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A research synthesis on heavy metals as emerging atmospheric pollutants: a systematic review and bibliometric analysis (1973–2024)

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Abstract

Atmospheric heavy metals are persistent, bioaccumulative, and toxic pollutants capable of long-range transport, posing significant ecological and public health risks. This review synthesizes five decades of research (1973–2024) on emission sources, transport mechanisms, deposition pathways, and monitoring approaches, supported by a bibliometric analysis of 1642 Scopus-indexed articles. Anthropogenic activities, including industrial operations, mining and smelting, vehicular emissions, and agricultural inputs, remain dominant contributors, while volcanic eruptions, geothermal activity, sea-spray aerosols, and soil-dust resuspension constitute important natural sources. Once emitted, metals associate with particulate matter (e.g., $PM_{2.5}$, PM_{10}), undergo atmospheric circulation, and are deposited through dry and wet processes, enabling transfer from urban centers to agricultural systems and remote environments. Urban areas exhibit the highest deposition loads, agricultural landscapes show substantial foliar uptake, and remote ecosystems display clear signatures of transboundary transport. Advances in analytical and biomonitoring techniques, including Atomic Absorption Spectroscopy, Inductively Coupled Plasma Mass Spectrometry, X-Ray Fluorescence, and moss-based bioindicators, have improved detection sensitivity. Mosses enhance sensitivity by acting as natural, long-term integrators of atmospheric deposition: their high surface-area-to-mass ratio, absence of cuticles and root systems, and direct uptake from precipitation and aerosols enable efficient accumulation of trace metals, revealing low-level and chronic deposition signals often missed by short-term instrumental air sampling. Bibliometric results reveal exponential growth in publications and strong collaboration networks centered in Asia, Europe, and North America, with underrepresentation in Africa, South America, and Central Asia. Key research gaps include limited long-term health assessments, insufficient real-time and low-cost monitoring technologies, low-resolution source apportionment, and minimal attention to emerging contaminants globally.

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1. Introduction

Heavy metals are metallic elements characterized by high atomic weights and densities [1], and they have emerged as pollutants of global concern due to their persistence, toxicity, and tendency to bioaccumulate in environmental and biological systems [2]. Although anthropogenic activities dominate modern emissions, potentially toxic elements also originate from natural geological and atmospheric processes, namely volcanic eruptions, sea-spray aerosols, soil-dust resuspension, and rock weathering, which can release lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and metalloids such as arsenic (As) into the atmosphere without human involvement [3].

In contemporary landscapes, however, atmospheric pollution has become the principal pathway through which heavy metals are dispersed, especially in rapidly urbanizing and industrial regions [4]. Industrial activities, smelting operations, coal combustion, and mining release large quantities of metals through high-temperature processes and dust disturbance [5–7], while urban transportation systems contribute additional emissions via exhaust gases, tire and brake wear, engine corrosion, and road surface abrasion [4]. Once emitted, heavy metals readily bind to fine particulate matter ($PM_{2.5}$ and PM_{10}) [8], enabling long-range atmospheric transport before depositing onto soils, vegetation, water bodies, and food sources [9]. This airborne mobility makes atmospheric pathways particularly critical for understanding exposure risks and environmental impacts.

The importance of air pollution as a research focus lies in its immediate and far-reaching implications for public health, national economies, and long-term sustainability. Airborne heavy metals contribute to the global burden of disease by increasing risks of respiratory illnesses [10], cardiovascular disease, systemic organ damage [11], neurotoxicity [12], and developmental impairments in children [13]. Countries with high ambient air pollution face significant economic losses through reduced labor productivity, increased healthcare expenditures, diminished agricultural output [14], and premature mortality [15]. According to the World Health Organization, approximately 4.2 million deaths were attributable to outdoor air pollution in 2016. In Europe, air pollution is regarded as one of the leading contributors to premature death and disease and remains the most critical environmental health risk that can be mitigated through targeted interventions and regulation [15].

Environmental impacts are equally severe. Heavy metals deposited from the atmosphere infiltrate soils and food webs, bioaccumulate across trophic levels, and disrupt ecological processes, ultimately threatening biodiversity and ecosystem services [16]. Their non-biodegradable nature allows them to persist and recirculate through air–soil–water systems for decades, emphasizing the need for targeted monitoring and policy intervention [17, 18].

Given accelerating industrialization, urban expansion, and rising public awareness, heavy metals are now recognized as emerging atmospheric pollutants with broad implications for environmental management, human health, and economic stability [19–21]. Understanding their sources, atmospheric behavior, deposition patterns, and ecological and health risks is therefore essential for developing evidence-based strategies to mitigate their impacts.

The primary objectives of this review are to i) conduct an in-depth evaluation of studies on heavy metal presence and distribution in the atmospheric environment, ii) provide a bibliometric analysis of atmospheric heavy metal pollution research from 1973 to 2024, and iii) address significant knowledge gaps within this field. For the bibliometric analysis, the review aims to map the evolution of research trends, identify influential contributors, such as key authors, institutions, and countries, and examine thematic clusters, including environmental impacts, health risks, and mitigation strategies. By conducting this analysis, the study seeks not only to reveal patterns of research collaboration and emerging focal points, but also to highlight areas that require further investigation. This review is significant for its potential to guide future studies by identifying underresearched areas, fostering interdisciplinary collaboration, and ultimately enhancing our understanding of the complex challenges posed by atmospheric heavy metal pollution. Such insights are essential for developing effective policies and strategies to mitigate the adverse effects of these pollutants on both human health and the environment.

2. Methods

2.1. Data source and search strategy

This study conducted a comprehensive bibliometric analysis of atmospheric heavy metal research using Scopus, selected for its broad disciplinary coverage, structured metadata, and strong compatibility with bibliometric tools. Scopus was preferred over Web of Science and Google Scholar because it indexes a wide range of peer-reviewed environmental science journals and provides detailed citation, affiliation, and authorship information essential for quantitative analysis [22], although its English-language emphasis and indexing biases are acknowledged as limitations. The search covered the period 1973–2024 to capture both foundational developments and contemporary research trends. The final search was executed on 27 October 2024 using the explicit query string: TITLE-ABS-KEY ("heavy metal") AND TITLE-ABS-KEY ("atmospheric deposition") AND (LIMIT-TO(LANGUAGE, "English")) AND (LIMIT-TO(DOCTYPE, "ar")). This query was chosen because it aligns directly with the study's focus on atmospheric heavy metals and ensures the retrieval of articles explicitly addressing heavy metal deposition in atmospheric contexts.

2.2. Screening, inclusion and exclusion criteria

The initial search retrieved 2071 records, which were screened through a structured, multi-stage workflow summarized in Figure 1. The PRISMA flowchart illustrates each step of the identification, screening, eligibility assessment, and final inclusion process. Inclusion criteria required that studies be peer-reviewed original research articles, written in English, and directly focused on atmospheric heavy metals, aerosols, or deposition processes. Exclusion criteria removed conference papers, review articles, book chapters, editorials, notes, and non-English publications (231 + 198). Additional exclusions targeted studies unrelated to atmospheric pathways (e.g., soil-only or sediment-only assessments), duplicates, and entries with incomplete metadata. After applying all criteria, 1642 articles met the eligibility requirements and were retained for bibliometric analysis (Supplementary data). This screening process ensured that the final dataset aligned with the conceptual scope and temporal boundaries of the study.

2.3. Bibliometric analysis procedures

Bibliometric analyses were conducted using Bibliometrix/Biblioshiny for R (version 4.2.1) and VOSviewer (version 1.6.20), following established methodologies for evaluating scientific

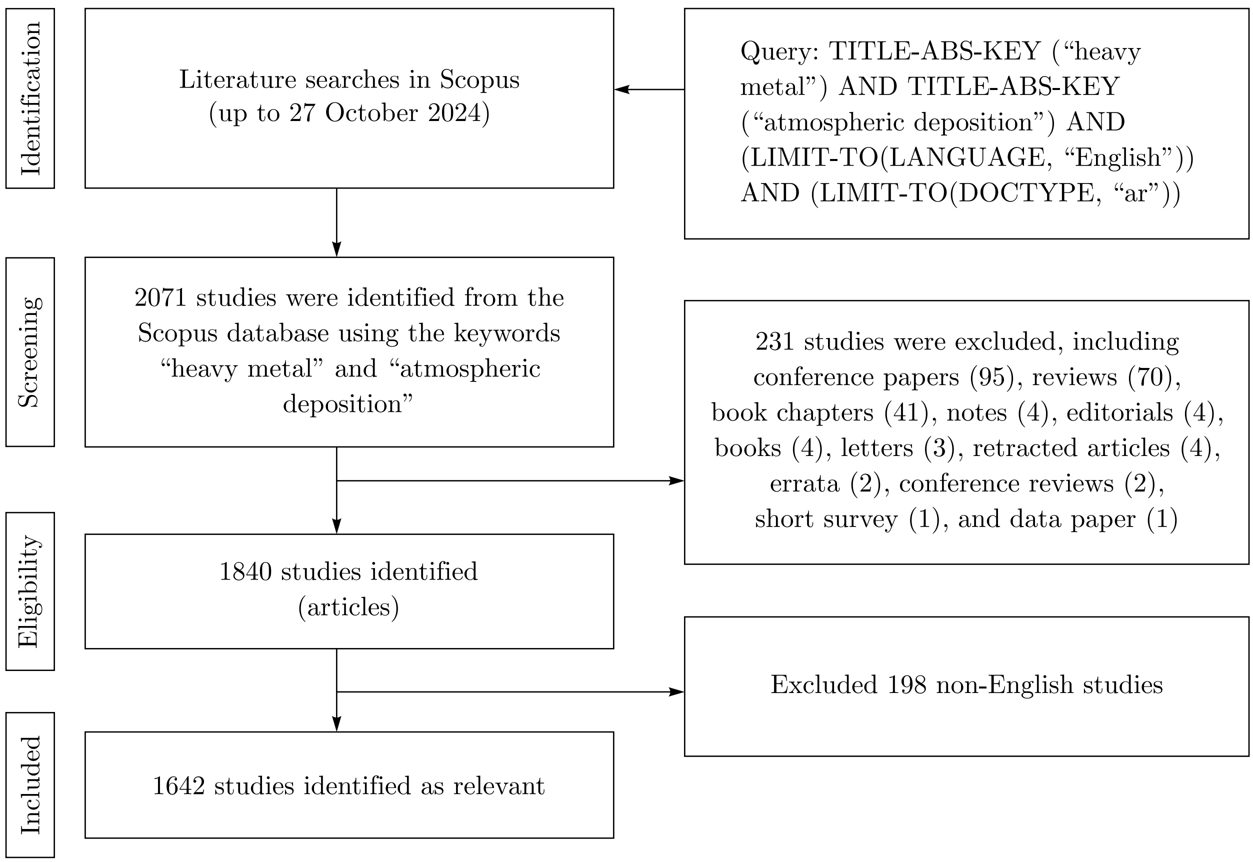

Figure 1. The PRISMA flowchart presenting the results and screening process of the original searches of research on heavy metals as emerging atmospheric pollutants, using the keywords "heavy metal" and "atmospheric deposition".

production, intellectual structure, and thematic evolution [23–27]. Bibliometrics, broadly defined, is the quantitative analysis of scholarly publications used to assess research performance, map scientific landscapes, and identify emerging themes within a field. The final curated dataset was exported in CSV format for processing across multiple platforms. Bibliometrix was used to compute descriptive indicators such as annual publication output, citation patterns, author productivity, and international collaboration metrics. Temporal trends were examined through time-series visualizations and the fitting of an exponential growth model to characterize long-term changes in research output.

2.4. Network mapping and thematic analysis

Network mapping was performed using VOSviewer's co-authorship and keyword co-occurrence algorithms. Co-authorship networks illuminated collaborative patterns across countries, institutions, and researchers. Keyword co-occurrence analysis, implemented using VOSviewer's full counting method, identified dominant themes and emerging research topics. Comparative analyses between early-period (1973–1999) and recent-period (2000–2024) keyword networks allowed thematic evolution to be assessed, highlighting shifts in scientific focus and the emergence of new research pathways.

2.5. Validation and replicability measures

To enhance transparency and replicability, this methodology explicitly details the search strategy, screening criteria, and software versions. The integration of multiple bibliometric indicators ensures analytic robustness, while manual verification steps reduce errors from automated text-mining tools that may misclassify entries or fail to detect metadata inconsistencies. By documenting each step, this study provides a replicable framework for future bibliometric assessments of atmospheric pollutants.

3. Key findings

3.1. Atmospheric sources, transport and deposition of heavy metals

Atmospheric heavy metals originate from a wide range of anthropogenic and natural sources that differ in emission intensity, spatial distribution, and chemical form, shaping their environmental behavior and potential ecological and human health impacts. Among human-driven contributors, industrial activities, including metal smelting, steel and cement manufacturing, coal combustion, and waste incineration, represent major emission sectors, collectively releasing approximately 78 653 tons of metal-enriched particulate matter annually [28]. Mining operations, particularly open-pit and coal mining, add substantial quantities of metal-rich dust through blasting, crushing, and ore transportation, emitting Fe, Cu, Zn, Mn, Pb, Cr, Cd, Ni, and As [29]. Traffic-related emissions further contribute Pb, Cd, Cu, Ni, and Zn through vehicular exhaust, brake wear, tire abrasion, and road-surface erosion [1, 30], while agricultural practices, including the application of fertilizers and pesticides, introduce additional trace metals to soils that may later re-enter the atmosphere via dust resuspension and erosion [31]. Natural processes, particularly volcanic eruptions, also contribute substantial metal loads to the atmosphere. Volcanic plumes carry S, Tl, As, Cd, Cu, Se, and Bi as aerosols and ash particles [32], exemplified by the 1783–1784 Laki eruption, which deposited an estimated 1 ton of Pb and Cd and 40 tons of Zn across the Greenland ice cap [33]. Sea-spray aerosols, rock weathering, and soil dust resuspension further supply crustal metals to the atmospheric background [1, 34]. Together, these anthropogenic and natural processes form the emission inputs into the atmospheric system, which are subsequently transported and deposited through multiple pathways illustrated in Figure 2.

