MgY_2O_4@g-C_3N_4 [33].

Equilibrium model	**Parameter**	**Cu^{2+}**
Langmuir	q_m (mg·g^{-1})	290.7
Freundlich	K_F (L.mg^{-1})	11.36
Temkin	*B* (J.mol^{-1})	85.65
Dubinin-Radushkevich	β (mol^2.J^{-2})	2.0.95 × 10^{-8}

The application of carbon-based nanomaterials is one of the main nanotechnologies developed for the removal of heavy metals. Carbon-based nanocomposites tend to have 95% structure composed of carbon, 1-6% oxygen, <1% chlorine, and 5% cobalt. A study of adsorption of $ZnSO_4$, $NiSO_4$, $CuSO_4$, $CoSO_4$, and $FeSO_4$ at a concentration of 10–250 mg/L, using carbon nanotubes (CNTs) and carbon nanoshells (CNSs) as adsorbent material revealed good results with emphasis on Ni adsorption by CNS and Zn by CNT [39].

Deb, Sapu, and Ali (2019) also evaluated the use of carbon nanotubes in the adsorption of heavy metals but associated the nanotechnology with a macrocyclic host for selective adsorption, a crown ester, and the nanomaterial was named CNT-B15C5. The results with the use of CNT-B15C5 showed that the associated nanotube has a higher adsorption capacity than free CNTs. CNT-B15C5 demonstrated high adsorption capacity for Na^+ and K^+ ions but has zero adsorption for Li^+ ions. Being an alternative to produce high-purity lithium compounds [40].

The environment needs lead adsorption, especially its Pb^{2+} ion, as it harms human and environmental health most. Several studies have begun to apply nanotechnologies to remove this contaminant. The synthesis of light-driven mesoporous silica-iron phthalocyanine (IP) nanomotor has been proposed by Pan *et al.* (2023) as an efficient alternative for removing Pb^{2+} ions from wastewater. Free mesopora silica demonstrates low adsorptive activity of only 18.2 mg/g for Pb^{2+} ions. The light-driven nanomotor of synthesized mesoporous silica has a high Pb^{2+} adsorption capacity, with saturated adsorption of 80.3 mg/g. Introducing the phthalocyanine functional group does not significantly improve adsorption capacity [37].

A renewable hydroxyapatite nanomaterial modified with ibandronate called ibandronate nanofunctionalized hydroxyapatite (IB-HAP), studied in the simultaneous removal of Cu^{2+} and Pb^{2+} ions, showed relevant adsorption capacity. Evaluating the influence of pH on adsorption by the nanomaterial, it is observed that the adsorption capacity of Cu^{2+} increases with the increase of the pH value; for the Pb^{2+} ion, the reverse process occurs. The synthesized nanomaterial obtained an adsorption capacity of 1565.3 (Pb^{2+}) and 246.71 (Cu^{2+}) mg/g, respectively [26].

The adsorption of coexisting organic and inorganic compounds by nanomaterials is reported by Huang *et al.* (2019). The author describes that the magnetic graphene nanomaterial in the adsorption of phenanthrene coexisting with Cd(II) and As(V) ions, the presence of the organic compound, and the metal ions are suppressed [25]. Wang *et al.* (2023) evaluated the adsorption capacity of a nanomaterial called Cu-ZIF-8, synthesized from 2-methylimidazole, zinc nitrate hexahydrate, and copper nitrate trihydrate, against the As(V) ion. The amount of As(V) adsorbed was calculated by equation 3:

$$q = \frac{(C_0 - C_e)V}{m} \quad (3)$$

Where q is the adsorption capacity of As(V) (mg/g), C_0 is the initial concentration of As(V), C_e is the concentration of As (V) in wastewater, V is the amount of wastewater (L), and m is the amount of Cu-ZIF-8 (g). The tests were performed with initial concentrations of As(V) ranging from 1.0 to 350 mg/L, at a constant pH of 7, with the highest adsorption capacity of 238.11 mg/g, when the initial concentration of As(V) was 300 mg/L [31].

