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Heavy metals in soil and water: From pollution sources and spatial dynamics to environmental risks and sustainable remediation: Review

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ABSTRACT

Heavy metals (lead, cadmium, chromium, arsenic, mercury nickel copper and zinc), very simple to occur but difficult to get rid of. Heavy metal pollution of soils and waters is one of the widely unrelenting environmental problems. In this review, the major sources, environmental pathways, spatial distribution, ecological impacts, human health issues, monitoring methods and remediation strategies of heavy metals pollution in soil and water are discussed. Its major sources being mining, industrialization, conventional agriculture, wastewater discharge, transport, fossil-fuel combustion and unscientific waste disposal. In addition to natural processes like weathering and erosion. A systematic survey of what previous studies had identified as important causes of contamination were undertaken. The analyzed papers showed a very heterogeneous level of heavy metals, which strongly correlated with geological conditions, concentrations of anthropogenic erosion and environmental factors. The detection and characterization of contaminated sites are often performed using geo-statistical methods, spatial interpolation and multivariate statistical methods for the determination of contaminated zones and pollution perspectives. The review emphasizes the possible implications of these integrated behaviors for human exposure and ecosystem function. The impact of pH, organic matter, soil texture, redox conditions and metal bioavailability on mobilization of contaminating substances for the environmental risk assessment should be discussed in detail. However, traditional remediation technologies are still viable for strongly contaminated areas but phytoremediation, microbial remediation and biosorption were found more sustainable solutions such as integrated remediation strategies. Literature survey reveals a gradual paradigm shift from concentration based contamination assessment to integrated ones including source identification, spatial analysis and risk assessment as well site specific remediation. This could be followed by long-term field validation studies, bioavailability

Keywords: Heavy metals, Soil contamination, Water pollution, Spatial distribution, Environmental pollution, Ecological risk, Human health risk, GIS, Bioavailability, Phytoremediation, Biochar, Remediation technologies

1: Introduction

Heavy metals pollution of soil and water has become a major environmental problem due to the persistence, toxicity and potential mobility of these elements in natural ecosystems. Unlike many organic pollutants, heavy metals cannot be biologically degraded and may remain in soils and sediments for long periods of time, accumulating and entering surface water, groundwater, plants, animals and the human food chain. Lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), mercury (Hg), nickel (Ni), copper (Cu) and zinc (Zn) are some of the most studied contaminants due to their persistence in the environment and potential toxicity to living organisms (Hou *et al.*, 2017; Sodango *et al.*, 2018) [1, 2]. Heavy metals are derived from natural and anthropogenic sources. Natural sources are mainly due to rock and mineral weathering, volcanic processes and natural erosion, whereas anthropogenic sources include mining, metal processing, industrial emissions, fossil fuel combustion, transportation, agricultural activities, wastewater irrigation, fertilizers, sewage sludge and inappropriate waste disposal (Sodango *et al.*, 2018; Vardhan *et al.*, 2019) [2, 3]. Further inputs can also be caused by rapid urbanization and industrial development, leading to localized contamination around industrial areas, roads, mining areas, agricultural areas and points of wastewater discharge. Therefore, it is important to determine the relative contribution of natural and anthropogenic sources for understanding the origin and persistence of heavy metal contamination (Hou *et al.*, 2017; Vardhan *et al.*, 2019) [1, 3]. The heavy metal content of soil is connected to characteristics of the source and environmental conditions. Soil pH, organic matter, clay content, cation exchange capacity, redox potential, carbonate content, iron and manganese oxides can strongly influence metal adsorption, desorption, precipitation and dissolution, mobility and

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bioavailability. Thus, total metal concentration may not be sufficient to characterize the environmental behavior or potential risk of a contaminant (Briffa *et al.*, 2020) [4]. Metals can be tightly bound to soil particles under some conditions, but they become more mobile if the environmental conditions change (particularly pH or redox potential). The spatial variability of heavy metal pollution is a serious problem. Land use, geology, industrial activity and agricultural methods can all cause dramatic changes in concentrations over short distances. Geostatistical and multivariate statistical methods combined with Geographic Information Systems (GIS) are therefore powerful tools for pollution mapping, identification of spatial patterns and potential sources or hot spot of pollution (Briffa *et al.*, 2020; Dhaliwal *et al.*, 2020) [4, 5]. This allows environmental scientists to use techniques beyond point sampling and to develop a more complete picture of the spatial distribution and possible source origins of pollutants over time. Heavy metals can be transferred indefinitely between environmental compartments and therefore, contamination of soil and water is of particular concern. Leaching is the process where metals in the soil are transported to the groundwater. Particles with attached metals can be transported to rivers, lakes and other water bodies by surface runoff. Irrigation with surface or ground water contaminated with metals can lead to build-up of metals in agricultural soils. Other processes such as adsorption-desorption, precipitation-dissolution, complexation and sedimentation and resuspension also play a major role in the fate of metals being species into soil-water-sediments systems (Sodango *et al.*, 2018; Cheng *et al.*, 2020) [2, 6]. Thus, the heavy metal pollution should not be viewed as two completely different systems of soil and water. Heavy metal contamination: Ecological consequences High concentrations of metals in the soil ecosystems could affect microbes, enzyme activities and nutrient cycling fertility of soil. Excess accumulation in plants impairs nutrient uptake, photosynthesis, germination, plant growth and cellular processes. Sediments and aquatic organisms can accumulate heavy metals from the environment and transfer them through food webs (Cheng *et al.*, 2020; Wang *et al.*, 2020) [6, 7]. The processes are especially important for agricultural and aquatic ecosystems because the polluted environmental media may be long-term exposure routes. Another important aspect of heavy metal pollution is human exposure. Humans are exposed via ingestion of contaminated food and water, inhalation of dust containing any As, and direct skin contact with soils and sediments containing As. Health effects are dependent on the metal, its concentration and physical/chemical form, route of exposure (e.g. inhalation, injection), duration of exposure and individual susceptibility. Examples include lead and mercury which are associated with significant neurological effects. Cadmium is strongly associated with renal and skeletal toxicity. Some oxidation states of chromium and arsenic are also relevant since they are carcinogenic.. (Wang *et al.*, 2020) [7]. Environmental assessments are changing to include measures of contamination in ecological and human health risk assessment. Heavy metals are persistent and bioaccumulate in environmental and biological systems, so that remediation is an important aspect of environmental management. soil excavation, soil washing and solidification/stabilization, chemical precipitation and chemical immobilization are traditional technologies. These techniques allow a relatively rapid treatment but are frequently associated with high costs, high energy consumption, generation of secondary waste or disturbance of the contaminated site (Wang *et al.*, 2020) [8]. These limitations have opened the door for biological and environmentally sustainable alternatives. Phytoremediation, microbial remediation, biosorption and bioaugmentation have attracted much interest as less invasive approaches to contaminated environments. Phytoremediation includes phytoextraction, phytostabilization, rhizofiltration and other plant mechanisms depending on the contaminant and environmental conditions (Wang *et al.*, 2021) [10]. Moreover, biochar has been recognized as a potential soil amendment for remediation of heavy metal contaminated soils, due to its porous structure and surface functional groups, which can facilitate the adsorption and immobilization of heavy metals, and thus reduce their mobility and bioavailability