Once emitted, heavy metals undergo a series of physical and chemical transport processes that determine their mobility, residence time, and deposition trajectories. Metals may be released as gases or as constituents of particulate matter of varying size, with fine particles (e.g., $PM_{2.5}$) capable of remaining suspended for long periods and undergoing long-range transport, while coarse particles settle more rapidly under gravity. Dry deposition occurs through gravitational settling and impaction, whereas wet deposition involves scavenging by rainfall, snow, or fog and often dominates long-distance movement due to the efficiency of precipitation in capturing fine aerosols. Atmospheric residence time strongly governs transport potential; Pb persists for approximately 2.9 days in the lower troposphere and up to 6.3 days in the upper troposphere, enabling regional and continental dispersion [35]. Monsoon-driven atmospheric circulation contributes to the long-range propagation of anthropogenic metals, as observed above the East China Sea where Pb, Se, and Zn in fine aerosols originate from inland industrial regions [36]. Particle size further influences transport behavior, with coarse dust depositing near sources and fine aerosols traveling hundreds to thousands of kilometers. Secondary emissions from resuspension also significantly increase airborne metal concentrations. Legacy contamination from historic industrial activities, residual leaded gasoline, construction debris, and contaminated roadside soils can be re-entrained by wind erosion, pedestrian movement, and vehicle-induced turbulence — an important yet underrepresented component of emission inventories [37–39].

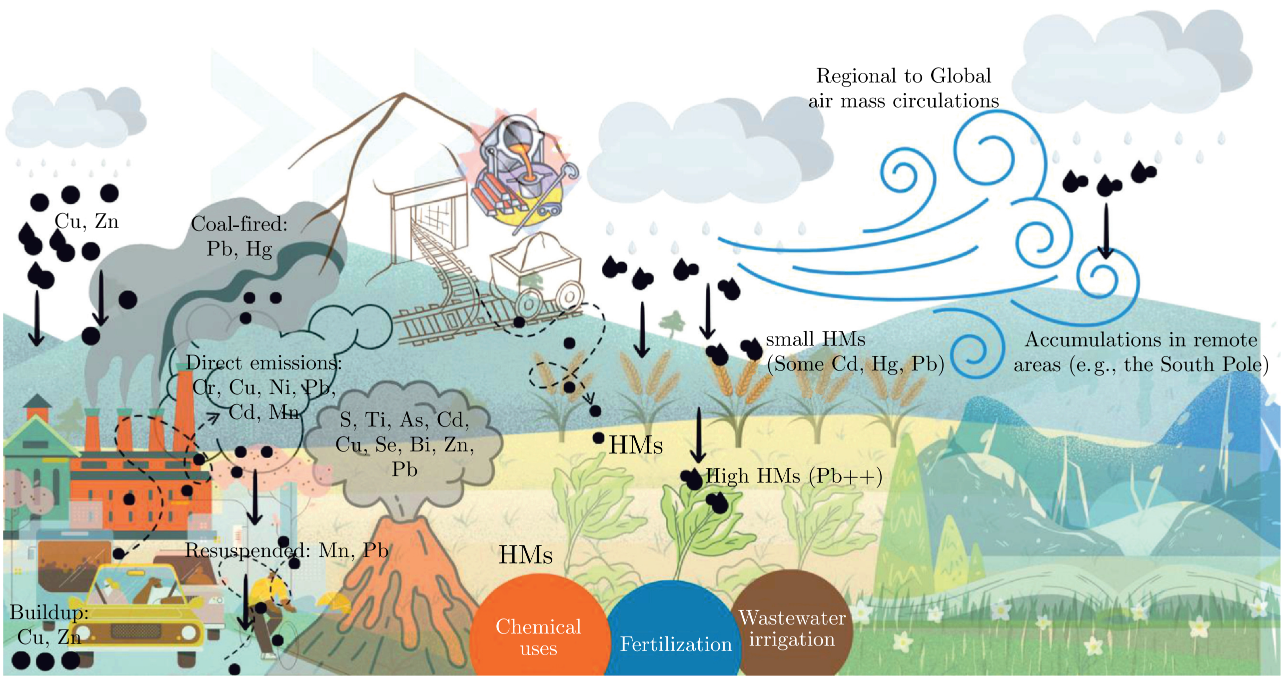

Figure 2. Schematic model showing pathway of heavy metals (HMs) in the atmosphere.

Deposition patterns vary across land-use types and environmental compartments due to differences in emission density, meteorological conditions, and surface characteristics. Urban environments exhibit some of the highest deposition rates, integrating emissions from traffic, industrial facilities, domestic heating, construction dust, and resuspended soils. Metals such as Cu, Ni, Pb, Cd, and Mn are deposited onto impervious surfaces via both dry and wet pathways [40]. Cu and Zn frequently accumulate in high concentrations because of their association with particulate matter and high solubility, enhancing wet deposition [40, 41]. Cr, largely emitted from industrial activities and heavy-duty vehicles, deposits primarily through dry processes due to low solubility, while Mn and Pb are strongly influenced by the resuspension of contaminated roadside soils [41]. Urban deposition patterns are additionally shaped by traffic volume, street geometry, industrial proximity, and vegetation cover [42].

In agricultural landscapes, deposition patterns reflect both regional industrial emissions and local agricultural activities. Areas near fossil-fuel-intensive industries or mining regions often receive elevated atmospheric inputs of Hg, Pb, and Cd [43–46]. Leafy vegetables efficiently capture airborne particulates, and metal concentrations in leaves commonly exceed those in roots, indicating that atmospheric deposition is a dominant contamination pathway [47]. Pb-bearing dust substantially elevates Pb levels in vegetables through foliar deposition [48, 49]. Atmospheric inputs of Hg, Pb, and Cd in wheat grains further underscore air-to-plant transfer as a major route of contamination [46–48].

Even remote and pristine regions are affected by long-range atmospheric transport. Wet deposition dominates these areas because precipitation efficiently scavenges fine aerosols. Examples include Cu and Pb deposition in the Daihai Lake region of Inner Mongolia due to monsoon-driven transport [50], long-distance inputs to the Mongolian–Manchurian grasslands and the East China Sea [36, 51], and seasonal deposition peaks in northern Russia, where up to 45% of annual deposition occurs in winter [52]. Antarctica also receives metal inputs via hemispheric atmospheric circulation, with deposition patterns reflecting seasonal snow accumulation and aerosol loading [53].

Mining and smelting operations act as concentrated point sources that substantially elevate metal deposition at local and regional scales. In the Kelly Lake watershed in Sudbury, Canada, atmospheric emissions from mining activities deposit approximately 1.4 kg of Ni per day, with 80% entering lakes via runoff and 20% leaching into deeper soils [54]. In Laoyingshan, China, Cd contamination from lead–zinc mining correlates closely with total suspended particles (TSP), confirming atmospheric dispersion as the primary mechanism influencing soil contamination patterns [55]. Smelting facilities in central China emit Cu, Zn, Cd, and Pb in windborne particulates, while Sb and As bind to fine aerosols transported by prevailing wind directions [56]. Hg, due to its high volatility, is dispersed especially efficiently through the atmosphere before deposition [44].

Volcanic activity contributes intermittently large but geographically extensive heavy metal loads to the atmosphere. Volcanic plumes emit S, Tl, As, Cd, Cu, Se, and Bi, which condense onto ash and aerosols that can travel long distances depending on plume height, wind fields, and atmospheric stability [32]. Major eruptions such as the 1783–1784 Laki event demonstrate the magnitude of volcanic inputs, depositing substantial quantities of Pb, Cd, and Zn across Greenland [33]. Beyond major eruptions, continuous low-level degassing and geothermal activity also influence heavy metal levels in the atmosphere. Studies from LUSI (Lumpur Sidoarjo) mud-volcano regions revealed very unhealthy air quality, with $PM_{2.5}$ reaching 399.9 $\mu g/m^3$ and elevated Pb, Cr, and Cd [57]. Similarly, the Holuhraun volcanic eruption produced plumes in which PM concentrations exceeded air-quality standards and were enriched with heavy metals and sulfate aerosols [58]. Monitoring in Indonesian cities showed that $PM_{2.5}$ frequently exceeded national standards, with Fe, Zn, and Pb elevated near industrial and geothermal project sites [59, 60]. Additional studies identified health risks associated with heavy-metal-enriched urban air pollution [61] and contributions from long-range aerosol transport, including biomass burning and volcanic degassing, to elevated Cr, Mn, Cd, and Ni levels in Colombia [62]. A summary of representative studies evaluating air quality in relation to atmospheric heavy metals from volcanic, geothermal, biomass-burning and mixed anthropogenic sources is presented in Table 1.

3.2. Sampling and analytical techniques for monitoring atmospheric heavy metals

Monitoring atmospheric heavy metals requires an integrated approach that combines appropriate sampling strategies with sensitive analytical techniques capable of detecting metals across a wide range of concentrations. Sampling methods determine how representative and reliable the collected material is, whereas analytical techniques govern detection limits, precision, and the range of elements quantified. Clear differentiation between these components is essential for interpreting air-quality data and comparing results across studies.

3.2.1. Sampling techniques

Filter-based active samplers are among the most widely used tools for atmospheric heavy metal monitoring because they efficiently capture particulate matter ($PM_{2.5}$, PM_{10}) and allow quantitative analysis of metal content using multiple analytical instruments. Their ability to process known air volumes enables robust comparisons across sites and time periods, making them particularly suitable for assessing spatial and temporal variations in air quality. For example, Wan et al. [64] used filter sampling to characterize settled dust across distinct urban functional zones, demonstrating its utility in identifying pollution gradients. However, active samplers require electrical power, regular maintenance, and can be costly to operate over large spatial networks or extended monitoring periods.

Table 1. Summary of studies evaluating air quality in relation to heavy metals.

Key focus	Heavy metals analyzed	Findings	Reference
Evaluated air pollution from LUSI mud-volcanic emissions	Pb, Cr, Cd	$PM_{2.5}$ ranged from 24.0 to 399.9 $\mu g/m^3$; Pb: 2.6–37.34 $\mu g/m^3$; Cr: 0.14–12.8 $\mu g/m^3$; Cd: 0.78–4.16 $\mu g/m^3$. AQI indicated 'very unhealthy' air quality.	[57]
Characterized plumes from the Holuhraun volcanic eruption (Iceland) and their impact on air quality	Trace heavy metals (associated with sulphate-rich PM)	The eruption emitted $\sim$ 11 Tg of SO_2 over six months. Hourly SO_2 exceeded 350 $\mu g/m^3$ 88 times in Reykjahlíð and 34 times in Reykjavík. Volcanic PM was sulphate-rich ($\sim$ 90% of PM mass) and dominated by fine particles (75–80% $PM_{2.5}$).	[58]
Long-term assessment of urban air quality and PM composition across major Indonesian cities (2010–2017)	Fe, Zn, Pb (with major elements Si, S, K)	$PM_{2.5}$ exceeded the annual standard (15 $\mu g/m^3$) at several Java sites and the daily limit (65 $\mu g/m^3$) during 2015 fires. Black carbon comprised 15–26% of $PM_{2.5}$, with elevated Fe, Zn, and Pb at industrial locations.	[59]
Air quality assessment and impact modeling for the Newberry Geothermal Pilot Project (Oregon, USA)	Airborne heavy metals (deposition), H_2S	Emissions from construction and geothermal operations were modeled using U.S. EPA dispersion tools. Predicted heavy metal deposition and H_2S impacts on nearby watersheds and protected areas were low, indicating acceptable air quality.	[60]
Health risks associated with urban air pollution from natural and anthropogenic sources	Mixed heavy metals	Urban air pollution, largely driven by transport emissions, poses acute and chronic respiratory and systemic health risks, highlighting the need for pollution control and worker protection.	[61]
Influence of long-range aerosol transport on urban $PM_{2.5}$ composition in the Aburrá Valley, Colombia	Cr, Mn, Cd, Ni	Long-range transport from biomass burning, dust, and volcanic degassing affected up to 13% of days and increased $PM_{2.5}$ (up to $\sim$ 11 $\mu g/m^3$), with elevated Cr, Mn, Cd, and Ni during biomass-burning and volcanic events.	[62]
Comprehensive review of outdoor air pollutants, their sources, health impacts, and regulatory considerations	Heavy metals, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs)	Reviewed sources and distribution of outdoor air pollutants from anthropogenic and natural origins highlight health impacts, monitoring approaches, and the need to manage noncriteria pollutants, including heavy metals, for effective air quality protection.	[63]

Passive samplers rely on natural diffusion or gravitational settling rather than mechanical pumping and therefore provide a cost-effective alternative for long-term monitoring. They are particularly useful in regions with limited infrastructure or where pollutant concentrations are low. Li et al. [65] applied passive sampling to assess heavy metal deposition in urban environments, highlighting their suitability for chronic exposure assessments. The main limitation of passive samplers is their lower temporal resolution and reduced precision for short-term pollution events compared with active sampling.

Biomonitoring represents a complementary sampling approach that uses living organisms to assess the presence, distribution, and long-term accumulation of atmospheric heavy metals. A wide range of organisms has been employed, including mosses [66], lichens [67], ectomycorrhizal fungi [68], leaves [69] or bark [70] of flowering plants, bird tissues [71], feathers [72], eggshells [73], and fish muscle [74]. These organisms integrate pollutant exposure over extended periods and provide spatially integrated information that is often difficult to obtain through short-term instrumental sampling alone.

Among biomonitors, mosses and lichens are particularly effective because they rely directly on atmospheric inputs for water and nutrients [75], making them highly responsive to airborne contaminants. Moss-based biomonitoring further improves detection sensitivity by acting as a natural, long-term integrator of atmospheric deposition [76]. Their high surface-area-to-mass ratio, absence of cuticles and true root systems, and direct uptake of nutrients from precipitation and aerosols enable efficient accumulation of trace metals [77]. As a result, mosses can record low-level and chronic atmospheric metal inputs that may fall below instrumental detection limits in short-term air sampling [78]. This integrative capacity allows moss biomonitoring to resolve fine-scale spatial gradients and long-term deposition trends that are frequently underestimated by conventional filter-based approaches [78].

Fish are also widely used as indirect bioindicators of heavy metal pollution in aquatic systems, including those affected by atmospheric inputs, because they efficiently accumulate metals and integrate exposure over space and time [79, 80]. Metals deposited from the atmosphere can enter surface waters through wet and dry deposition, precipitation and runoff, and are then transported via rivers to lakes, estuaries and coastal zones [81]. Once in surface waters, these metals often accumulate in sediments, which act as both a long-term sink and a secondary source of exposure to the overlying water and biota [82, 83]. Metals taken up from water, sediments, and diet then bioaccumulate in fish tissues, with distinct patterns among organs such as liver, kidney, gills and muscle, and with higher burdens generally in predatory species [84]. Analysis of fish muscle and organs therefore provides insights into the integrated effects of deposition, watershed transport, and food-web transfer over time [85], and is widely used for environmental monitoring and human health risk assessment [84]. This approach is especially valuable for assessing chronic exposure and long-range transport of metals such as Hg and Pb, which persist in sediments and move through aquatic food webs [82]. However, its interpretation is influenced by species-specific traits, including trophic position, growth rate, age, and habitat use, which modulate metal uptake and internal distribution [77, 84].