The synthesis of nanotubes for heavy metal adsorption has been described by Saleh *et al.* (2021) and Delavar *et al.* (2021). The application of titanium nanotubes (TNT) and hydrated manganese oxide (HMO) synthesized via hydrothermal synthesis against Cd^{2+} and Cu^{2+} ions proved feasible. Kinetic studies revealed that the kinetic model of TNTs and HMOs is pseudo-second order. The equilibrium data shows an increase in the adsorption of ions with the increase of the initial concentration, with the TNTs having a greater adsorption capacity, so that the concentrations of Cd^{2+} and Cu^{2+} ions were 49 and 47 mg/g, respectively, at a concentration of 200 mg/L for TNTs and 37 and 34 mg/g for HMO1, respectively. Carbon nanotubes with amine functionalization were tested against Ni, Cd, Pb, As, Cr, Cu, and Fe ions, showing adsorption capacity for all ions and demonstrating a maximum capacity of 100% at different pH [28,41].

Studies evaluate the use of sustainable composite hybrid nanomaterial (HCM) synthesized by the acid organic ligand (3-(methoxycarbonyl)benzylidene)hydrazinyl) benzoic acid and the magnetic hybrid nanomaterial coated with triazine-based dendrimer (Fe_3O_4@SiO_2@D-G3). HCMs were tested against lutetium ions (Lu(II)), and pH had a strong influence on the adsorption isotherms. The maximum adsorption capacity was 171.76 mg/g Lu(II). The magnetic hybrid evaluated for adsorption of Pb(II) and Cd(II) ions showed high adsorption efficiency in an aqueous medium (93.6% and 98.5%, respectively). Metal ions were adsorbed by coordination with amine and hydroxyl groups, triazine amine, and electrostatic interactions [29, 35].

Alginate mixed with cellulose nanocrystals (CNC), cellulose nanofibers (CNF), and tricarboxylate cellulose nanofibers (TPC-CNF) were also the object of study for the removal of metal ions from Cu(II), Pb(II), Mg(II) and Fe(II). The Alg-TPC-CNF composite demonstrated excellent removal capacity, around 95% for Pb, 92% for Cu, 43% for Fe, and 54% for Mg [30]. The use of nanomaterial-based on α-Fe_2^{2+} oxide for the adsorption of Mg^{2+} metal ions also presents relevant results. The nanomaterial synthesized from α-Fe_2^{2+} oxide has demonstrated an adsorption rate of 85% for Mg^{2+} ions in seawater [34].

Nanomaterials are reported to be good adsorbents of heavy metals in liquid media. Silver nano agglomerates (AgNCs) encapsulated in porous metal-organic structures of ZIF-8 (MOF-AgNCs) used as adsorbents of Pb^{2+} and Mg^{2+} revealed that the amount of dispersed Ag^+ is lower when encapsulation occurs, being less harmful to the environment. Due to the porosity of ZIF-8, metal ions enter more easily inside the MOF, facilitating adsorption by AgNCs [36].

Synthesis of nanomaterials for the removal of thallium(I) and mercury(II) from water have been reported by Wang *et al.* (2020) and Wang and He (2020). Titanium nanomaterials used in aqueous solutions to remove thallium (I) were developed through TNM-6, TMN-30, and TNM-72 nanotubular structures. The difference in the nanotubes is linked to the alkaline hydrothermal method applied in the synthesis of obtainment. TNM-6 and TNM-72 showed increased Tl(I) adsorption capacity in the first 15 minutes, while TNM-30 increased after 2 hours. The maximum adsorption capacities of Tl(I) in TNM-6, TNM-72, and TNM-30 were 609.756, 657.895, and 710.400 mg/g, respectively. A CuS magnetic composite nanomaterial (Fe_3O_4@SiO_2@CuS) employed for H^{2+} removal in aqueous medium exhibited fast adsorption kinetics, high adsorption capacity, and excellent selective capture of Hg^{2+} in the presence of other metal ions, achieving an adsorption rate of 99.9% [38,42].

Ceramic nanocomposite membranes synthesized by a Fe-based hydrothermal method for Cd^{2+} removal have been shown to be efficient.

The weight of the Cd^{2+} ions adsorbed by the membrane was calculated using the equation (4):

$$q_e = \frac{(C_0 - C_e).V}{m} \quad (4)$$

Where q_e is the weight of Cd^{2+} adsorbed ($(mg \cdot g^{-1})$, C_0^{2+}), respectively, V volume of total solution (L) and m weight of adsorbent (g), the contact time of the solution with Cd^{2+} ions and the amount of adsorption are directly linked. The mean time for the passage of the solution through the membrane was 30 seconds, and a decrease in the concentration of Cd^{2+} was observed [32].