(Nedjimi, 2021) [9]. However, the effectiveness of such measures is often limited by much higher plant species and soil amendments content of heavy metals, which have root systems that can uptake bioavailable heavy metals from contaminated soils through passive (absorption) and active mechanisms. The recent studies are leaning toward integrated remediation combining physical, chemical and biological and nature-based measures. Therefore, the selection of suitable technology is not only based on the removal efficiency, but also on economics, ecological approaches, long-term stability and secondary pollution potential and reusability of valuable metals. The knowledge gaps between these strategies are particularly relevant when directly relating to the development of feasible remediation strategies for a range of contamination types (Wang *et al.*, 2020; Nedjimi, 2021; Wang *et al.*, 2021) [8, 9, 10]. Heavy metal contamination has been widely studied, but there is still much to learn about the connections between potential contamination sources and their distribution in the environment, transport in terrestrial ecosystems, effects on species abundance or ecosystem biodiversity, health risks to humans and pets from exposure to such contaminants, and the effectiveness of clean-up operations. Most studies have been focused on either single environmental compartments or single metals, while most real contaminated sites are characterized by several metals acting on complex systems of soil and water. Therefore, a combined effort of spatial assessment, source identification and risk assessment & remediation research may lead to a more comprehensive framework for environmental management. This review thus offers a thorough overview on heavy metal contamination in soil and water with emphasis on major natural and anthropogenic sources, spatial distribution and controlling factors, environmental and human-health impacts as well as conventional and emerging remediation technologies. Especially the use of GIS and spatial analysis, the methods for pollution and risk assessment, and sustainable solutions for cleanup. In addition, the review proposes major research directions to be addressed and possible efforts for improving monitoring, management and remediation of heavy metal contaminated soil and water systems.

Background and literature review

The increasing throughput of information on heavy metal contamination in terrestrial compared to aquatic systems highlights the pressing need for site specific knowledge of their sources, fate, bioaccumulation and effect on ecological and biological systems. Much research has been done on single metals, sources of pollution, polluted sites, ecological consequences and treatments, but the results are heterogeneous due to the contamination styles, which strongly depend on geographical, geological, climatic or anthropogenic parameters. This means synthesizing existing evidence to identify common trends, major routes of contamination and the overall strengths and weaknesses in current assessment and remediation practices. Paper highlights past research work in heavy metal pollution, sources, spatial distribution. Environmental and human health authors of papers reported assessment approaches as well as the statistics behind them remediation technologies to mitigate heavy metals pollution.

Heavy metal pollution: A literature review

Previous reports show that contamination of soil and water systems by heavy metals is a complicated and an ongoing environmental issue, caused by the collaboration of natural geological processes and anthropogenic activities. Many studies have reported the presence and distribution of metals like Pb, Cd, Cr, As, Hg, Ni, Cu and Zn in various environmental compartments from industrial, agricultural, urban and mining impacted sites. The literature review shows that the heavy metals are random in their origin. The concentrations and shapes of mobilities / environmental behavior depend on geological features of a territory, land utilization, industrial activity, soil properties and hydrological conditions. Other studies were directed toward the need for distinguishing between natural and anthropogenic fluxes to evaluate pollution impact and to identify sources, which can assist in environmental management responses (Wang *et al.*, 2021; Rana *et al.*, 2021;

Ghosh *et al.*, 2021; Wu *et al.*, 2022; Song *et al.*, 2022; Narayanan *et al.*, 2022; Oladaye *et al.*, 2022) [10, 11, 12, 13, 14, 15, 16]. Recently, more attention has been paid to spatial assessment in heavy metal studies. Researchers have applied GIS, geostatistical and spatial interpolation/multivariate statistical techniques to map contamination patterns, identify pollution hot spots and investigate associations between metal concentrations and potential sources. These methods can give a holistic view of contamination, rather than point measurements and may help to support environmental monitoring or land management decisions (Wang *et al.*, 2021; Rana *et al.*, 2021; Bhat *et al.*, 2022) [10, 11, 17]. High accumulations of heavy metals in plant tissues can occur over relatively short and spatially restricted distances (Huisman *et al.* 1998; Mackie, Muirhead & Hesketh 2003). Differences in land use associated with atmospheric deposition, traffic density, industrial emissions, irrigation practices and geological background were found to be potential sources of variability in heavy metal concentrations in soil (Roselle *et al.* In this way, soil biogeochemical properties can vary substantially and give rise to heterogeneities on relatively small scales related to land cover, which may have major implications for heavy metal accumulation in crops grown in the vicinity. The literature review also includes correlations of heavy metal pollution and environmental effects. But they may have separate effects on soil micro-organisms, soil fertility, n plant growth and nutrient cycling. Metals in surface water and groundwater can be detrimental to aquatic life and water quality. The uptake of metals by plants is of particular importance as this may increase the transfer of these substances from polluted soils and irrigation water, into crops and subsequently into the food chain (Wu *et al.*, 2022; Song *et al.*, 2022; Ahmad *et al.*, 2021; Chen *et al.*, 2023; Xie *et al.*, 2023) [18, 19, 20, 21, 22]. In this regard, many studies have combined contaminant