Prasetia et al. [86] demonstrated that the bark of *Mangifera indica* effectively retains heavy metals, offering fine-scale resolution of localized pollution. Across studies summarized in Table S1, bryophytes, particularly *Hylocomium splendens* and *Pleurozium schreberi*, dominate biomonitoring applications (72% of studies), followed by lichens (10%) and angiosperms (12%), with gymnosperms and fauna used less frequently ($\leqslant$ 4%) (Figure 3). This preference reflects the high sensitivity and consistency of bryophytes in responding to atmospheric deposition [87].

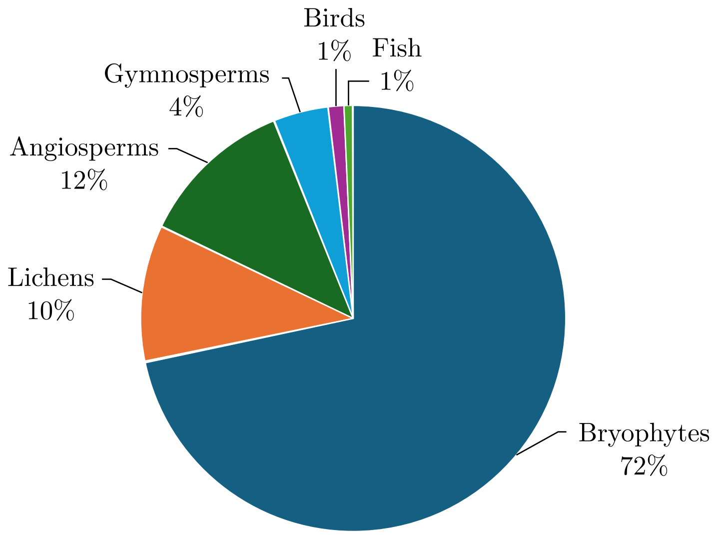

Figure 3. The percentage of biomonitoring species data available in the Scopus database.

3.2.2. Analytical techniques

Once samples are collected, heavy metals are typically quantified using Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and X-Ray Fluorescence (XRF), each offering distinct strengths and limitations.

AAS remains widely used due to its relatively low cost, high accuracy for single-element quantification, and suitability for routine monitoring. Behera et al. [88] used AAS to analyze $PM_{2.5}$-bound metals in Paradip city, India, identifying seasonal dominance of Fe, Al, Zn, and Pb in winter aerosols. Adegunwa et al. [89] applied AAS to rainwater samples in southwestern Nigeria and showed that metal speciation varied among land-use types. Despite its reliability, AAS is limited by single-element analysis and reduced sensitivity for ultratrace concentrations unless preconcentration steps are applied.

ICP-MS provides simultaneous multi-element detection at extremely low concentrations (ng/L to pg/L), making it one of the most powerful tools for atmospheric metal analysis. Ammann [90] emphasized its precision and suitability for complex environmental matrices. Shahrukh et al. [91] applied ICP-MS to quantify leaf-deposited metals in Dhaka, Bangladesh, revealing species-specific tolerance patterns. The primary limitations of ICP-MS are high instrument cost and the need for specialized technical expertise.

XRF offers rapid, nondestructive analysis of solid samples such as dust, soil, and filter-collected particles, with minimal sample preparation. Although less sensitive for light elements, XRF allows sample preservation and repeated measurements. Ye et al. [92] demonstrated that automated systems like AMMS-100 can achieve relative errors below 10% for metals such as Pb and Fe, supporting near-real-time monitoring applications.

3.2.3. Integrated monitoring approaches

Overall, combining complementary sampling strategies with appropriate analytical techniques provides a comprehensive toolkit for detecting, quantifying and interpreting atmospheric heavy metals. Instrument-based sampling captures short-term pollution events with high precision, while biomonitoring, particularly using mosses, enhances sensitivity to low-level and chronic deposition. Their combined application improves source attribution, spatial resolution, and long-term trend detection, thereby supporting robust air-quality assessment and effective pollution mitigation strategies.

3.3. Bibliometric analysis of heavy metal research in the atmosphere

3.3.1. Global research trends and collaborative efforts in atmospheric heavy metals (1973–2024)

A shift in publication volume is a key indicator of the developmental trajectory of a scientific field, and the growth of atmospheric heavy metal research clearly reflects this progression. Analysis of Scopus-indexed publications from 1973 to 2024 shows a marked long-term increase, totaling 1642 articles from 385 sources, demonstrating a consistently active and expanding research domain (Table 2). Publication counts remained low and sporadic during the 1970s and 1980s, but began accelerating in the 1990s and rose sharply after 2000, with peak outputs of 119 articles in 2022 and over 100 articles annually in 2023–2024 (Figure 4). Fitting an exponential growth model to the dataset yielded the function $y = 8.42 \cdot 10^{-5}\, e^{0.0679x}$, corresponding to an approximate annual growth rate of 7.03%, indicating that research output has increased exponentially over the past five decades. The strong fit of this model, particularly post-1990, highlights the expanding scientific and policy-driven attention to atmospheric heavy metals. The bibliometric indicators reinforce this pattern: the field exhibits a high average citation rate (41.53) and a relatively young average document age (11.3 yr), signaling both scholarly impact and rapid evolution. The breadth of keywords (9588 Keywords Plus and 3416 Author's Keywords) reflects diverse research directions, while the involvement of 5207 authors and an average of 5.2 co-authors per paper demonstrates a high degree of collaboration. International co-authorship (25.33%) further underscores the global relevance of atmospheric heavy metal research. Collectively, these trends show that this field is rapidly growing, highly collaborative, and globally impactful, driven by urgent scientific and environmental concerns (Table 2).

Table 2. Main information on publications in atmospheric heavy metal studies.

Description	Results
Main information about data	
TimeSpan	1973–2024
Sources (journals, books, etc.)	385
Documents	1642
Annual growth rate, %	0
Document average age, yr	11.3
Average citations per publication	41.53
References	0
Document contents	
Keywords Plus (ID)	9588
Author's Keywords (DE)	3416
Authors	5207
Authors of single-authored publications	66
Authors collaboration	
Single-authored publications	71
Co-authors per publication	5.2
International co-authorship, %	25.33
Document types	
Article	1642

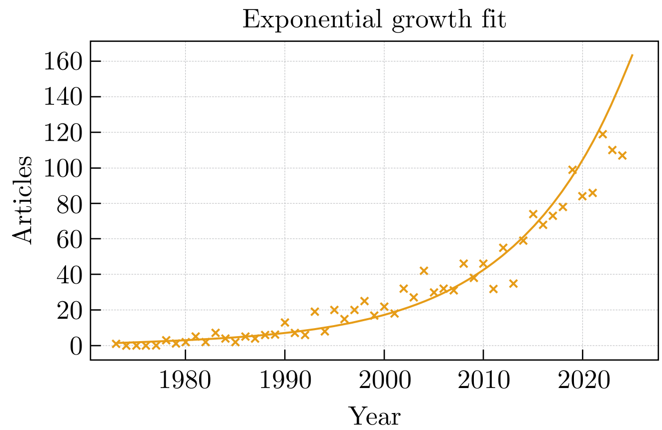

Figure 4. Long-term publication trend and exponential model fit for atmospheric heavy metal studies (1973–2024).

3.3.2. Leading subject areas in atmospheric heavy metal research

Figure 5 presents a circular bar chart of publications on atmospheric heavy metals across subject areas, based on data from Scopus. The top five fields include Environmental Science (1371 publications), which leads due to its focus on pollution impacts, followed by Earth and Planetary Sciences (311), covering atmospheric systems and pollutant transport. Agricultural and Biological Sciences (270) ranks third, examining ecosystem and health impacts, while Pharmacology, Toxicology and Pharmaceutics (165) emphasizes toxicology and respiratory health effects. Medicine (158) completes the top 5, focusing on pollutant composition and reactions. The chart also highlights multidisciplinary contributions, including Chemical Engineering (26), Decision Sciences (15), Computer Science (14), and Physics and Astronomy (11), which provide insights into pollutant processes, policy, and modeling.

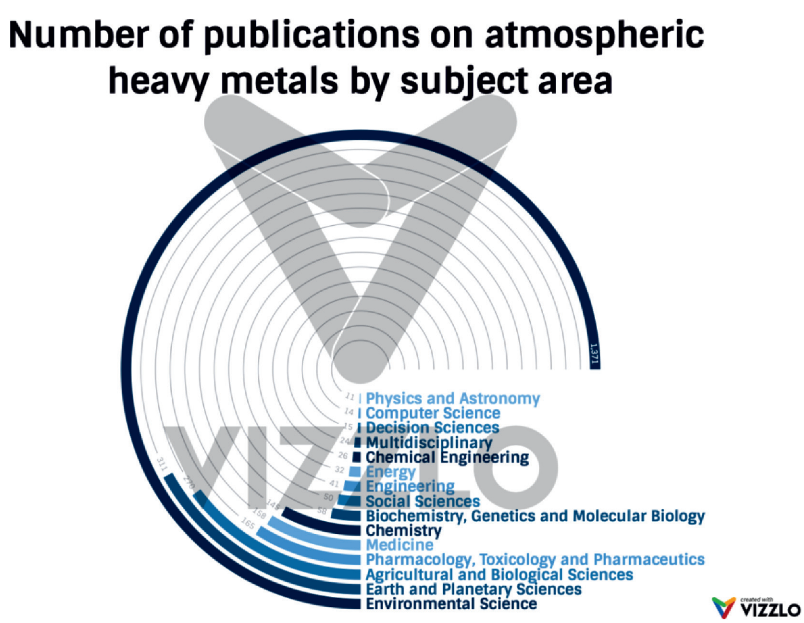

Figure 5. The distribution of atmospheric heavy metal research across scientific disciplines, with each publication potentially categorized into more than one research field.

3.3.3. Key journals in atmospheric heavy metal research

Figure 6 presents the top 10 most relevant sources for articles on atmospheric heavy metals in Scopus, reflecting high-quality journals with significant contributions to this research field. Leading the list, *Science of the Total Environment* (162 articles, Q1) from the Netherlands and *Environmental Pollution* (111 articles, Q1) from the UK rank highest, both known for their global impact on environmental science. Other prominent sources include *Environmental Science and Pollution Research* (91 articles, Q1, Germany) and *Water, Air, and Soil Pollution* (73 articles, Q2, Switzerland), which also focus on pollution impacts. Mid-ranked journals such as *Chemosphere* (63 articles, Q1, UK) and *Environmental Monitoring and Assessment* (51 articles, Q2, Germany) contribute substantially to understanding pollution effects on ecosystems. Journals like *Atmospheric Environment* (58 articles, Q1, UK) and *Ecotoxicology and Environmental Safety* (35 articles, Q1, USA) address atmospheric and ecotoxicology safety, while the *Journal of Hazardous Materials* (34 articles, Q1, Netherlands) and the *International Journal of Environmental Research and Public Health* (32 articles, Q2, Switzerland) focus on public health and environmental hazards, underscoring the multidisciplinary relevance of this research area.

Figure 6. Top 10 sources of Scopus-indexed articles on atmospheric heavy metal research.

3.3.4. Trends in author productivity and influence in atmospheric heavy metal research

Figure 7 visually represents the publication output and citation impact of the top 10 authors in atmospheric heavy metal research, indexed in Scopus. Analyzed using the bibliometric tool Bibliometrix, the figure displays author names on the left and spans the years 1980 to 2024 along the horizontal axis. Each circle's size reflects the number of publications per author per year, with larger circles indicating higher output, while color intensity signifies total citations, with darker shades representing greater citation counts. This visualization captures trends in publication activity, revealing that some authors have maintained steady output, while others have fluctuated over time. The color intensity further highlights each author's citation impact, with darker circles marking highly influential contributions. By comparing circle size and color across authors, key contributors who have been both productive and highly cited are easily identified, offering insights into leading figures and evolving expertise in atmospheric heavy metal research. Notably, Steinnes E. pioneered research in this field, publishing a landmark article in 1980 in the *Journal of Radioanalytical Chemistry*. His study analyzed moss samples from various parts of Norway to determine atmospheric deposition of 28 trace elements, finding

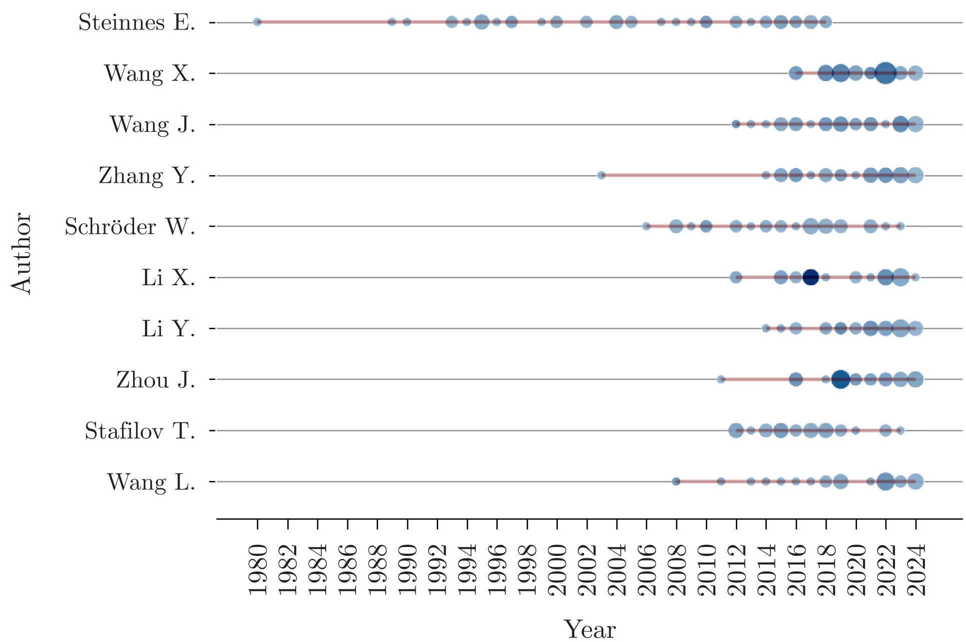

Figure 7. Publication and citation trends of the top 10 researchers in atmospheric heavy metal studies. Circle size represents the number of articles published per year, while color intensity indicates the total number of citations received in that year.

higher concentrations of lead (Pb), antimony (Sb), vanadium (V), and cadmium (Cd) in southern Norway compared to the northern regions. This indicated that sources to the south and southwest of Scandinavia significantly contribute to heavy metal deposition in Norway [93].