4. Conclusions

The use of nanotechnologies has proven to be an effective alternative in the removal of heavy metals and their metal ions since different nanomaterials have excellent adsorption activity and act in the simultaneous removal of different heavy metals, which allows the decontamination of an environment contaminated by more than one heavy metal with only one adsorbent material lowering deployment costs.

Further studies should be carried out to expand the knowledge about the synthesis of nanomaterials, the use associated with other adsorptive technologies, and the expansion of their applicability against other heavy metals and their ions. The present study contributes to the synthesis of relevant studies on the subject. It helps to expand the knowledge on removing metals by applying adsorptive nanotechnologies.

Funding

This research received no external funding.

Acknowledgments

University State of Ceará – UECE.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Khellaf, N.; Zerdaoui, M. Growth response of the duckweed *Lemna gibba* L. to copper and nikel phytoaccumulation. *Ecotoxicology* **2010**, *19*, 1363-1368, https://doi.org/10.1007/s10646-010-0522-z.
2. Divan, A.M.; Oliveira, P.L.d.; Perry, C.T.; Atz, V.L.; Azzarini-Rostirola, L.N.; Raya-Rodriguez, M.T. Using wild plant species as indicators for the accumulation of emissions from a thermal power plant, Candiota, South Brazil. *Ecol. Indic.* **2009**, *9*, 1156-1162, https://doi.org/10.1016/j.ecolind.2009.01.004.
3. Marcon, J.S.; Tochetto, G.A.; Dervanoski, A.; Pasquali, G.D.L. GEOPOLÍMEROS POROSOS SÃO ADSORVENTES ALTERNATIVOS PARA A ADSORÇÃO DE METAIS PESADOS? ANÁLISE DAS RECENTES DESCOBERTAS. *Rev. AIDIS* **2023**, *16*, 535-562, http://dx.doi.org/10.22201/iingen.0718378xe.2023.16.2.83134.
4. Dotto, G.L.; McKay, G. Current scenario and challenges in adsorption for water treatment. *J. Environ. Chem. Eng.* **2020**, *8*, 103988, https://doi.org/10.1016/j.jece.2020.103988.
5. Ma, X.; Xu, D.; Li, Y.; Ou, Z.; Howard, A. Synthesis of a new porous geopolymer from foundry dust to remove Pb^{2+} and Ni^{2+} from aqueous solutions. *J. Clean. Prod.* **2022**, *349*, 131488, https://doi.org/10.1016/j.jclepro.2022.131488.
6. Penna, I.C.; Martins, T.S.; da Silveira, J.V.W. Fibras Eletrofiadas Aplicadas na Remoção de Metais Pesados em Águas Residuárias da Mineração: uma Revisão Sistemática. *Rev. Virtual Quim.* **2022**, *14*, https://doi.org/10.21577/1984-6835.20220088.