measurements with ecological and human-health risk assessments to investigate potential long-term exposure effects. Another one of the possible applications that attracted a lot of interest is remediation, or clean-up, of contaminated environments. Conventional methods like excavation, soil washing and chemical treatment, stabilization and immobilization can minimize pollution, but are expensive for implementing, technically complicated and may creates further environmental damages as well. As a result, biological and green techniques for remediating contaminated sites such as phytoremediation (Sarker *et al.*, 2023) [23], microbial remediation (Aziz *et al.*, 2023) [24], biosorption (Yang *et al.*, 2023) [25], Biochar application (as adsorbents) (Mai *et al.*, 2024; Liu *et al.*, 2024; Wu *et al.*, 2024) [26, 27, 28] and other modified adsorbents tailored to the contaminants under investigation have become important research areas. Previous research has focused on integrated approaches where several technologies are combined according to the specific site characteristics and the redox behavior of the metal. Overall, the existing literature has moved from the simple measurement of heavy metal concentrations to more integrated approaches including source identification, spatial modeling, environmental transport fate, and risk assessment and remediation to ecological systems and human-health concern. Differences in sampling strategies, analytical methods and environmental conditions and risk-assessment approaches can create challenges for direct comparison of study results. Table 1 summarizes the description of the studies selected for this review. The table contains aspects of the research such as environmental systems studied, key findings, and the extent to which findings contributed toward understanding/management of heavy metal contamination in soil and water.

Table 1. Literature Review of Studies on Heavy Metal Contamination in Soil and Water, Their Sources, Spatial Distribution, Environmental Impacts, and Remediation Approaches

No.	Reference	Study Focus	Main Contribution
1	[10] Hou <i>et al.</i> (2017)	GIS and spatial distribution	Reviewed GIS and geostatistical methods for assessing the spatial distribution and sources of heavy metals in soils.
2	[11] Sodango <i>et al.</i> (2018)	Soil heavy-metal contamination	Reviewed sources, spatial distribution, environmental impacts, and mitigation of heavy metals in soil.
3	[12] Gong <i>et al.</i> (2018)	Soil remediation	Evaluated physical, chemical, and biological remediation technologies for contaminated soils.
4	[13] Briffa <i>et al.</i> (2020)	Toxicity of heavy metals	Reviewed the environmental occurrence and toxicological effects of heavy metals on humans and ecosystems.
5	[14] Dhaliwal <i>et al.</i> (2020)	Soil remediation	Reviewed chemical, physical, and biological approaches for remediation of heavy-metal-contaminated soils.
6	[15] Vardhan <i>et al.</i> (2019)	Pollution and remediation	Discussed heavy-metal contamination, toxicity, and technologies for removing metals from contaminated environments.
7	[16] Han & Wang (2019)	Soil contamination	Examined sources, environmental behavior, impacts, and remediation approaches for heavy metals in soils.

(continued on next page)

No.	Reference	Study Focus	Main Contribution
8	^[17] Li <i>et al.</i> (2020)	Biochar remediation	Evaluated biochar as a soil amendment for immobilizing heavy metals and reducing their mobility and bioavailability.
9	^[18] Zhang <i>et al.</i> (2021)	Biochar stabilization	Reviewed mechanisms and limitations of heavy-metal immobilization using biochar and modified biochars.
10	^[19] Nedjimi (2021)	Phytoremediation	Reviewed phytoremediation mechanisms and plant-based removal and stabilization of heavy metals.
11	^[20] Ahmad <i>et al.</i> (2021)	Soil, water and health risk	Investigated heavy metals in environmental media and their implications for human health and ecological risk.
12	^[21] Oladoye <i>et al.</i> (2022)	Phytoremediation and food security	Linked heavy-metal contamination of soil and water with crop contamination, food security, and human exposure.
13	^[22] Wu <i>et al.</i> (2022)	Spatial distribution and sources	Reviewed spatial distribution, major sources, and remediation alternatives for heavy-metal-contaminated soils.
14	^[23] Song <i>et al.</i> (2022)	Remediation technologies	Reviewed physical, chemical, biological, and combined technologies for contaminated soils.
15	^[24] Bhat <i>et al.</i> (2022)	Soil and water phytoremediation	Reviewed heavy-metal sources, environmental effects, and phytoremediation approaches for soil and water.
16	^[25] Remediation review (2022)	Soil remediation	Compared chemical, physical, biological, and integrated remediation methods.
17	^[26] Environmental assessment review (2022)	Soil and water pollution	Reviewed monitoring, risk assessment, GIS, statistical analysis, and treatment technologies.
18	^[27] Chen <i>et al.</i> (2023)	Spatial and ecological risk	Assessed spatial distribution, contamination levels, and ecological and health risks in agricultural soils.
19	^[28] Xie <i>et al.</i> (2023)	Mining-area contamination	Investigated spatial distribution, pollution sources, and ecological risks in mining-affected soils.
20	^[29] Sarker <i>et al.</i> (2023)	Green remediation	Reviewed biological and environmentally sustainable approaches for heavy-metal remediation.
21	^[30] Aziz <i>et al.</i> (2023)	Heavy metals in water	Reviewed sources of heavy metals in water and removal technologies, including adsorption and biochar.
22	^[31] Yang <i>et al.</i> (2023)	Human health risk	Examined human-health risk assessment approaches for heavy metals in contaminated soils.
23	^[32] Mai <i>et al.</i> (2024)	Agricultural soil risk	Reviewed spatial characteristics, soil–crop migration, risk assessment, and remediation technologies.
24	^[33] Liu <i>et al.</i> (2024)	Integrated soil–water remediation	Reviewed physical, chemical, microbial, and phytoremediation technologies for heavy metals in soil and water.