3.3.5. Bibliometric analysis of the co-authorship

Table 3 ranks the top 10 authors by citations and total link strength, indicators of academic influence and collaborative potential. Higher total link strength reflects not only prolific output, but also an author's centrality in the research network. This interconnectedness suggests that these authors play a crucial role in shaping research directions and fostering collaborations, which are essential for advancing atmospheric heavy metal studies. For example, Schröder W. has published 24 articles, with 362 citations and a total link strength of 45, while Steinnes E. has authored 22 articles with 1550 citations and a total link strength of 37. These metrics indicate that both authors have collaborated extensively in atmospheric heavy metal research.

The VOSviewer co-authorship network visualization reveals that 6668 prolific authors contributed to 1642 publications on atmospheric heavy metals. Of these, only 67 authors published at least five articles. The largest group of connected authors includes these 67 individuals, organized into five distinct clusters of co-authorship, each represented by a different color in Figure 8. The collaboration patterns among researchers in atmospheric heavy metal studies are visualized with different colors, indicating clusters of closely collaborating authors. Larger nodes, such as Steinnes E. and Schröder W., signify these authors' central roles in their clusters, reflecting significant influence and strong collaborative ties. Thick lines between nodes, particularly between Steinnes E. and Schröder W., highlight frequent co-authorship and suggest that these authors play pivotal roles in fostering research partnerships. The presence of cross-cluster connections, such as between Steinnes E. in the green cluster and Frontasyeva M. V. in the yellow cluster, indicates interdisciplinary collaborations, while isolated clusters like the blue one suggest specialized research areas. Overall, the network highlights a collaborative landscape in

Table 3. Summary of the bibliometric analysis of the top 10 authors contributing to research on atmospheric heavy metals, based on citations, number of publications, and total link strength.

Author	Affiliated institution	No. of documents	Citations	Total link strength
Schröder W.	University of Vechta (Germany)	24	362	45
Steinnes E.	University of Trondheim (Norway)	22	1550	37
Zhou Jun	Chinese Academy of Sciences (China)	17	907	54
Nickel S.	University of Vechta (Germany)	14	176	26
Šajn R.	Geological Survey of Slovenia (Slovenia)	13	326	35
Huang B.	Chinese Academy of Sciences (China)	13	1124	35
Lazo P.	University of Tirana (Albania)	12	260	46
Qarri F.	University of Vlora (Albania)	10	241	37
Zhou Jing	Chinese Academy of Sciences (China)	11	424	30
Stafilov T.	University of Ss. Cyril and Methodius (North Macedonia)	8	220	30

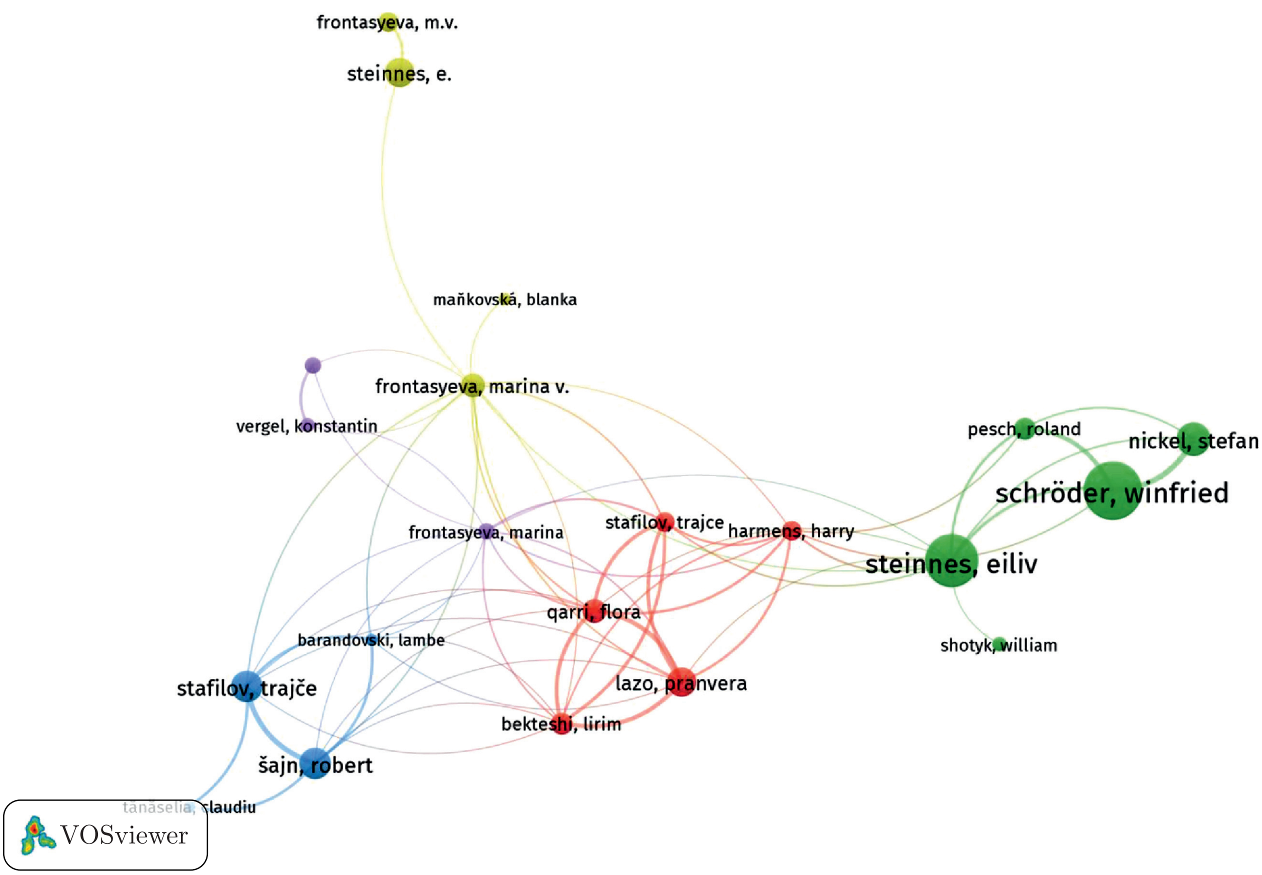

Figure 8. Co-authorship network.

atmospheric heavy metal research, with key authors serving as hubs for knowledge exchange and shaping research directions within and across clusters.

3.3.6. Global distribution and collaboration patterns in atmospheric heavy metal research

Global research output on atmospheric heavy metals shows a distinctly uneven yet geographically widespread pattern, as illustrated in Figure 9. The regional frequency map highlights the dominant role of Asia, where China alone contributes 3217 publications, far surpassing all other

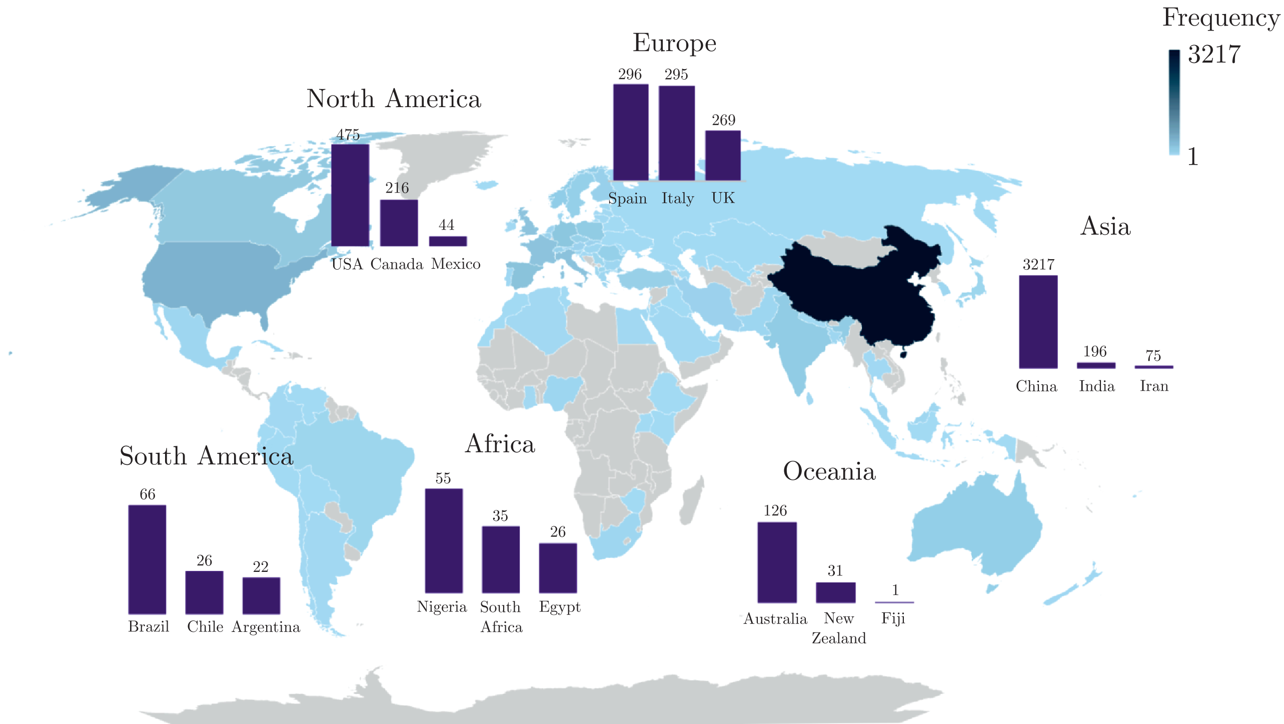

Figure 9. Global publication frequency on atmospheric heavy metal research across major world regions.

countries. Asia's next leading contributors — India (196) and Iran (75) — also appear prominently but remain considerably behind China's exceptional research productivity. In North America, the USA (475) leads regional output, followed by Canada (216) and Mexico (44), while Europe forms the second-largest research bloc globally. Europe's top contributors — Spain (296), Italy (295), and the UK (269) — are complemented by strong participation from Germany, France, Poland, and Norway, demonstrating a broad and mature research landscape. In South America, Brazil (66) leads, followed by Chile (26) and Argentina (22). Africa shows increasing engagement through Nigeria (55), South Africa (35), and Egypt (26), and in Oceania, Australia (126) and New Zealand (31) serve as major contributors, with Fiji (1) representing emerging regional participation. Collectively, these patterns reveal a global but uneven distribution of research capacity, concentrated primarily in Asia, Europe, and North America.

Figure 10 further illustrates global collaboration patterns using Single-Country Publications (SCPs) and Multiple-Country Publications (MCPs). Each bar represents a country's publication output, with teal indicating SCPs and coral indicating MCPs. China again leads in total output and shows strong international engagement, producing the highest number of MCPs and reflecting intensive participation in global research networks. The USA, Germany, and Italy also exhibit substantial collaborative productivity, with Germany in particular showing a high MCP proportion, indicating strong integration into international research consortia. Countries such as Spain, France, and India contribute meaningfully to cross-border collaborations, while smaller research nations, including North Macedonia, Saudi Arabia, Singapore, Israel, Morocco, Tunisia, and the UAE, produce 100% MCPs, indicating complete reliance on international partnerships. Conversely, countries such as Portugal, Algeria, Latvia, Vietnam, and several others produce only SCPs, signaling emerging but still isolated research activity.

The prominence of MCPs across leading nations underscores the inherently global and transboundary nature of atmospheric heavy metal research. It highlights the increasing reliance

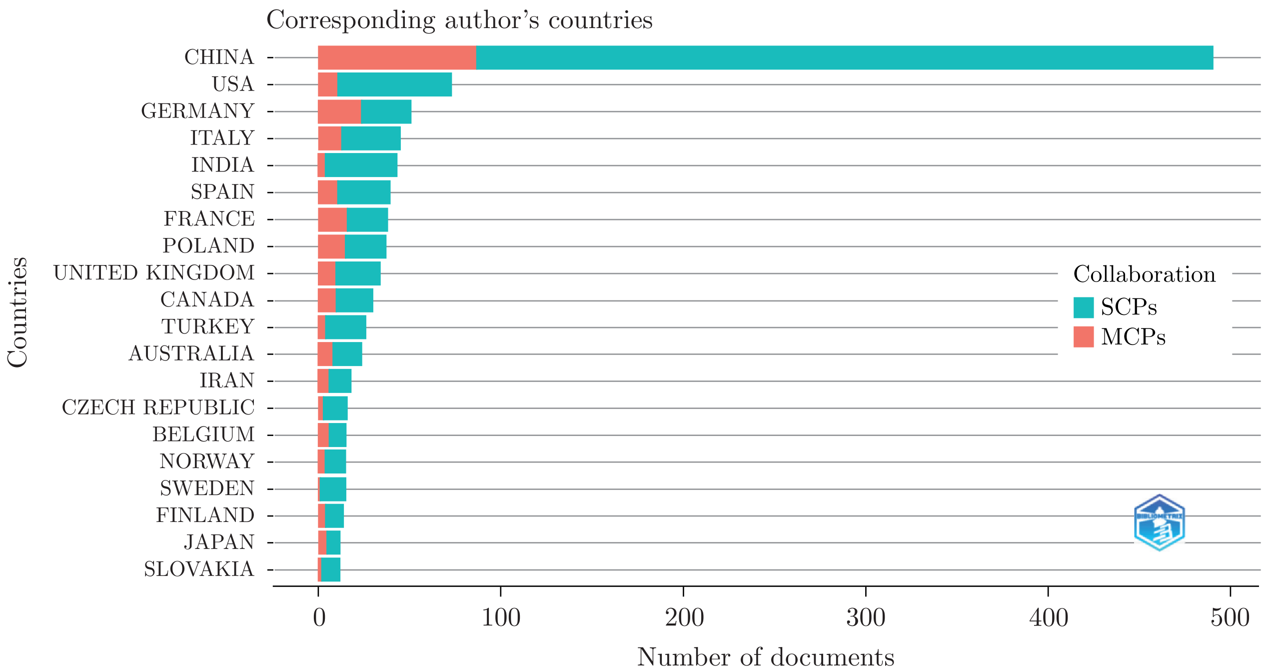

Figure 10. Top 20 countries/territories of publication based on corresponding author.

on international scientific cooperation to address shared environmental challenges, while also revealing disparities in collaborative capacity and research infrastructure among countries and regions.