7. da Costa Filho, M.C.; Neto, A.M.d.A.P.; Martelli, M.C. The use of zeolitic compounds as adsorbents for the removal of heavy metals (Pb, Cu, Cr and Mn): a review. *Res. Soc. Dev.* **2022**, *11*, e250111638159, https://doi.org/10.33448/rsd-v11i16.38159.
8. Lekshmi, R.; Rejiniemon, T.S.; Sathya, R.; Kuppusamy, P.; Al-mekhlafi, F.A.; Wadaan, M.A.; Rajendran, P. Adsorption of heavy metals from the aqueous solution using activated biomass from *Ulva flexuosa*. *Chemosphere* **2022**, *306*, 135479, https://doi.org/10.1016/j.chemosphere.2022.135479.
9. Abatal, M.; Avendaño, Y.S.D.; Hernández, N.C.; Giannakoudakis, D.A.; Anastopoulos, I.; Gutierrez, M.T.O. Chapter 12 - Leucaena leucocephala as biomass material for the removal of heavy metals and metalloids. In Biomass-Derived Materials for Environmental Applications, Anastopoulos, I., Lima, E., Meili, L., Giannakoudakis, D., Eds.; Elsevier, **2022**; 287-306, https://doi.org/10.1016/B978-0-323-91914-2.00002-7.
10. Nwagbara, V.U.; Sika, F.O.; Iyama, W.A.; Chigayo, K.; Kwaambwa, H.M. Evaluating the Potential Effectiveness of Moringa oleifera Seeds Biomass as an Adsorbent in the Removal of Copper (Cu) in Water. *J. Geosci. Environ. Prot.* **2022**, *10*, 120-143, https://doi.org/10.4236/gep.2022.103010.
11. Nwagbara, V.U.; Chigayo, K.; Iyama, W.A.; Kwaambwa, H.M. Removal of lead, cadmium, and copper from water using *Moringa oleifera* seed biomass. *J. Water Clim. Change* **2022**, *13*, 2747-2760, https://doi.org/10.2166/wcc.2022.091.
12. Baskaran, P.; Abraham, M. Adsorption of cadmium (Cd) and lead (Pb) using powdered activated carbon derived from Cocos Nucifera waste: A kinetics and equilibrium study for long-term sustainability. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102709, https://doi.org/10.1016/j.seta.2022.102709.
13. Nepal, D.; Kang, S.; Adstedt, K.M.; Kanhaiya, K.; Bockstaller, M.R.; Brinson, L.C.; Buehler, M.J.; Coveney, P.V.; Dayal, K.; El-Awady, J.A.; Henderson, L.C.; Kaplan, D.L.; Keten, S.; Kotov, N.A.; Schatz, G.C.; Vignolini, S.; Vollrath, F.; Wang, Y.; Yakobson, B.I.; Tsukruk, V.V.; Heinz, H. Hierarchically structured bioinspired nanocomposites. *Nat. Mater.* **2023**, *22*, 18–35, https://doi.org/10.1038/s41563-022-01384-1.
14. Moghaddam, F.D.; Heidari, G.; Zare, E.N.; Djatoubai, E.; Paiva-Santos, A.C.; Bertani, F.R.; Wu, A. Carbohydrate polymer-based nanocomposites for breast cancer treatment. *Carbohydr. Polym.* **2023**, *304*, 120510, https://doi.org/10.1016/j.carbpol.2022.120510.
15. Xie, Y.; Song, Y.; Sun, G.; Hu, P.; Bednarkiewicz, A.; Sun, L. Lanthanide-doped heterostructured nanocomposites toward advanced optical anti-counterfeiting and information storage. *Light Sci. Appl.* **2022**, *11*, 150, https://doi.org/10.1038/s41377-022-00813-9.
16. Mehdizadeh, P.; Jamdar, M.; Mahdi, M.A.; Abdulsahib, W.K.; Jasim, L.S.; Raheleh Yousefi, S.; Salavati-Niasari, M. Rapid microwave fabrication of new nanocomposites based on Tb-Co-O nanostructures and their application as photocatalysts under UV/Visible light for removal of organic pollutants in water. *Arab. J. Chem.* **2023**, *16*, 104579, https://doi.org/10.1016/j.arabjc.2023.104579.
17. Zhao, Y.; Xie, W.; Li, L.; Tahir, M.U.; Guan, Q.; Chu, S.; Hu, S.; Yongneng, X.; Ivanets, A.; Su, X. Highly Active Nico2s4-(Fe, Co, Ni)9s8/C Hybrid Nanosheets for the Reduction of 4-Nitrophenol to 4-Aminophenol. *SSRN* **2023**, 4523924, https://dx.doi.org/10.2139/ssrn.4523924.
18. Martins, P.M.; Santos, B.; Salazar, H.; Carabineiro, S.A.C.; Botelho, G.; Tavares, C.J.; Lanceros-Mendez, S. Multifunctional hybrid membranes for photocatalytic and adsorptive removal of water contaminants of emerging concern. *Chemosphere* **2022**, *293*, 133548, https://doi.org/10.1016/j.chemosphere.2022.133548.
19. Maciel, C.C.; de Barros, A.; Mazali, I.O.; Ferreira, M. Flexible biodegradable electrochemical sensor of PBAT and CNDs composite for the detection of emerging pollutants. *J. Electroanal. Chem.* **2023**, *940*, 117491, https://doi.org/10.1016/j.jelechem.2023.117491.
20. Pagani, R.N.; Kovaleski, J.L.; Rezende, L.M. Methodi Ordinatio: a proposed methodology to select and rank relevant scientific papers encompassing the impact factor, number of citation, and year of publication. *Scientometrics* **2015**, *105*, 2109–2135, https://doi.org/10.1007/s11192-015-1744-x.
21. Mancini, M.C.; Cardoso, J.R.; Sampaio, R.F.; Costa, L.C.M.; Cabral, C.M.N.; Costa, L.O.P. Tutorial for writing systematic reviews for the Brazilian Journal of Physical Therapy (BJPT). [Tutorial para elaboração de revisões sistemáticas para o Brazilian Journal of Physical Therapy (BJPT).] *Braz. J. Phys. Ther.* **2014**, *18*, 471-480.
22. Linde, K.; Willich, S.N. How objective are systematic reviews? Differences between reviews on complementary medicine. *J. R. Soc. Med.* **2003**, *96*, 17-22, https://doi.org/10.1177/014107680309600105.
23. Critical Appraisal Skills Programme. CASP. Available online: https://casp-uk.net/casp-tools-checklists/ (accessed on 25 November **2023**).