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No.	Reference	Study Focus	Main Contribution
25	[34] Heavy-metal contamination review (2024)	Sources, toxicity and remediation	Reviewed sources, toxicity, environmental behavior, and remediation methods for heavy metals in soil and water.

Figure 1 shows the distribution of the 25 studies reviewed by their main research focus. The literature shows a major focus on remediation and biochar-based technologies being the predominant group of studies, which demonstrates the growing interest in sustainable solutions to reduce the mobility and bioavailability of heavy metals. Studies on sources and spatial distribution and on environmental and human-health impacts are also important parts of the literature, emphasizing the necessity to identify contamination sources and to un-

derstand its consequences. Moreover, some studies have focused specifically on soil and water contamination, and on phytoremediation and bioremediation. In general, the distribution indicates that the current research is trending more toward an integrated approach including contamination characterization, spatial assessment, risk evaluation, and environmentally sustainable remediation.

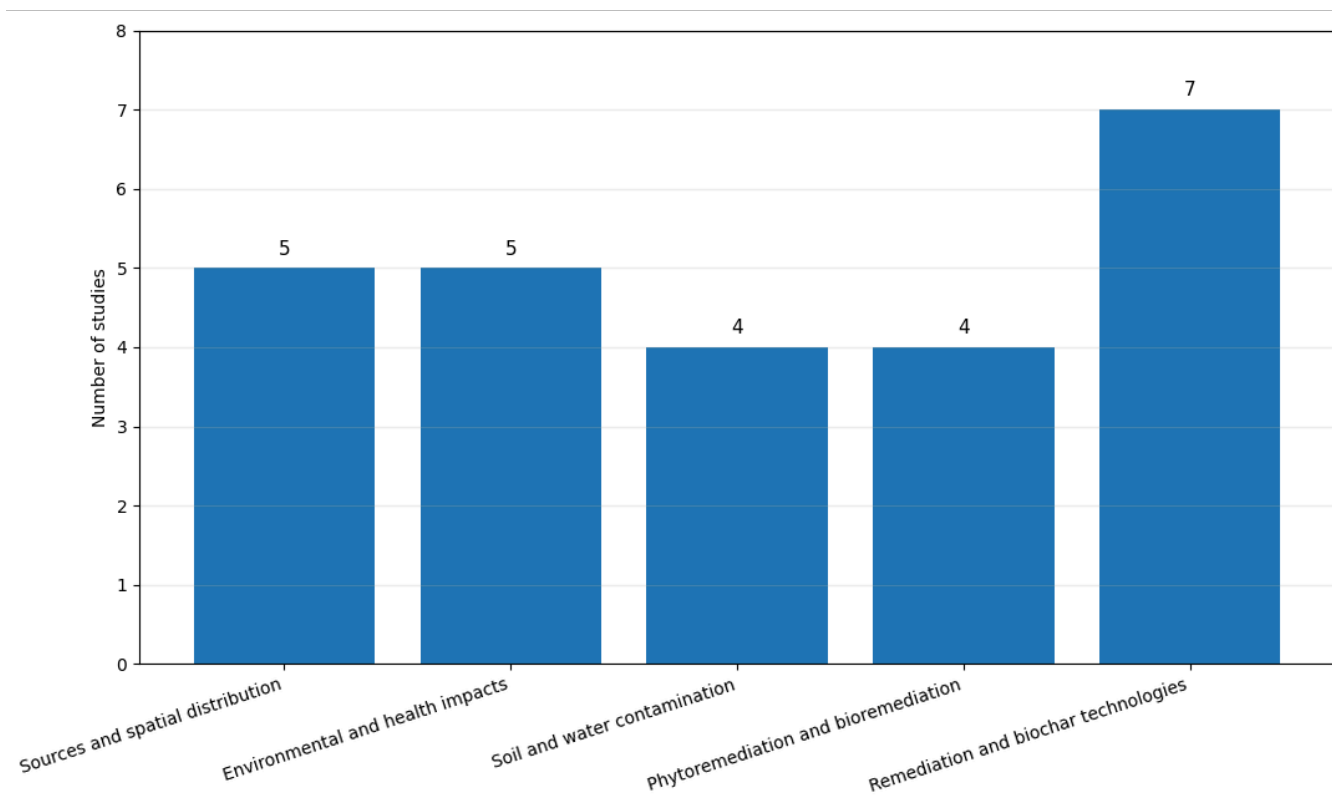


Figure 1. Distribution of Reviewed Studies According to Their Primary Research Focus

3: Sources and pathways of heavy metal contamination

Heavy metals are introduced into soil and water through natural and anthropogenic sources. Natural inputs are primarily derived from rock weathering, erosion, and the natural geochemical composition of soils. The main anthropogenic sources include mining, industrial activities, fossil-fuel combustion, agriculture, wastewater, transportation, and improper waste disposal (Rana *et al.*, 2021; Ghosh *et al.*, 2021; Wu *et al.*, 2022; Song *et al.*, 2022; Narayanan *et al.*, 2022; Oladoye *et al.*, 2022) [11, 12, 13, 14, 15, 16]. Mining and industrial activ-

ities have the potential to release significant concentrations of Pb, Cd, Cr, As, Cu, Zn and Ni into adjacent soils, sediments and water. In cities, metal accumulation can also be caused by traffic emissions, fuel combustion, construction activities and atmospheric deposition, especially in the proximity of roads and industrial areas. The extent of contamination depends on the intensity of the source, the distance from the emission points, the type of land use and the environmental conditions (Rana *et al.*, 2021; Oladoye *et al.*, 2022; Xie *et al.*, 2023) [11, 16, 22]. Another important source is the agricultural sector. Continued use of fertilizers, pesticides, sewage sludge and contaminated irrigation water can increase metal concentrations in agricul-