3.3.7. Leading and emerging nations/territories in atmospheric heavy metal research

The analysis of countries contributing to global research on atmospheric heavy metals, as measured by total citations and average citations per article (see Table S2), indicates that China leads with the highest total citations (20 681), although its average citations per article are moderate (42.1). In contrast, the United Kingdom, despite having fewer total citations (3471), boasts the highest average citation rate (102.1), suggesting that its research is highly influential. Other significant contributors include the USA, France, and Norway, each with high citation counts and averages above 50, reflecting the impact of their publications. Emerging contributors, such as Jordan and Argentina, also show impressive average citations (104.2 and 90.2, respectively), signaling their growing influence in the field. Additionally, smaller countries such as Hong Kong and Croatia stand out with exceptionally high average citations (140.3 and 139.7, respectively), which reflects high-impact studies despite their lower publication volumes. This analysis underscores both established leaders and emerging countries in atmospheric heavy metal research, highlighting the importance of global collaboration and knowledge exchange in this field. Countries such as Jordan, Argentina, Hong Kong, and Croatia are emerging contributors and may play a significant role in shaping future research trends.

3.3.8. Key insights from high-impact research on atmospheric heavy metals

Table 4 presents the top 10 most-cited articles on atmospheric heavy metals published in Scopus, highlighting key studies that investigate the sources and impacts of metals such as mercury (Hg), cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), and nickel (Ni) in various environments. Notable contributors include Nicholson F. A., who identifies atmospheric deposition as a major source of heavy metals in agricultural soils in England and Wales, while Zheng N. reveals significant contamination in street dust in China, primarily affecting children's health. Lindqvist O. discusses increased mercury pollution in remote lakes due to long-range transport, emphasizing the need for substantial emission reductions, whereas Obrist D. reviews the global mercury cycle, noting human activities as key sources. Shi G. focuses on pollution hotspots in Shanghai, linking heavy metal concentrations to traffic and industrial activities,

Table 4. Top 10 most-cited articles on atmospheric heavy metals published in Scopus.

Author	Journal	Year	Total citations (TC)	TC per year	Key findings
Nicholson F. A. [94]	*Science of the Total Environment* (Q1, Netherlands)	2003	1078	49.00	The study inventories metal(loid) inputs (Zn, Cu, Ni, Pb, Cd, Cr, As, and Hg) to agricultural soils in England and Wales in 2000, highlighting atmospheric deposition as the main source, contributing 25–85% of total inputs. Livestock manures and sewage sludge were also significant, providing about 37–40% of total zinc and 8–17% of total copper inputs. At the field level, sewage sludge, livestock manures, and industrial wastes can be the predominant sources.
Zheng N. [95]	*Science of the Total Environment* (Q1, Netherlands)	2010	756	50.40	A study of street dust contamination from metal smelting in Huludao city in China revealed high levels of Hg, Pb, Cd, Zn, and Cu, especially near the Huludao zinc plant, with atmospheric deposition as the main source. Health assessments indicated increased noncancer risks for children and adults, primarily from dust ingestion, while inhalation risks were negligible. Children faced higher potential health risks from Pb and near-threshold risks from Cd, though cancer risk from Cd inhalation was low.
Lindqvist O. [96]	*Water, Air, and Soil Pollution* (Q2, Switzerland)	1991	674	19.82	Recent studies reveal a marked increase in mercury (Hg) pollution in remote Scandinavian and North American lakes, primarily due to widespread air pollution and long-range transport. In Sweden, around 10 000 lakes exceed the national Hg limit for pike, with fish levels 2–6 times above background levels. Remedial measures have reduced Hg in fish by 20–30% within two years, but achieving a long-term solution requires an 80% reduction in atmospheric Hg emissions to mitigate contamination in fish and forest soils effectively.

Continuation of Table 4.

Author	Journal	Year	Total citations (TC)	TC per year	Key findings
Obrist D. [97]	*Ambio* (Q1, Netherlands)	2018	543	77.57	Recent findings on global mercury (Hg) cycling indicate that major reservoirs — atmosphere (4.4–5.3 Gt), soils (250–1000 Gg), and oceans (270–450 Gg) — are affected by human activities. While Hg emissions have decreased in Europe and the United States, they are rising in East Asia. Terrestrial areas are now seen as net sinks for atmospheric Hg due to plant uptake, and significant freshwater Hg releases originate from artisanal gold mining in China and India. Future changes in Hg cycling are expected due to shifts in emissions, land use, and climate.
Shi G. [98]	*Environmental Pollution* (Q1, UK)	2008	477	28.06	A study in Shanghai assessed the contamination of potentially toxic metals (Pb, Zn, Cu, Cr, Cd, and Ni) in 273 soil and dust samples. Findings revealed significant metal concentrations, particularly in roadside dust. Geostatistical analysis identified pollution hotspots linked to the city core, major road junctions, and industrial areas. Source analysis indicated that Pb, Zn, and Cu were primarily from traffic, while Cd was associated with industrial pollution. Soil Ni was related to natural concentrations, and Cr and Ni in dust were largely linked to atmospheric deposition.
Liang J. [99]	*Environmental Pollution* (Q1, UK)	2017	476	59.50	A study in Lianyuan, Hunan Province, analyzed 6078 soil samples for heavy metal pollution. Most metals were below China's Grade II Soil Quality Standards, except for Hg, but many exceeded local background levels. Differences in metal concentrations were linked to anthropogenic sources, with spatial variation assessed using GIS. The PMF model revealed source contributions of 33.6% from natural sources, 26.05% from atmospheric deposition, 23.44% from industrial activities, and 16.91% from agricultural activities.

Continuation of Table 4.

Author	Journal	Year	Total citations (TC)	TC per year	Key findings
Hernandez L. [100]	*Science of the Total Environment* (Q1, Netherlands)	2003	470	21.36	This study examines heavy metal distribution in French nonpolluted forest soils, finding Cr, Zn, Pb, Ni, Cu, and Co in the order of abundance. Some soils exceed European thresholds for Pb, Cr, and Ni, with higher concentrations in calcaric cambisol and mollic andosol. Lead isotopes reveal significant anthropogenic contributions from atmospheric pollution, especially from leaded gasoline, particularly in northern France.
Huang S. S. [101]	*Chemosphere* (Q1, UK)	2007	446	24.78	This study assessed atmospheric heavy metals/metalloids (Hg, Cd, Pb, Zn, Cu, As, Ni, and Cr) in soil, cereals, and vegetables from Yangzhong district, China. Topsoils showed higher concentrations of these metals compared to subsoils, particularly in urban areas. Increases in Cd and Hg since 1990 are attributed to agrochemical use, while Cr and Ni levels remained stable. Atmospheric deposition from urban sources also contributed to slight increases in As, Cu, Pb, and Zn, impacting the quality of agricultural products.
Lu A. [102]	*Science of the Total Environment* (Q1, Netherlands)	2012	446	34.31	This study analyzed atmospheric heavy metals/metalloids (As, Cd, Cu, Hg, Pb, and Zn) in agricultural soils in Shunyi, Beijing, using 412 samples. Most metal concentrations were slightly above background levels but below Chinese environmental guidelines. Cd, Cu, and Zn contamination primarily stemmed from agricultural practices, while As and Pb were from soil parent materials, and Hg resulted from atmospheric deposits. Identifying these sources is crucial for soil quality protection.

Continuation of Table 4.

Author	Journal	Year	Total citations (TC)	TC per year	Key findings
Miraglia M. [103]	*Food and Chemical Toxicology* (Q1, UK)	2009	439	27.44	This review explores the effects of climate change on food safety in Europe, emphasizing atmospheric heavy metals. It highlights issues such as mycotoxin formation, pesticide residues from changing pest pressures, and heavy metals in crops linked to soil conditions. The review also addresses concerns about polycyclic aromatic hydrocarbons, marine biotoxins from harmful algal blooms, and increased pathogenic bacteria due to extreme weather.

while Liang J. correlates elevated soil metal levels in Hunan Province to atmospheric deposition and industry. Hernandez L. finds significant anthropogenic contributions to heavy metals in French forest soils, and Huang S. S. assesses the impact of urban deposition on agricultural products in Yangzhong district, China. Lu A. analyzes heavy metal sources in Shunyi, Beijing, attributing contamination to agricultural practices and atmospheric inputs, and Miraglia M. reviews the effects of climate change on food safety in Europe, emphasizing the relevance of atmospheric heavy metals on crops. Collectively, these studies highlight the critical role of atmospheric deposition in heavy metal contamination and its implications for environmental and public health.

3.3.9. Global research collaborations: key partnerships and trends

The collaboration frequency data presented in Figure 11 and Table S3 highlight significant international research partnerships, with China and the USA leading with 38 collaborations, indicating a particularly strong bilateral research connection. Several collaborations also involve

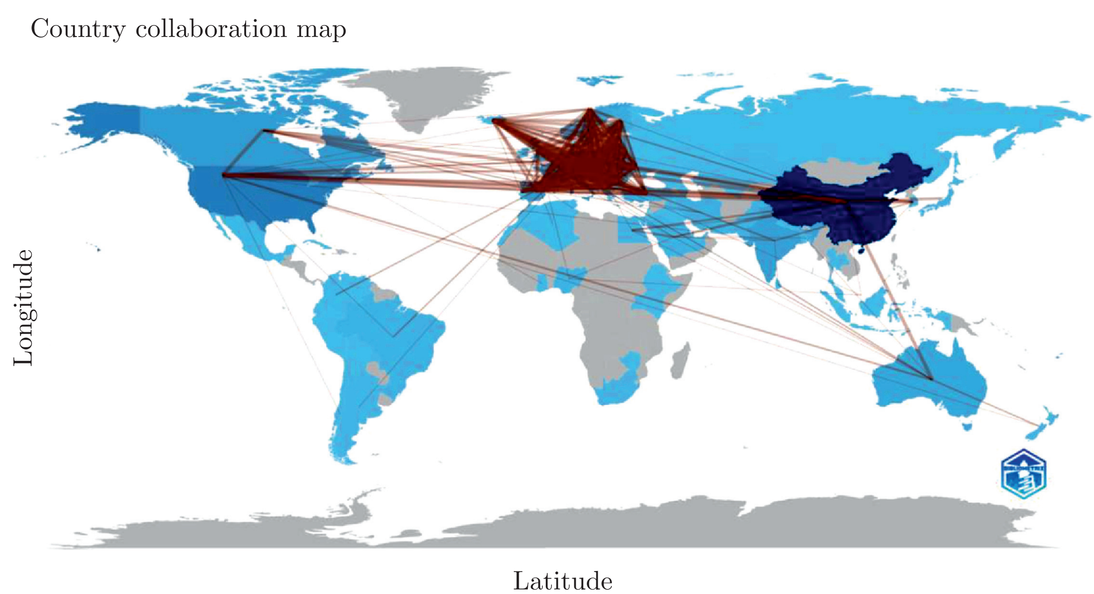

Figure 11. International collaboration in atmospheric heavy metal research.

European countries, reflecting active regional research networks. Notably, partnerships involving North Macedonia and Slovenia show substantial collaboration intensity, with a frequency of 21. Other European countries, including Germany, the United Kingdom, and Norway, also demonstrate strong collaborative ties, frequently partnering with nations such as Sweden and Poland.

As suggested by Cisneros et al. [104], collaboration among researchers enhances information exchange and boosts research efficiency by reducing costs. Furthermore, promoting partnerships among authors, agencies, and countries can lead to a greater number of published authors and improved research outcomes in the field [105]. Therefore, fostering international cooperation is essential for advancing studies on atmospheric heavy metals.

The analysis further reveals a tendency for European countries to form regional alliances, likely facilitated by geographic proximity, shared regulatory frameworks, and common research priorities, particularly within the European Union context [105]. Overall, these findings underscore the global nature of scientific collaboration, with countries from multiple regions, including China, the USA, and Europe, actively contributing to knowledge advancement. At the same time, the results highlight a notable gap in collaborative research involving low-income countries, where environmental pollution burdens are often high but international research engagement remains limited.

3.3.10. Research theme analysis

The thematic map analysis, constructed using Keywords Plus in Bibliometrix for atmospheric heavy metal research, reveals key insights into the research landscape (Figure 12). The x-axis indicates relevance (centrality), reflecting each theme's importance in the overall field, while the y-axis represents development (density), showing the extent of active research. Themes in the top right quadrant, including a large cluster around "heavy metal", "atmospheric deposition", and "article", are both central and actively researched, marking them as motor themes that drive current investigations. Conversely, themes like "air pollution", "nonhuman", and "atmospheric pollution" form a small cluster between niche and emerging (or declining) themes; while these areas are established and referenced in a notable number of articles, they remain less explored, suggesting potential for revisiting and expanding established knowledge. Similarly, topics like "soil pollution", "China", and "soil", positioned between the lower left and

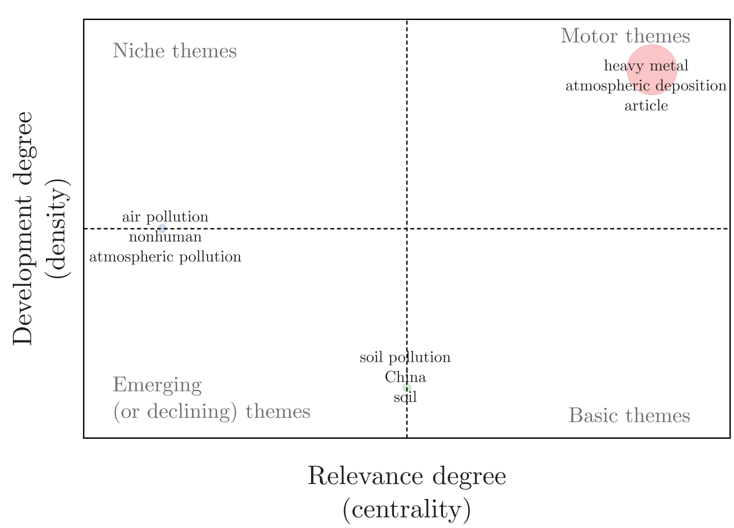

Figure 12. Visualization of thematic mapping of atmospheric heavy metal studies.

lower right quadrants, show limited relevance, fitting the profile of basic themes that offer foundational knowledge without recent development. Overall, the map underscores the significance of motor themes like "heavy metal", "atmospheric deposition", and "article" while highlighting emerging trends and areas, such as "soil pollution", "China", "soil", "nonhuman", and "atmospheric pollution", that warrant further exploration in atmospheric heavy metal research.