24. Amarray, A.; El Ghachtouli, S.; Leroy, J.; Bonnaillie, P.; Khaless, K.; Dahbi, M.; Azzi, M. Mesoporous nanomaterials based on manganese with different interlayer alkali cations: An efficient approach for the removal of Pb(II) and Cd(II) from aqueous medium. *J. Water Process. Eng.* **2021**, *40*, 101944, https://doi.org/10.1016/j.jwpe.2021.101944.
25. Huang, D.; Xu, B.; Wu, J.; Brookes, P.C.; Xu, J. Adsorption and desorption of phenanthrene by magnetic graphene nanomaterials from water: Roles of pH, heavy metal ions and natural organic matter. *Chem. Eng. J.* **2019**, *368*, 390-399, https://doi.org/10.1016/j.cej.2019.02.152.
26. Ma, J.; Xia, M.; Belver, C.; Zhang, Y.; Wang, F. A facile synthesis of ibandronate modified hydroxyapatite renewable nanomaterials for simultaneous removal of Cu^{2+}/Pb^{2+} and chlortetracycline: Experimental design and adsorption mechanism study. *J. Clean. Prod.* **2022**, *361*, 132173, https://doi.org/10.1016/j.jclepro.2022.132173.
27. Adamu, D.B.; Tufa, L.T.; Lee, J.; Zereffa, E.; Segne, T.A.; Razali, M.H. Facile synthesis of bismuth and iron co-doped hydroxyapatite nanomaterials for high-performance fluoride ions adsorption. *J. Environ. Chem. Eng.* **2023**, *11*, 111196, https://doi.org/10.1016/j.jece.2023.111196.
28. Saleh, T.A.; Elsharif, A.M.; Bin-Dahman, O.A. Synthesis of amine functionalization carbon nanotube-low symmetry porphyrin derivatives conjugates toward dye and metal ions removal. *J. Mol. Liq.* **2021**, *340*, 117024, https://doi.org/10.1016/j.molliq.2021.117024.
29. Hasan, M.N.; Salman, M.S.; Hasan, M.M.; Kubra, K.T.; Sheikh, M.C.; Rehan, A.I.; Rasee, A.I.; Awual, M.E.; Waliullah, R.M.; Hossain, M.S.; Islam, A.; Khandaker, S.; Alsukaibi, A.K.D.; Alshammari, H.M.; Awual, M.R. Assessing sustainable Lutetium(III) ions adsorption and recovery using novel composite hybrid nanomaterials**.** *J. Mol. Struct.* **2023**, *1276*, 134795, https://doi.org/10.1016/j.molstruc.2022.134795.
30. Abou-Zeid, R.E.; Ali, K.A.; Gawad, R.M.A.; Kamal, K.H.; Kamel, S.; Khiari, R. Removal of Cu(II), Pb(II), Mg(II), and Fe(II) Adsorption onto Alginate/Nanocellulose Beads as Bio-Sorbent. *J. Renew. Mater.* **2021**, *9*, 601-613, https://doi.org/10.32604/jrm.2021.014005.
31. Wang, H.; Qi, X.; Yan, G.; Shi, J. Copper-doped ZIF-8 nanomaterials as an adsorbent for the efficient removal of As(V) from wastewater. *J. Phys. Chem. Solids* **2023**, *179*, 111408, https://doi.org/10.1016/j.jpcs.2023.111408.
32. Wu, J.; Xue, S.; Bridges, D.; Yu, Y.; Zhang, L.; Pooran, J.; Hill, C.; Wu, J.; Hu, A. Fe-based ceramic nanocomposite membranes fabricated via e-spinning and vacuum filtration for Cd^{2+} ions removal. *Chemosphere* **2019**, *230*, 527-535, https://doi.org/10.1016/j.chemosphere.2019.05.084.