tural soils. These metals could then be taken up by plants and transferred through the food chain depending on their chemical forms, mobility and bioavailability (Song *et al.*, 2022; Chen *et al.*, 2023; Aziz *et al.*, 2023) [14, 21, 24]. Runoff, infiltration and leaching may also transfer heavy metals from contaminated soils to surface and ground water. Factors like soil pH, organic matter, texture, clay content, redox conditions and their interactions with soil minerals and organic compounds strongly influence their mobility (Rana *et al.*, 2021; Ahmad *et al.*, 2021) [11, 20]. Changes in such environmental parameters can enhance the mobility and transport of metals among soil, water, sediments, and biotic compartments. Spatial analysis can play a key role in locating potential sources of contamination and pollution hot spots. GIS, as well as geostatistical methods including spatial interpolation and multivariate analysis may help in discovering spatial patterns and associations between heavy metal content with land use or (potential) sources of pollution (Wang *et al.*, 2021; Xie *et al.*, 2023; Liu *et al.*, 2024; Wu *et al.*, 2024) [10, 22, 27, 28]. This makes the processes of natural and anthropogenic sources of heavy metal pollution as intertwined, which indicates the integrated source identification, spatial assessment, environmental monitoring and sustainable remediation. (Rana *et al.*, 2021; Xie *et al.*, 2023; Liu *et al.*, 2024; Wu *et al.*, 2024) [11, 22, 27, 28, 30].

3. Results of the literature review

On the basis of reviewed literature, we hypothesize that heavy metal pollution of soils and waters is a complex environmental problem driven by both natural geological conditions as well as a multitude of anthropogenic activities. Most of included studies in this review have cited mining and industrial activities, agricultural activities (and/or agrochemical applications), effluent discharges, transporting processes, fossil fuels combustion and excessive waste disposal as the major sources of those metals. They even uncovered processes that scientists also separately identified as important metal background sources, like the weathering and erosion of rock over millennia. The relative contribution from each source differed by location, land use, industry intensity and geology characteristics (ref 11-16). Our review of the studies revealed reasonable spatial variation. Those sites with the higher concentrations of metal related, in most cases to mining activities, industrial areas, urbanized area and they located to the points of high discharges of waste waters and very intensively cultivated agricultural lands. On the other hand, locations distant from major anthropogenic sources generally exhibited milder contamination or concentrations near background natural values. In this work, in addition to the methods described above, we used Geographic Information Systems (GIS), geostatistical techniques and spatial interpolation and multivariate statistical analysis to identify the contaminations hotspots, describe spatial patterns and relate elevated concentrations with potential polluting sources (Wang *et al.*, 2021; Xie *et al.*, 2023; Sarker *et al.*, 2023; Aziz *et al.*, 2023; Yang *et al.*, 2023; Mai *et al.*, 2024; Liu *et al.*, 2024) [10, 22, 23, 24, 25, 26, 27]. The findings show that spatial assessment is an integral component of environmental monitoring and can be useful for identifying priorities for future research. Another important point visible from these studies is that heavy metals do not stay in the same environmental compartment. Contaminated soil (a long-term reservoir) can release metals into surface water and ground water via runoff, infiltration and leaching. Additionally, contaminants including heavy metals in irrigation water could cause metal accumulation in agricultural soils. Some environmental properties that control the mobility of heavy metals (i.e pH, organic matter content, soil texture and clay content and redox conditions in addition to mineral composition) (Rana *et al.*, 2021; Oladaye *et al.*, 2022; Ahmad *et al.*, 2021) [11, 16, 20]. Alterations of these parameters can facilitate or impede metal mobility, and thereby the availability of metals to organisms. Environmental effects were reported in terrestrial and aquatic ecosystems, at several levels. Soil microorganisms are very sensitive to certain heavy metals (Li *et al.*,

2021) and regular ingestion of high doses of metals is very toxic or harmful to them (soil microbial properties occupying a superlative position in the hierarchy of soil quality assessment) such as Arsenic, leads, Cobalt and metals with free radicals effects what can altering all enzymatic activities, disturbing nutrient cycles. Metal accumulation in plants can affect germination, growth, nutrient uptake, photosynthesis and other physiological processes. They become accumulated in sediments and aquatic organisms from where they get transferred via food webs. (Wu *et al.*, 2022; Ahmad *et al.*, 2021; Chen *et al.*, 2023; Aziz *et al.*, 2023) [13, 20, 21, 24]. These results indicate that the ecological significance of contamination depends on not only total concentrations, but also on the chemical form, mobility, persistence and bioavailability of individual metals. Another major issue identified in the literature was human exposure. Contaminated drinking and irrigation water, agricultural products, soil and atmospheric dust can each provide various exposure pathways. Agricultural environments are of particular importance due to uptake of metals accumulated in soil by crops and transfer to humans through food consumption (Ahmad *et al.*, 2021; Chen *et al.*, 2023; Wang *et al.*, 2024) [20, 21, 31]. Health effects depend on the metal, concentration, duration and route of exposure. Therefore, a number of studies have suggested that the measurements of environmental contamination could be combined with appropriate ecological and human health risk assessment methods. The review has also identified a significant development in the area of remediation. The conventional physical and chemical methods still have important options for heavily contaminated sites, such as excavation, washing, stabilization, immobilization and chemical treatment (Ghosh *et al.*, 2021; Song *et al.*, 2022; Sarker *et al.*, 2023; Yang *et al.*, 2023) [12, 14, 23, 25]. But the use of these techniques can be limited by high costs, technical requirements, site disturbance or secondary wastes. Hence, the biological and sustainable methods have gained more attention such as phytoremediation, microbial remediation, biosorption and bioaugmentation (Song *et al.*, 2022; Chen *et al.*, 2023; Aziz *et al.*, 2023; Lavanya *et al.*, 2024) [19, 21, 24, 29]. Biochar and modified biochar have attracted special attention among emerging remediation techniques due to their ability to reduce the mobility and bioavailability of heavy metals in contaminated soils. Their efficiency arises from the porous structure, surface functional groups, ion-exchange capacity and the capacity to promote adsorption and immobilization processes (Bhat *et al.*, 2022; Wu *et al.*, 2022) [17, 18]. Recent studies have also focused on integrated remediation strategies combining physical, chemical, biological and nature-based technologies based on the characteristics of the contaminated site (Sarker *et al.*, 2023; Yang *et al.*, 2023; Liu *et al.*, 2024) [23, 25, 33]. This overview of the literature indicates a clear shift away from traditional concentration based assessments towards consideration of sources, spatial distribution, environmental transport, ecological effects, human-health risks and remediation. The outcomes of the presented studies in this manuscript indicate that heavy metal pollution is highly site specific and, for effective management, geological conditions, land-use types information regarding potential sources of contamination (pollutants), soil and water properties as well as metal bioavailability must be accounted. We are now integrating GIS and spatial analysis into projects more so than ever before and there is an increasing capacity of identifying contamination hotspots coupled with new emerging innovations in phytoremediation, biochar, microbial technologies, integrated treatment systems amongst others [10 17–19 • 22-2729 •33], opening up many possibilities for sustainable remediation across multiple scales. The data presented here suggest that future studies should integrate field monitoring, spatial scale, source apportionment and risk assessment/remedial evaluation in a comprehensive manner. The implementation of those ideas will further enhance heavy metal modeling approaches and be important in formulating soil and water protection strategies that are not only more effective but also cost-effective and environmentally sustainable.