3.3.11. Research trend analysis

The word cloud analysis of the most frequently used keywords in publications related to atmospheric heavy metals, as shown in Figure 13, highlights the key terms discussed. "Heavy metal" leads with 1743 mentions, followed by "atmospheric deposition" (1386) and "lead" (1159). Other prominent terms include "environmental monitoring" (1143), "cadmium" (1047), and "China" (976), which reflect a geographic focus. Additionally, keywords such as "article" (889), "zinc" (835), "soil pollution" (775), and "copper" (756) indicate a range of metals studied and the monitoring of pollution levels in various environmental media.

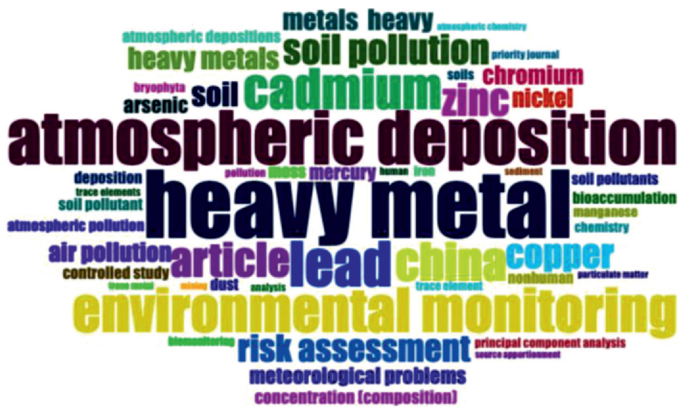

Figure 13. Word clouds depicting the 50 most frequently used keywords in articles on atmospheric heavy metals. The font size is positively correlated with the frequency of word usage.

3.3.12. Co-keyword network analysis and dominant themes in atmospheric heavy metal research

Analyzing the frequency of co-keywords in publications to create a co-keyword network facilitated the identification of internal structures and trends within a research field [106]. Table 5 presents the top 10 co-occurring keywords from publications on atmospheric heavy metals, detailing their occurrences and link strengths. The term "heavy metal" leads with 1221 occurrences and a total link strength of 35 861, closely followed by "atmospheric deposition", which has 1163 occurrences and a link strength of 35 807. Other notable keywords include "article" (878 occurrences, link strength 31 945), "lead" (762 occurrences, link strength 26 909), and "cadmium" (676 occurrences, link strength 23 970). Additional keywords such as "environmental monitoring", "zinc", "copper", "soil pollution", and "China" further illustrate key research areas in the field.

This robust research landscape reflects a growing concern and active inquiry into atmospheric heavy metals and their implications. In contrast, terms such as "niobium", "dysprosium", and "radium-226" received very little attention, with occurrences of fewer than six (data not shown here), highlighting a disparity that suggests that while heavy metals dominate the research focus, other potentially significant elements and issues remain underexplored. Identifying these understudied areas presents a valuable opportunity for future research to broaden the understanding of heavy metal contamination and its implications, particularly regarding less common elements that may pose risks to human health and the environment.

Table 5. Top 10 co-occurring keywords from publications on atmospheric heavy metals.

Keyword	Occurrences	Total link strength
Heavy metal	1221	35 861
Atmospheric deposition	1163	35 807
Article	878	31 945
Lead	762	26 909
Cadmium	676	23 970
Environmental monitoring	632	23 799
Zinc	618	22 810
Copper	573	21 503
Soil pollution	478	14 910
China	438	15 495

The analysis of 11 240 keywords in the field of atmospheric heavy metal research yielded 822 terms that met the minimum occurrence threshold of 10 and were selected for visualization in Figure 14, *a*. This comprehensive keyword analysis identified five major clusters, each highlighting distinct thematic focuses that reveal critical areas for future study and policymaking. The identification and categorization of these clusters provide insights into the current research landscape and underline the interconnected nature of various subfields in atmospheric heavy metal pollution.

Cluster 1 (red): Broad ecological and chemical perspectives. Cluster 1, the largest with 317 items, encompasses keywords with an overarching focus on the ecological and chemical analysis of heavy metals. Prominent terms such as "heavy metals", "trace metals", "ecosystem", "river pollution", and "sediment" underscore the cluster's emphasis on the environmental impact of heavy metals in various aquatic and terrestrial systems. The presence of terms like "anthropogenic source" and "atmospheric deposition" highlights the human-driven origins of these pollutants and their deposition processes. Mining and industrial activities are major contributors to heavy metal contamination, leading to detrimental effects on water quality and sediment composition [107]. Research has shown that heavy metals emitted into the atmosphere from both natural and anthropogenic sources can be deposited through various mechanisms, including dry deposition (where pollutants settle onto surfaces directly from the air without precipitation) and wet deposition (where pollutants are captured by precipitation such as rain or snow and deposited on the Earth's surface, leading to potential contamination of water, soil, and vegetation) [108, 109]. This cluster's composition reflects an integrative approach that connects pollution sources to ecosystem responses, highlighting the importance of studying pollutant pathways and impacts on water bodies and sediment.

Cluster 2 (green): Monitoring, health risk, and spatial analysis. Cluster 2, consisting of 158 items, focuses on environmental monitoring and the assessment of health risks associated with heavy metals. Key terms include "environmental monitoring", "mercury", "risk assessment", and "health risk", indicating a strong connection to human health and public safety. Assessing these risks is essential, as heavy metals can lead to severe health issues, including chronic diseases and acute poisoning [110]. The inclusion of terms like "principal component analysis" and "spatial distribution" suggests a methodological emphasis on geographic and statistical analyses, with specific reference to regions such as "China", a significant case study in heavy metal pollution research. The methodological focus on geographic and statistical analyses, particularly in regions like China, underscores the importance of localized studies in understanding heavy metal pollution dynamics. Research has shown that heavy metal contam-

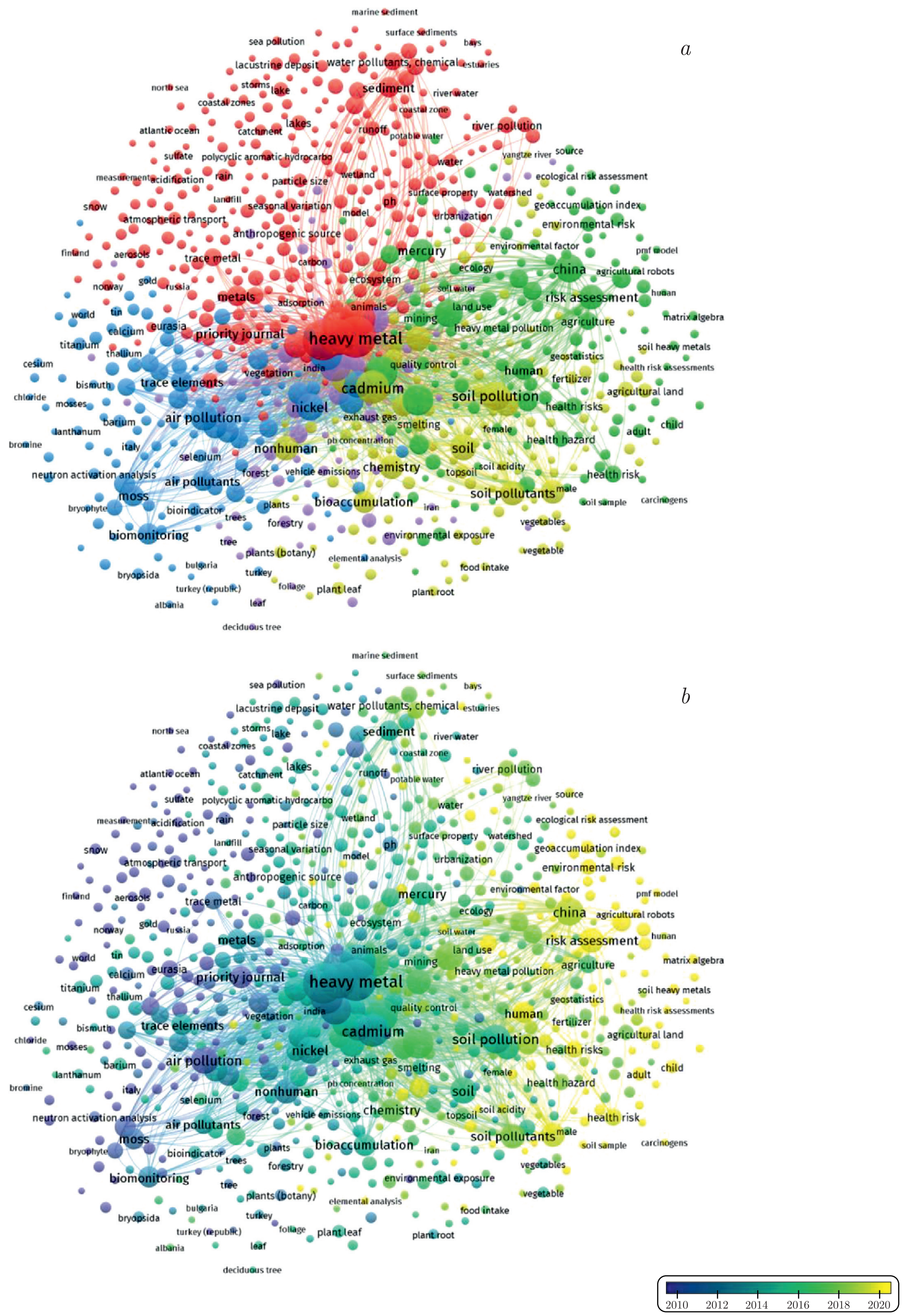

Figure 14. *a*) The co-occurrence analysis of all keywords in atmospheric heavy metal publications revealing patterns in keyword relationships. The size of each node indicates the frequency of a keyword's occurrences across publications, while the lines connecting nodes represent their co-occurrence within the same publication. Closer proximity between two nodes indicates a higher frequency of co-occurrence. *b*) The research focus of global atmospheric heavy metal studies over time, with earlier years shown in blue and more recent years in yellow.

ination in soil and crops can significantly impact food safety and human health, necessitating comprehensive risk assessments to evaluate exposure pathways [111, 112]. Overall, this cluster emphasizes the need for comprehensive monitoring frameworks and risk assessment models to mitigate health hazards related to heavy metal exposure.

Cluster 3 (blue): Elemental analysis and air quality. Cluster 3, comprising 137 items, emphasizes specific trace elements and their role in atmospheric and air quality studies. Keywords such as “zinc”, “chromium”, “arsenic”, and “air pollution” highlight the analysis of metal(loid)s that contribute to air quality degradation. The inclusion of keywords related to air pollution signifies a significant concern regarding how these trace metals impact air quality and the potential health risks associated with exposure. Studies have shown that trace elements in airborne particulate matter can have serious health implications, including respiratory issues and other chronic diseases [113]. The mention of “biomonitoring” and “Bryophyta” (moss) in the cluster indicates the use of natural organisms to monitor and assess atmospheric pollution levels. Biomonitoring is an effective approach to evaluate air quality, as these organisms can accumulate heavy metals from the air, reflecting the environmental quality of their surroundings [114]. Research has demonstrated that mosses can serve as reliable indicators of air quality, particularly in urban areas where industrial activities contribute to elevated levels of trace metals [115]. The geographic references to “Europe” and “Eurasia” also highlight key regions where these studies are concentrated. This cluster is crucial for advancing knowledge about the behavior of trace elements in the atmosphere and their implications for human and environmental health. A study by Moreno et al. [116] in Spain illustrated the complex chemical composition of urban aerosols, revealing significant variations in trace metal content across different towns. Similarly, research in heavily polluted regions of China has documented the spatiotemporal variations of trace elements in the atmosphere, linking them to industrial emissions and other anthropogenic activities [117]. These findings emphasize the need for comprehensive monitoring frameworks to effectively track air quality and assess the associated health risks from trace metal exposure. Overall, this cluster provides a comprehensive overview of elemental analysis and air quality concerning trace metals. The integration of biomonitoring approaches, geographic studies, and health risk assessments is essential for advancing knowledge in this field and addressing the challenges posed by air pollution.

Cluster 4 (yellow): Atmospheric pollutants. Cluster 4 encompasses a significant body of research focusing on “cadmium”, “bioaccumulation”, and “soil pollution”, highlighting the intricate relationships between terrestrial environments and pollutant behavior in soil matrices. The studies within this cluster emphasize the importance of understanding how heavy metals, particularly cadmium, accumulate and move within soil systems. Other keywords such as “controlled study”, “chemistry”, and “contamination” reflect the experimental approaches used to analyze heavy metal accumulation and mobility within soils. The emphasis on “atmospheric deposition” ties this cluster to the transference of pollutants from air to land, underscoring the cross-compartmental movement of heavy metals. Stewart et al. [118] demonstrate that quantum dots, which contain cadmium, exhibit less bioaccumulation in earthworms compared to free cadmium ions, suggesting that the form of cadmium influences its bioavailability and accumulation in soil organisms. This finding underscores the necessity of considering the chemical form of pollutants when evaluating their ecological impacts. The mobility of cadmium in soils is also influenced by various factors, including organic acids produced by soil microorganisms. Navarro et al. [119] discuss how these organic acids can enhance the release of heavy metal contaminants from soils, thereby affecting their mobility and bioavailability. This relationship is critical for understanding the dynamics of cadmium in soil environments, particularly in the context of atmospheric deposition, which can introduce cadmium into terrestrial systems from airborne sources [120]. The atmospheric deposition of cadmium is a significant concern, as it contributes to soil contamination and poses risks to both ecological and human health [121]. This cluster thus suggests a vital area of study for understanding how atmospheric pollutants contribute to soil contamination and subsequent ecological effects.