33. Modwi, A.; Idriss, H.; Khezami, L.; Albadri, A.; Ismail, M.; Assadi, A.A.; Nguyen-Tri, P. Stripping of Cu Ion from Aquatic Media by Means of MgY_2O_4@g-C_3N_4 Nanomaterials. *Water* **2023**, *15*, 1188, https://doi.org/10.3390/w15061188.
34. Ramutshatsha, D.; Ngila, J.C.; Ndungu, P.G.; Nomngongo, P.N. Application of response surface methodology for simultaneous removal of major cations from seawater using metal oxide nanostructures. *Water SA* **2020**, *46*, 313-321, https://doi.org/10.17159/wsa/2020.v46.i2.8247.
35. Ahangarani-Farahani, R.; Bodaghifard, M.A. A polyethanolamine nanodendrimer as a magnetic hybrid material for fast adsorption of heavy metal contaminants. *J. Mater. Sci. Mater. Electron.* **2022**, *33*, 25674-25686, https://doi.org/10.1007/s10854-022-09263-w.
36. Zhuang, P.; Zhang, P.; Li, K.; Kumari, B.; Li, D.; Mei, X. Silver Nanoclusters Encapsulated into Metal–Organic Frameworks for Rapid Removal of Heavy Metal Ions from Water. *Molecules* **2019**, *24*, 2442, https://doi.org/10.3390/molecules24132442.
37. Pan, K.; Tang, X.; Qu, G.; Tang, H.; Wei, K.; Lv, J. Mesoporous Silica/Iron Phthalocyanine Light-Driven Nanomaterials for Efficient Removal of Pb^{2+} Ions from Wastewater. *ACS Appl. Nano Mater.* **2023**, *6*, 12816-12827, https://doi.org/10.1021/acsanm.3c01499.
38. Wang, N.; Su, Z.; Deng, N.; Qiu, Y.; Ma, L.; Wang, J.; Chen, Y.; Hu, K.; Huang, C.; Xiao, T. Removal of thallium(I) from aqueous solutions using titanate nanomaterials: The performance and the influence of morphology. *Sci. Total Environ.* **2020**, *717*, 137090, https://doi.org/10.1016/j.scitotenv.2020.137090.
39. Ali, I.; Alyona, S.; Tatiana, K.k.; Anastasiya, G.; Albishri, H.M.; Alshitari, W.H. Facile adsorption-electroflotation method for the removal of heavy metal ions from water using carbon nanomaterials. *Environ. Sci. Pollut. Res.* **2023**, *30*, 38970-38981, https://doi.org/10.1007/s11356-022-24509-0.
40. Singha Deb, A.K.; Sahu, P.; Ali, S.M. Macrocyclic host appended carbon nanotubes for selective adsorption of metal ions: combined experimental, DFT and MD studies. *Mol. Syst. Des. Eng.* **2019**, *4*, 616-625, https://doi.org/10.1039/C9ME00003H.

41. Delavar, M.; Bakeri, G.; Hosseini, M.; Nabian, N. Synthesis and Application of Titania Nanotubes and Hydrous Manganese Oxide in Heavy Metal Removal from Aqueous Solution: Characterization, Comparative Study, and Adsorption Kinetics. *Theor. Found. Chem. Eng.* **2021**, *55*, 180-197, https://doi.org/10.1134/S004057952101005X.
42. Wang, Q.; He, J. Synthesis of Magnetic CuS Composite Nanomaterial and Its Specific Adsorption of Hg(II) in Water. *Chin. J. Appl. Chem.* **2020**, *37*, 1316-1323, https://doi.org/10.11944/j.issn.1000-0518.2020.11.200119.