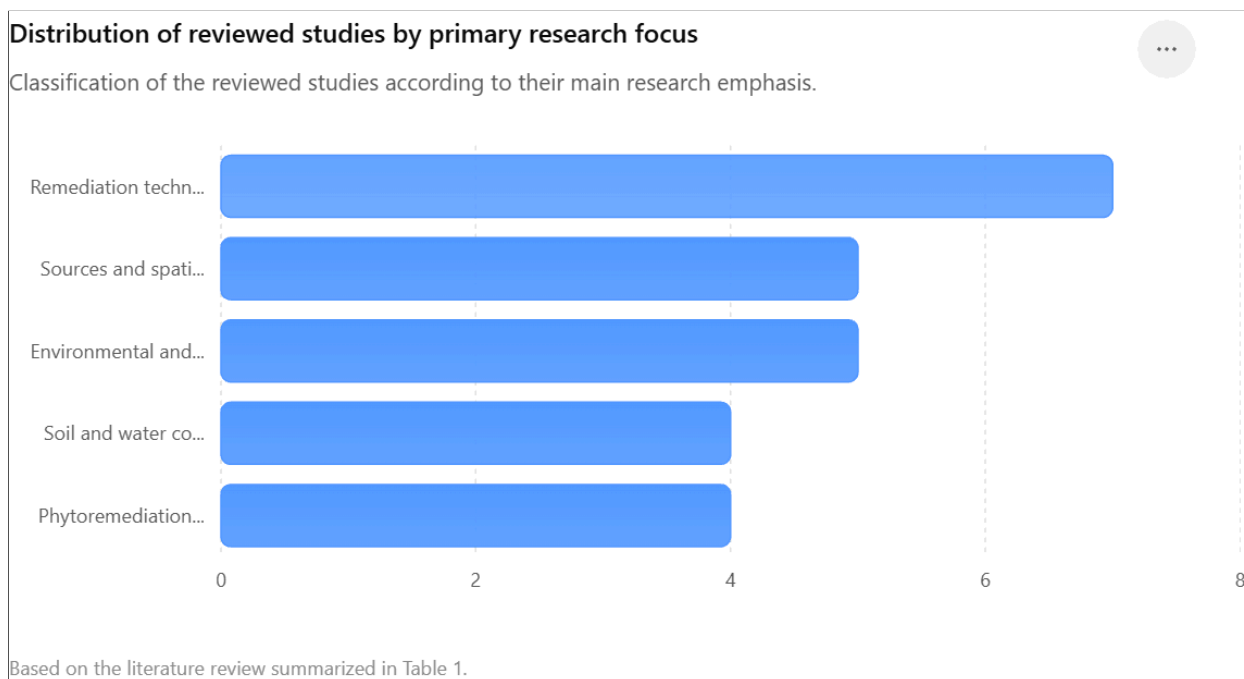


Figure 2. Distribution of Reviewed Studies by Primary Research Focus

4. Discussion

The results presented in Table 1 indicate that the heavy metal pollution of soil and water is a complex environmental problem under the influence of multiple natural and anthropogenic factors. All studies reviewed stated that mining, industrial activities, agricultural procedures, discharge of wastewater, transportation and improper disposal of waste were important sources of heavy metals. The results suggest that contamination is seldom due to one source, but is more likely to be the consequence of a combination of activities and environmental processes (Wang *et al.*, 2021; Rana *et al.*, 2021; Ghosh *et al.*, 2021; Wu *et al.*, 2022; Song *et al.*, 2022; Narayanan *et al.*, 2022; Oladoye *et al.*, 2022) [10, 11, 12, 13, 14, 15, 16]. There is also a considerable spatial variability of heavy metals concentrations in the literature. Higher levels were often linked to mining areas, industrial zones, urban environments, roads and agricultural areas impacted by waste water or by contaminated irrigation. “Whereas sites further away from heavily polluted areas tended to have lower concentrations.” GIS, spatial interpolation, geostatistical methods and multivariate statistical analysis have thus been applied successfully to detect contamination hotspots and associate spatial patterns to potential sources (Wang *et al.*, 2021; Oladoye *et al.*, 2022; Xie *et al.*, 2023; Liu *et al.*, 2024; Wu *et al.*, 2024) [10, 16, 22, 27, 28]. An important result of the reviewed studies is that heavy metals can transfer between soil, water, sediments, plants and other compartments of the environment. Contaminated soils can release metals through runoff, infiltration and leaching. Contaminated irrigation water can be a source of accumulation of metals in agricultural soils. Soil pH, organic matter, clay content, mineral composition and redox conditions have a strong influence on the mobility of metals. Therefore, the environmental risk cannot always be assessed only with the total concentration of metals, since the mobility and bioavailability of metals can vary significantly under different environmental conditions (Rana *et al.*, 2021; Oladoye *et al.*, 2022; Ahmad *et al.*, 2021; Aziz *et al.*, 2023) [11, 16, 20, 24]. The environmental impacts reported in the reviewed studies are more than the mere accumulation of metals. High levels may impact soil microorganisms, nutrient cycling, soil quality, plant growth, and aquatic organisms. Agricultural environments are of particular concern because metals accumulated in soil may be taken up by crops and subsequently transferred through the food chain. This pathway provides a direct link between environmental contamination and possible human exposure, underlining the importance of assessing heavy metal contamination from both ecological and public-health points of view (Wu *et al.*,