Cluster 5 (violet): Urban and industrial impact. The smallest cluster, Cluster 5, with 76 items, centers on "copper", "pollution", and "atmospheric chemistry", highlighting research that focuses on urban and industrial sources of heavy metal pollution. The presence of terms like "urban area", "rural", "forest", "dust", and "particulate matter" emphasizes the diverse environments impacted by industrial emissions and exhaust gases. Işinkaralar and Bayraktar [122] assert that traffic is a primary source of copper pollutants in urban areas, underscoring the need for effective urban planning strategies to mitigate these emissions. The atmospheric chemistry of urban environments is complex, as noted by Harrison [123], who emphasizes the unique characteristics of urban atmospheric chemistry that necessitate specialized study. The interactions of various pollutants, including particulate matter and volatile organic compounds, contribute to the overall air quality and health risks associated with urban pollution. This complexity is compounded by the findings of Boynard et al. [124], who discuss how industrialization and increased vehicle ownership in urban centers lead to significant air quality challenges, particularly in regions like North China. The inclusion of "India" in the cluster suggests regional studies addressing pollution challenges specific to the country and similar contexts. The temporary reduction in fine particulate matter during the COVID-19 lockdown, illustrates how anthropogenic activities directly influence air quality in Indian cities, as documented by Kumar et al. [125]. Overall, this cluster underscores the importance of studying the dispersion of pollutants in various settings and the interactions between urban-industrial activities and surrounding ecosystems.

3.3.13. Evolution of global research focus on atmospheric heavy metal pollution: shifts in themes, regions, and health implications

Figure 14, *b* illustrates the evolving focus of global atmospheric heavy metal research over time, particularly highlighting shifts in thematic emphasis. Prior to 2013, studies predominantly concentrated on air pollution, trace metals, aerosols, and pollutant transport, with significant regional focus on Europe, Eurasia, the United States, and Scandinavia. This period also featured research on biological monitoring using moss species such as *Hypnum cupressiforme*, *Pleurozium schreberi*, and *Hylocomium splendens*, which are recognized as effective bioindicators for assessing atmospheric metal deposition [126–129]. The use of mosses as bioindicators of metal deposition has been widely accepted in environmental monitoring. Mosses can reflect atmospheric inputs of heavy metals, although they may also accumulate metals from non-atmospheric sources such as soil dust and root uptake [130]. This highlights the complexity of interpreting moss data in relation to atmospheric pollution. Jiang et al. [131] demonstrate that mosses are superior to vascular plants for monitoring atmospheric heavy metal pollution, as their simpler uptake mechanisms allow for clearer correlations with atmospheric deposition. This is particularly relevant in urban areas where heavy metal concentrations can be significantly elevated due to industrial emissions.

Between 2014 and 2018, research interests in atmospheric heavy metal pollution expanded significantly, encompassing a broader array of pollutants, particularly cadmium (Cd), nickel (Ni), and copper (Cu). This period marked a notable shift towards addressing soil pollution, bioaccumulation, and the role of anthropogenic sources in metal emissions. The growing focus on atmospheric chemistry and environmental monitoring reflects heightened concerns regarding the complex interactions between heavy metals and various environmental media. Research by Amadi et al. [132] highlights the use of pollution indices to assess soil quality, revealing significant contamination with heavy metals such as Cd and Pb in mining areas. Their findings underscore the anthropogenic contributions to soil pollution, particularly in regions impacted by industrial activities. Similarly, Banerjee et al. [133] provide evidence of heavy metal contamination in aquatic ecosystems, emphasizing bioaccumulation of metals in plankton, mollusks, and fish — processes influenced by water quality and sediment composition. This study illustrates the interconnectedness of soil and water pollution and its implications for food chains.

From 2018 to the present, the research landscape regarding heavy metal pollution has shifted significantly, emphasizing the human and ecological risks associated with these contaminants. This period has seen an increased focus on risk assessment, health implications, particularly for children, and source identification and apportionment. China has emerged as a significant focal point due to its rapid industrial growth and the associated environmental challenges. Research has broadened to encompass agricultural land and the impact of metal concentrations on human health, highlighting a multidisciplinary approach that integrates public health, environmental science, and policy considerations. Li et al. [134] discusses the establishment of geochemical baselines and source-oriented ecological risk assessments for heavy metals in agricultural soils, emphasizing the importance of understanding both the sources of contamination and their potential health impacts. This study reflects the growing recognition of the need for comprehensive risk assessments that consider the specific toxicities of different metals, which is crucial for effective environmental management. A literature review by Xiao et al. [135] highlights the pathways through which heavy metals affect human health, particularly through the food chain, and notes the limited research on the health implications of heavy metal exposure. Their findings underscore the urgent need for further studies to explore the health risks associated with heavy metal contamination in agricultural settings, particularly for vulnerable populations such as children.

4. Research gaps and future directions in atmospheric heavy metal studies

Although research on atmospheric heavy metals has grown markedly over the past five decades, the bibliometric analysis reveals several high-priority gaps that must be addressed to improve exposure assessment, strengthen monitoring capacity, and support effective policy action. These gaps are organized below by urgency, highlighting areas where progress would yield the greatest scientific and societal benefits.

Priority 1: Monitoring and protecting vulnerable populations. Long-term, cohort-based studies on chronic exposure among vulnerable groups remain critically lacking. Most existing research is cross-sectional, with limited focus on children, pregnant women, and the elderly, despite well-documented evidence of heightened susceptibility to heavy metal toxicity [136]. Studies show that children face substantially higher hazard indices and carcinogenic risks from atmospheric metals, underscoring the need for targeted, long-term monitoring and the integration of biomonitoring tools [137]. Future work should prioritize cohort studies, link biomonitoring with atmospheric measurements, and adopt multipathway exposure assessments that incorporate inhalation, dietary intake, and dermal routes. Programs such as the U.S. EPA AirNow network [138] and the EU Human Biomonitoring Initiative (HBM4EU) [139] offer scalable frameworks that could be adapted for vulnerable populations.

Priority 2: Real-time, field-deployable and low-cost monitoring technologies. A major limitation in current monitoring is the continued reliance on laboratory-based AAS, ICP-MS, and XRF analyses [140], which restrict temporal resolution and delay early warnings. Recent advances in portable spectrometers, autonomous XRF systems, Internet-of-Things (IoT)-enabled low-cost sensors, and drone-based atmospheric surveillance [141, 142] offer promising alternatives. Microsensing platforms used in programs such as AirNow and PurpleAir could be adapted for heavy metal aerosols with metal-oxide nanocoating technologies. Real-time systems are crucial for detecting acute pollution episodes from industrial accidents, volcanic eruptions, and biomass-burning events.

Priority 3: Higher-resolution source apportionment and atmospheric transport modelling. Most studies still rely on bulk concentration data, limiting the ability to differentiate among industrial, traffic, volcanic, biomass-burning and resuspension sources. Machine-learning approaches show strong potential to improve resolution. Dong et al. [143] used Random Forest and LightGBM to map Cr, Cd, As and Pb emissions across 367 Chinese municipalities, achieving high predictive accuracy ($R^2 = 0.58{-}0.84$). Zheng et al. [144] combined Self-Organizing Map (SOM), Positive Matrix Factorization (PMF), and Gradient Boosted Decision Tree (GBDT) to reduce subjectivity in source apportionment, revealing traffic and atmospheric deposition as major Pb contributors and identifying sewage irrigation as a key source of Cd and Zn. These advances demonstrate the need to integrate machine learning with emission inventories, meteorological data, and land-use parameters to generate high-resolution source attribution maps and accurately predict deposition hotspots.

Priority 4: Reducing geographic disparities and strengthening monitoring networks. Research output remains geographically imbalanced, dominated by China, Europe, and North America. Although global networks such as the Global Atmospheric Passive Sampling (GAPS) are beginning to address these disparities [145], large regions, including parts of Africa, South America, and Central Asia, remain underrepresented. Expanding international monitoring networks and building local capacity are crucial steps toward more equitable global assessments.

Priority 5: Investigating emerging and understudied metal species. Research continues to focus primarily on Pb, Cd, Hg, Zn, and Cu, while rare earth elements, nanoparticle-bound metals, and organometallic compounds remain substantially understudied. Recent reviews highlight the need for advanced speciation methods and expanded investigation into these emerging contaminants [146].

Priority 6: Linking atmospheric inputs to soil–plant–water systems. Few studies integrate monitoring across air, soil, vegetation, and water, despite the critical role of atmospheric deposition in food-chain contamination and ecosystem risk. Cross-compartment analyses and isotopic tracing approaches are needed to better quantify the fate and transport of metals in coupled environmental systems [147].

Priority 7: Standardizing methods, QA/QC protocols, and data reporting. Substantial methodological heterogeneity persists in sampling, sample preparation, digestion protocols, and reporting practices, impeding cross-study comparisons. Reviews emphasize the need for harmonized global protocols and strengthened long-term monitoring networks, particularly in developing regions [145–148].

Priority 8: Integrating socio-economic, regulatory and policy dimensions. Only a small proportion of studies assess the effectiveness of emission controls, economic costs of exposure, or public perception of heavy metal risks. Greater interdisciplinary research connecting environmental science with policy, economics, and social sciences is essential for developing effective and equitable mitigation strategies [148].

5. Implications for practice

The findings of this systematic review and bibliometric analysis have several important implications for environmental management, public health protection, and regulatory practice. First, the strong evidence for persistent and spatially heterogeneous atmospheric heavy metal deposition underscores the need for expanded and harmonized monitoring networks, particularly in rapidly urbanizing and industrializing regions. Environmental agencies should integrate conventional instrumental monitoring (e.g., $PM_{2.5}/PM_{10}$ metal analysis) with biomonitoring approaches, especially moss-based monitoring, to improve detection sensitivity for low-level and chronic deposition that may not be captured by short-term air sampling.

Second, public health authorities should prioritize vulnerable populations, including children, pregnant women, and occupationally exposed groups, by linking atmospheric monitoring data with targeted biomonitoring and exposure assessments. Integrating atmospheric deposition data into urban health surveillance systems can support early identification of high-risk areas and guide localized interventions, such as traffic management, zoning restrictions, and emission controls near schools and residential areas.

Third, the demonstrated importance of long-range transport highlights the need for regional and transboundary cooperation. Atmospheric heavy metals do not respect political boundaries; therefore, regional organizations and international frameworks should promote standardized sampling protocols, Quality Assurance and Quality Control (QA/QC) procedures, and shared databases. Such harmonization would improve comparability among studies and strengthen cross-border pollution assessments, particularly in regions affected by biomass burning, dust transport, or volcanic activity.

Fourth, urban and industrial planning can benefit from high-resolution source attribution tools that combine atmospheric measurements with meteorological data and machine-learning approaches. These tools can help decision-makers identify dominant emission sources, evaluate the effectiveness of mitigation measures, and prioritize interventions near traffic corridors, smelting facilities, mining areas, and geothermal installations.

Finally, disaster-risk management and climate-adaptation strategies should explicitly incorporate atmospheric heavy metal monitoring. Volcanic eruptions, dust storms, and large-scale biomass-burning events can rapidly elevate airborne metal concentrations, posing acute health risks. Integrating metal monitoring into early-warning systems and emergency response plans would improve preparedness and reduce exposure during extreme events.

Overall, translating advances in atmospheric heavy metal research into practice requires closer integration between scientists, regulators, and public health practitioners. By combining improved monitoring technologies, biomonitoring tools, regional cooperation, and evidence-based policy design, atmospheric heavy metal research can more effectively inform mitigation strategies and protect both ecosystems and human health.

6. Conclusion

This review synthesizes current knowledge on atmospheric heavy metals by integrating evidence from monitoring studies, analytical techniques, and biomonitoring approaches across diverse environments. The findings highlight that atmospheric heavy metal pollution remains a persistent and spatially heterogeneous challenge, shaped by complex interactions among emission sources, transport processes, and environmental sinks. Advances in sampling and analytical methods, combined with the growing use of biological indicators such as mosses, lichens, and aquatic organisms, have improved detection sensitivity and our understanding of long-term deposition patterns. However, substantial gaps remain, particularly in standardized methodologies, long-term and multicompartment assessments, and research coverage in low- and middle-income regions. Addressing these gaps through coordinated monitoring strategies, methodological harmonization, and strengthened international collaboration is essential for improving exposure assessment, informing policy, and mitigating the ecological and human health risks associated with atmospheric heavy metal contamination.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Weerachon Sawangproh. The first draft of the manuscript was written by Weerachon Sawangproh, Chetsada Phaenark, and Arika Bridhikitti. All authors commented on previous version of the manuscript. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