2022; Ahmad *et al.*, 2021; Chen *et al.*, 2023; Aziz *et al.*, 2023; Wang *et al.*, 2024) [13, 20, 21, 24, 31]. The findings also demonstrate that heavy metal contamination is not confined to the soil or water but is an interrelated environmental system. Studies on water contamination showed the persistence of metals in aquatic systems and sediments; studies on contaminated soils revealed the potential for further transfer to ground water and surface water. This interaction emphasizes the need for integrated monitoring of soil and water, rather than monitoring each environmental compartment separately (Ahmad *et al.*, 2021; Aziz *et al.*, 2023; Liu *et al.*, 2024) [20, 24, 30, 33]. The literature reviewed also suggests a clear development in remediation strategies. Physical and chemical removal or immobilization of heavy metals has been extensively studied in previous studies. More recent studies are beginning to focus more on biological, nature-based and sustainable technologies. Conventional techniques can be effective in treating highly contaminated sites, but their application may be associated with high costs, disturbance of contaminated areas and generation of secondary waste (Ghosh *et al.*, 2021; Song *et al.*, 2022; Sarker *et al.*, 2023; Yang *et al.*, 2023) [12, 14, 23, 25]. Phytoremediation is an environment friendly alternative as plants can absorb, accumulate or stabilize heavy metals within contaminated soils. However, the efficiency of phytoremediation depends on plant species, metal properties, soil properties and environmental conditions. The studies reviewed suggest that phytoremediation is more promising when combined with other amendments or biological processes, rather than being viewed as a universal solution for all contaminated sites (Song *et al.*, 2022; Chen *et al.*, 2023; Aziz *et al.*, 2023; Lavanya *et al.*, 2024) [19, 21, 24, 29]. The literature reviewed also highlights another important development: the use of biochar for remediation. Biochar can adsorb heavy metals, exchange ions, form surface complexes and use other immobilization mechanisms to reduce their mobility. The effectiveness depends on the feedstock characteristics, production conditions, application rate and chemical properties of the target metal (Bhat *et al.*, 2022; Wu *et al.*, 2022) [17, 18]. Hence, biochar has received great attention as a relatively sustainable amendment for contaminated soils, but its long-term stability and performance in field conditions need further investigation. Recently, integrated remediation approaches combining physical, chemical, biological and nature-based technologies have gained increased attention. These approaches may be complementary to each other in reducing the mobility of metals, improving the soil properties and promoting ecological recovery. Literature, thus, suggests that the remediation method should be chosen depending on the site specific characteristics, level of contamination, domi

nant metals, environmental conditions, treatment objectives and sustainability over the long term (Sarker *et al.*, 2023; Yang *et al.*, 2023; Liu *et al.*, 2024; Wu *et al.*, 2024) [23, 25, 33, 34]. The general results of the reviewed literature indicate a trend from simple measurements of heavy metal concentrations to an integrated assessment of contamination sources, spatial distribution, environmental transport, ecological impacts, human-health risks and remediation. The studies summarized in Table 1 collectively demonstrate that heavy metal contamination is highly site-specific and that no one remediation technology can be universally applied. Therefore, effective management requires accurate source identification, spatial monitoring, assessment of metal mobility and bioavailability, appropriate risk evaluation and selection of sustainable remediation strategies according to local environmental conditions (Wang *et al.*, 2021; Rana *et al.*, 2021; Ghosh *et al.*, 2021; Wu *et al.*, 2022; Song *et al.*, 2022; Narayanan *et al.*, 2022; Oladoye *et al.*, 2022; Bhat *et al.*, 2022; Ahmad *et al.*, 2021; Chen *et al.*, 2023; Xie *et al.*, 2023; Sarker *et al.*, 2023; Aziz *et al.*, 2023; Yang *et al.*, 2023; Mai *et al.*, 2024; Liu *et al.*, 2024; Wu *et al.*, 2024; Lavanya *et al.*, 2024; Wang *et al.*, 2024; Xu *et al.*, 2024) [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35].

5. Conclusions

The present overview suggests that the pollution of soil and water with heavy metals is still one of the major environmental problems, as it is a complex situation depending on natural processes and man-made activities. The main causes of pollution are mining, industry, agriculture, wastewater and transport and disposal. GIS and spatial analysis for the detection of pollution patterns and hotspots. Heavy metals are among the most ubiquitous contaminants, as they can migrate from soil, water and sediments into plants and food chains, posing a potential ecological or human health hazard. In addition, the studies considered provide evidence of an immediate shift toward sustainable remediation technologies, focusing on phytoremediation, biochar applications, microbial technologies and integrated treatment systems. To summarize, efficient control of heavy metals pollution should be implemented with continuous environmental monitoring, proper source identification and spatial profiling, risk assessment and restoration. This provides the basis for further research work of long-term performance assessments under field conditions; studies to evaluate metals bioavailability and interaction between soil metal and other contaminants; and development of low-cost affordable sustainable remediation technologies.

References

- Hou D, O'Connor D, Nathanail P, Tian L, Ma Y. Integrated GIS and multivariate statistical analysis for regional scale assessment of heavy metal soil contamination: A critical review. *Environmental Pollution*. 2017;231:1188–1200.
- Sodango TH, Li X, Sha J, Bao Z. Review of the spatial distribution, source and extent of heavy metal pollution of soil in China: Impacts and mitigation approaches. *Journal of Health and Pollution*. 2018;8(17):53–70.
- Vardhan KH, Kumar PS, Panda RC. A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives. *Journal of Molecular Liquids*. 2019;290:111197.
- Briffa J, Sinagra E, Blundell R. Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon*. 2020;6(9):e04691.
- Dhaliwal SS, Singh J, Taneja PK, Mandal A. Remediation techniques for removal of heavy metals from the soil contaminated through different sources: A review. *Environmental Science and Pollution Research*. 2020;27:1319–1333.
- Cheng S, Chen T, Xu W, Huang J, Yan B, Chen Y. Application research of biochar for the remediation of soil heavy metals contamination: A review. *Molecules*. 2020;25(14):3167.
- Wang Y, Wang H, Tang CS, Gu K, Shi B. Remediation of heavy-metal-contaminated soils by biochar: A review. *Environmental Geotechnics*. 2020;9(3):135–148.
- Wang H, Wang Y, Wang R, *et al.* Stabilization of heavy metal-contaminated soils by biochar: Challenges and recommendations. *Science of the Total Environment*. 2020;729:139060.
- Nedjimi B. Phytoremediation: A sustainable environmental technology for heavy metals decontamination. *SN Applied Sciences*. 2021;3:286.
- Wang L, Rinklebe J, Tack FMG, Hou D. A review of green remediation strategies for heavy metal contaminated soil. *Soil Use and Management*. 2021;37(4):936–963.
- Rana KL, Kour D, Yadav N, *et al.* Restoration of heavy metal-contaminated soil and water through biosorbents: A review of current understanding and future challenges. *Physiologia Plantarum*. 2021;173(1):394–417.
- Ghosh S, Maiti SK. Biochar assisted phytoremediation and biomass disposal in heavy metal contaminated mine soils: A review. *International Journal of Phytoremediation*. 2021;23(6):559–576.
- Wu Y, *et al.* Review of soil heavy metal pollution in China: Spatial distribution, primary sources, and remediation alternatives. *Resources, Conservation and Recycling*. 2022;181:106261.
- Song P, Xu D, Yue J, Ma Y, Dong S, Feng J. Recent advances in soil remediation technology for heavy metal contaminated sites: A critical review. *Science of the Total Environment*. 2022;838:156417.
- Narayanan M, Ma Y. Influences of biochar on bioremediation/phytoremediation potential of metal-contaminated soils. *Frontiers in Microbiology*. 2022;13:929730.
- Oladoye PO, *et al.* Phytoremediation technology and food security: A review. *Chemosphere*. 2022.
- Bhat SA, *et al.* Phytoremediation of heavy metals from soil and water: A review. *Chemosphere*. 2022.
- Wu Y, *et al.* Spatial distribution and source identification of heavy metals in contaminated soils. *Resources, Conservation and Recycling*. 2022;181:106261.
- Song B, *et al.* Recent advances in remediation technologies for heavy-metal-contaminated soils. *Science of the Total Environment*. 2022;838:156417.
- Ahmad K, *et al.* Heavy metal contamination in soil and water and associated human health risks. *Environmental Research*. 2021.
- Chen, *et al.* Spatial distribution and ecological risk assessment of heavy metals in contaminated environments. *Science of the Total Environment*. 2023.
- Xie, *et al.* Heavy metal contamination and ecological risk assessment in mining-impacted areas. *Science of the Total Environment*. 2023.
- Sarker, *et al.* Green and sustainable approaches for remediation of heavy metal contaminated environments. *Chemosphere*. 2023.
- Aziz, *et al.* Heavy metal contamination in water: Sources, environmental impacts and remediation approaches. *Environmental Research*. 2023.
- Yang, *et al.* Human health risk assessment associated with heavy metal contamination. *Environmental Research*. 2023.
- Mai, *et al.* Heavy metal contamination and ecological and health risks in agricultural soils. *Science of the Total Environment*. 2024.
- Liu N, Zhao J, Du J, Hou C, Zhou X, Chen J, Zhang Y. Non-phytoremediation and phytoremediation technologies of integrated remediation for water and soil heavy metal pollution: A comprehensive review. *Science of the Total Environment*. 2024;948:174237.

28. Wu Y, *et al.* Biochar application for the remediation of soil contaminated with potentially toxic elements: Current situation and challenges. *Journal of Environmental Management*. 2024;351:119775.
29. Lavanya, *et al.* Phytoremediation: An eco-friendly approach for remediation of heavy metal-contaminated soils—A comprehensive review. *Environmental Nanotechnology, Monitoring & Management*. 2024;22:100975.
30. Liu, *et al.* Recent advances in synthesis and application of modified biochar for mitigation of heavy metals from soil and water: A critical review. *International Journal of Environmental Science and Technology*. 2024.
31. Wang *et al.* Preparation and applications of iron/biochar composites in remediation of heavy metal contaminated soils: Current status and further perspectives. *Environmental Technology & Innovation*. 2024;35:103671.
32. Xu W, Jin Y, Zeng G. Introduction of heavy metals contamination in the water and soil: A review on source, toxicity and remediation methods. *Green Chemistry Letters and Reviews*. 2024;17(1).
33. Liu *et al.* Integrated remediation approaches for heavy metal pollution in soil and water. *Science of the Total Environment*. 2024.
34. Wu *et al.* Biochar-based remediation of potentially toxic element contaminated soils: Current advances and future perspectives. *Journal of Environmental Management*. 2024.
35. Song P, Xu D, Yue J, Ma Y, Dong S, Feng J. Recent advances in soil remediation technology for heavy metal contaminated sites: A critical review. *Science of the Total Environment*. 2022;838:156417.

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