Table S1. A summary of species or groups of organisms used as biomonitors for atmospheric heavy metals.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hylocomium splendens	Bryophytes	Norway	33	INAA, AAS, ICP-ES, ICP-MS	Cd, Cr, Ni, Pb, Cu, Zn, Fe, Mn, etc.	Steinnes et al. (1993)
Pleurozium schreberi, *Hylocomium splendens*	Bryophytes	Poland	8	Biomonitoring	Cd, Cr, Ni, Pb, Cu, Zn, Fe, Mn	Grodzińska et al. (1990)
Pleurozium schreberi, *Hylocomium splendens*	Bryophytes	Poland	8	Biomonitoring	Cd, Cr, Ni, Pb, Cu, Zn, Fe, Mn	Miller et al. (1990)
Hylocomium splendens	Bryophytes	Norway	Multiple	Multi-element moss survey	General focus on heavy metals and atmospheric deposition elements	Steinnes (1995)
Epiphyte lichens	Lichens	Italy	—	Bioaccumulators, observation	Primarily heavy metals from vehicle traffic and industry	Frigoli and Quartieri (1999)
Hylocomium splendens, *Pleurozium schreberi*	Bryophytes	Norway	48	Wet deposition, regression analysis	V, Fe, Co, As, Y, Mo, Cd, Sb, Ce, Sm, Er, Tl, Pb, etc.	Berg and Steinnes (1997)
Hylocomium splendens	Bryophytes	Norway	6	Correlation analysis	Ca, Cd, K, Mg, Pb, Cu	Økland et al. (1999)
Hylocomium splendens	Bryophytes	Norway	38	INAA (epithermal neutrons)	Cr, Fe, Mo, Sr, Se, Zr, Re, Hf, Ta, Th, U, V, Mn, Co, Cu, Zn, As, Sb, etc.	Frontasyeva and Steinnes (1995)
Pleurozium schreberi	Bryophytes	Poland	33	INAA, AAS	Al, Cl, Sc, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, etc.	Grodzińska et al. (2003)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hylocomium splendens, *Pleurozium schreberi*, *Eurhynchium angustirete*	Bryophytes	Lithuania	7	Concentration analysis	As, Cd, Cr, Mn, Pb, V, Zn	Čeburnis and Steinnes (2000)
Hypnum cupressiforme, *Scleropodium purum*, *Pleurozium schreberi*, and *Hylocomium splendens*	Bryophytes	France	14	INAA, ICP-MS	As, Cd, Cr, Cu, Fe, Hg, Pb, Ni, V, Zn, Ba, Ce, Cs, La	Ayrault et al. (2002)
Hypnum cupressiforme, *Pleurozium schreberi*, *Scleropodium purum*	Bryophytes	France	36	INAA, ICP-MS	Al, As, Co, Cs, Fe, La, Mn, Rb, Sc, Sm, Cl, Mn, Pb, Sb, Zn, etc.	Galsomiès et al. (2003)
Hypnum cupressiforme, *Scleropodium purum*	Bryophytes	Spain	9	Flame Atomic Absorption Spectroscopy (FAAS), Atomic Fluorescence Spectrophotometry (AFS)	Al, As, Cr, Cu, Fe, Hg, Ni, Pb, Zn	Fernández et al. (2002)
Plegiothecium denticulatum	Bryophytes	India	4	Not specified	Mn, Ni, Pb, Zn	Gupta and Gupta (2001)
Pinus sylvestris L. (bark)	Gymnosperms	Germany, Norway, Poland, Russia	5	Multivariate statistics, cluster and factor analysis	Various heavy metals, sulphate, nitrate, ammonia	Schulz et al. (2000)
Moss (unspecified species)	Bryophytes	Lithuania	2	Semi-empirical model, emission data and moss uptake	Ni, V	Čeburnis et al. (2002)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Pleurozium schreberi, Pseudoscleropodium purum, Rhytidiadelphus squarrosus	Bryophytes	Romania	31	ENAA, FAAS	Pb, As, Cu, Cd, Na, Mg, Al, Ti, Fe, Zn, etc.	Culicov et al. (2002)
Cetraria islandica, Evernia prunastri, Ramalina farinacea	Lichens	Germany, Italy, Romania	15	INAA, Energy Dispersive X-Ray Fluorescence Analysis (EDXRFA)	As, Br, Ca, Co, Cr, Cu, Fe, K, Mn, Ni, Pb, S, Sb, V, Zn	Cercasov et al. (2002)
Hypnum cupressiforme	Bryophytes	Turkey	6	Not specified	Cr, Cd, Pb, Fe, Ni, Mn	Acar (2006)
Evernia prunastri	Lichens	Italy	Not specified	Not specified	Not specified	Frati et al. (2005)
Parmelia sulcata	Lichens	Ghana	6	Thermal Neutron Activation Analysis (TNAA)	Al, Cr, Mn, Fe, Ti, Th, V	Nyarko et al. (2006)
Horse chestnut, Linden leaves	Angiosperms	Serbia	3	Bioaccumulation analysis	Cu, Pb, Cd	Tomašević et al. (2004)
Pleurozium schreberi	Bryophytes	Czech Republic	36	Moss monitoring techniques	Ag, As, Cd, Cu, Hg, In, Pb, Sb, Zn, Al, As, Be, Ce, Cr, Fe, Ga, La, Li, Nd, Pr, Sc, Th, U, V, Y, Cs, Rb, Tl, Mo, etc.	Sucharová and Suchara (2004b)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Pleurozium schreberi (Brid.) Mitt., *Hylocomium splendens* (Hedw.) B.S.G., and *Scleropodium purum* (Hedw.)	Bryophytes	Austria	Not specified	Moss analysis	Varied based on industrial sites	Zechmeister et al. (2004)
Spinacia oleracea, Lactuca sativa, Cichorium endivia, and *Valerianella locusta*	Angiosperms	Belgium	2	Bioaccumulation analysis	Cd, Pb	De Temmerman and Hoenig (2004)
Moss	Bryophytes	Netherlands	Not specified	Factor-analytical methods	Not specified, linked with health data	Wolterbeek and Verburg (2004)
Hypogymnia physodes	Lichens	Russia	4	MC-ICP-MS, Pb isotope analysis	^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb	Spiro et al. (2004)
Hylocomium splendens, *Pleurozium schreberi*	Bryophytes	Latvia	7	National survey, temporal trends	Cd, Cr, Cu, Pb, Ni, V, Zn	Nikodemus et al. (2004)
Hypnum cupressiforme, *Hylocomium splendens*, *Brachytechium salebrosum*, *B. rutabulum*	Bryophytes	Romania	40	NAA, AAS	As, Cd, Cu, Ni, V, Zn, etc.	Lucaciu et al. (2004)
Evernia prunastri	Lichens	Italy	5	Microwave digestion, GFAAS	Pb, Cd, Cr, Cu, Zn	Conti et al. (2004)
Tillandsia capillaris, *T. permutata*, *T. tricholepis*, and *T. retorta*	Angiosperms	Argentina	6	Total atmospheric deposition, foliar damage index	Pb, Ni, Fe, Zn, Cu, S	Wannaz and Pignata (2006)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hypogymnia physodes (L.) Nyl.	Lichens	Slovenia	4	Atomic absorption spectrophotometry	Zn, Pb, As, Cd	Poličnik et al. (2004)
Hypnum cupressiforme, Pleurozium schreberi, Dicranum scoparium, Polytrichum piliferum	Bryophytes	Portugal, Netherlands	15	Plant digests analyzed by various statistical methods	Al, Ba, Ca, Cr, Fe, K, Mg, Mn, Ni, Sr, V, Zn, Pb, Cu, Cd	Samecka-Cymerman et al. (2005)
Lolium italicum, Festuca arundinacea	Angiosperms	Italy	3	Active biomonitoring, plant age influence on data	Cd, Cr, Ni	Caggiano et al. (2005)
Pleurozium schreberi	Bryophytes	Czech Republic	36	Element content determination via bioindication	Al, Ce, Co, Ga, La, Li, Pr, S, Th, U, V, Y, etc.	Sucharová and Suchara (2004a)
Hylocomium splendens, Pleurozium schreberi, Dicranum sp.	Bryophytes	Slovakia (Carpathian Mountains)	39	INAA, AAS, elemental analyzer	As, Cd, Cu, Hg, Pb, Fe, Zn, Cr, Mn, V, etc.	Maňkovská et al. (2008)
Hypnum cupressiforme	Bryophytes	India (Mussoorie)	4	Active monitoring (moss transplantation), metal precipitation analysis	Cu, Zn, Cd, Pb	Saxena, Srivastava, and Singh (2008)
Rhodobryum giganteum, Hypnum cupressiforme	Bryophytes	India (Garhwal Hills, Uttaranchal)	4	Passive monitoring (moss sampling), metal precipitation analysis	Cd, Zn, Cu, Pb	Saxena, Singh, and Srivastava (2008)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Pleurocarpous mosses	Bryophytes	Turkey (Düzce)	7	Wet digestion, Graphite-Furnace Atomic Absorption Spectrometry (GFAAS)	Fe, Pb, Cu, Co, Cr, Ni, As	Uyar, Ören and Ince (2007)
Pleurozium schreberi, Hylocomium splendens	Bryophytes	Slovakia	38	INAA, AAS	Cd, Cu, Hg, Pb, S, Fe, Zn, and other trace elements	Florek et al. (2007)
Hypnum cupressiforme	Bryophytes	Spain	11	ICP-MS, CV-AA, Kjeldahl method	V, Cr, Mn, Ni, Cu, Zn, As, Zr, Cd, Hg, Pb	González-Miqueo et al. (2009)
Pleurozium schreberi, Hylocomium splendens	Bryophytes	Europe	10	UNECE ICP Vegetation moss analysis	As, Cr, Cu, Fe, Ni, V, Zn, etc.	Harmens et al. (2007)
Brachythecium sp., *Eurhynchium* sp.	Bryophytes	Serbia	36	INAA	Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, As, Se, Br, Rb, Sr, Mo, Sb, I, Cs, Ba, La, Ce, Sm, Tb, Dy, Hf, Ta, W, Hg, Th, U	Aničć et al. (2007)
Epiphytic/epigeic plants	Mainly bryophytes	Multinational	Multiple	Various analytical techniques	Heavy metals, including those specific to urban environments and traffic pollution	Markert et al. (2008)
Pleurocarp mosses	Bryophytes	Turkey	7	GFAAS	Fe, Pb, Ni, Cr, Cu, Co, As	Uyar, Ören, Yildirim, et al. (2007)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Tillandsia usneoides L.	Angiosperms	Brazil (Sao Paulo)	Multiple	Multimarker bioindication concept	Various heavy metals relevant to urban pollution in megacities	Markert et al. (2011)
Pleurozium schreberi, Hylocomium splendens, Hypnum cupressiforme, Pseudoscleropodium purum, and other species	Bryophytes	Europe	10+	UNECE ICP Vegetation moss analysis	Declining levels of As, Cd, Fe, Pb, V, Cu, Ni, Zn (no significant reduction for Hg, Cr)	Harmens et al. (2010)
Racomitrium lanuginosum, Hylocomium splendens, Pseudocalliergon brevifolium	Bryophytes	Canada (Arctic)	7	Sampling and isotope analysis	As, Cd, Cr, Cu, Ni, Zn, Pb	Wilkie and La Farge (2011)
Phoenix dactylifera L. (leaves)	Angiosperms	Jordan	6	AAS	Fe, Pb, Zn, Cu, Ni, Cr	Al-Khashman et al. (2011)
Sphagnum moss peat	Bryophytes	Romania	5	Graphite-furnace electrothermal AAS	Pb, Cd, Cu, Mn, Fe	Sandu et al. (2012)
Barbula indica	Bryophytes	Vietnam	38	AAS, INAA	Various metal elements	Viet et al. (2010)
Scorpiurum circinatum	Bryophytes	Italy	Not specified	Biomonitoring, ultrastructural analysis	Heavy metals in particulate form	Basile et al. (2009)
Hylocomium splendens, Pleurozium schreberi, Dicranum sp.	Bryophytes	Slovakia	9	Biomonitoring	Cd, Cr, Cu, Fe, Hg, Ni, Pb, V, Zn	Mankovská and Oszlányi (2009)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hypnum cupressiforme	Bryophytes	Portugal	5	Multiple correspondence analysis, kriging	Cu, Pb, Zn, Cr, As	Reis et al. (2010)
Moss species	Bryophytes	Romania	5	NAA, AAS, ICP-AES	Cr, Fe, Mn, Ni, Zn	Popescu et al. (2010)
Pleurozium schreberi, Hylocomium splendens, Dicranum sp.	Bryophytes	Slovakia	45	Biomonitoring	Various metal elements (Ag, Al, As, Au, Ba, Br, Ca, Cd, Ce, Cl, etc.)	Maňkovská and Oszlányi (2010)
Jacaranda mimosifolia	Angiosperms	South Africa	7	ICP-MS	Ca, Mg, Fe, Pb, Zn, Cu, Sb	Olowoyo et al. (2010)
Phaeophyscia hispidula, Parmotrema praesorediosum, Caloplaca subsoluta, Diploschistes candidissmus, Peltula euploca, Phylliscum indicum	Lichens	India	7	Biomonitoring	Al, Cd, Cr, Cu, Fe, Ni, Zn	Bajpai et al. (2009)
Racomitrium crispulum	Bryophytes	India	4	Statistical analysis, DMR, SURFER	Zn, Cu, Cd, Pb	Saxena and Arfeen (2010)
Evernia prunastri	Lichens	Turkey	Not specified	Biomonitoring, bioaccumulation	Heavy metals in atmospheric deposition	Cansaran-Duman et al. (2011)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Plagiomnium undulatum, Plagiomnium cuspidatum, Rhizomnium punctatum, Polytrichum strictum, Thamnobryum alopecurum, Polytrichum commune	Bryophytes	Romania (Dorna Basin)	2	Passive monitoring, metal concentration in bryophytes and soil	Zn, Fe	Pata et al. (2010)
Hylocomium splendens, Pleurozium schreberi, Hypnum cupressiforme, Pseudoscleropodium purum	Bryophytes	Croatia	41	NAA, AAS	Pb, Cd, Hg, Cu, and other toxic metals	Špirić et al. (2012)
Pinus halepensis (Miller) (bark, cones)	Gymnosperms (bark and cones)	Portugal (Lisbon Botanical Garden)	2	Analysis of Pb and Ni in plant tissues and atmospheric deposition	Pb, Ni	Reboredo et al. (2012)
Fabronia ciliaris (epiphytic moss)	Bryophytes	Mexico (Toluca Valley)	13	Total Reflection X-Ray Fluorescence (TXRF) technique	K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Rb, Sr, Pb	Zarazúa-Ortega et al. (2013)
Homolothecium lutescens, Hypnum cupressiforme	Bryophytes	North Macedonia	41	ENAA, AAS	Pb, Cd, Hg, Ni, Cr, etc.	Barandovski et al. (2012)
Hypnum plumaeforme, Taxithelium instratum	Bryophytes	Malaysia (Kerteh Terengganu)	11	EDXRFA	V, Cr, Cu, Hg, and other trace metals related to petroleum refinery emissions	Bin Abdullah et al. (2012)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hypnum cupressiforme, Xanthoria parietina	Bryophytes	Spain (Prades Mountains)	12	Enrichment factor, biomonitoring	Al, As, Cd, Co, Cu, Cr, Ni, Pb, Sb, Ti, V, Zn	Achotegui-Castells et al. (2013)
Lichens (*Hypogymnia physodes*) and mosses (*Pleurozium schreberi*)	Bryophytes and lichens	Poland (village area)	7	AAS, GC, IC, biomonitoring	Mn, Zn, Pb, Ni, Cd, Cu, and gaseous pollutants (SO_2, NO_2, C_6H_6)	Olszowski et al. (2012)
Xanthoria parietina	Lichens	Turkey (Kocaeli)	14	XRF, biomonitoring	Al, As, Co, Cd, Cu, Fe, Hg, Mn, Ni, Pb, Ti, Tl, V, Zn	Doğrul Demiray et al. (2012)
Hypnum cupressiforme	Bryophytes	Albania (Elbasan)	10	AAS, CVAAS, AES, biomonitoring	Cu, Pb, Cd, Zn, Cr, Mn, Ni, Co, Fe, Hg	Lazo et al. (2013)
Tree bark (*Quercus* spp.), moss (*Hypnum cupressiforme*)	Angiosperms (bark) and bryophytes	Romania	13	ICP-MS, Principal Component Analysis (PCA)	V, Cr, Ni, Cu, Zn, As, Mo, Cd, In, Tl, Sn, Pb, Bi	Cucu-Man and Steinnes (2013)
Hypnum cupressiforme, Campothecium lutescens, Homolothecium sericium	Bryophytes	North Macedonia	46	ICP-MS	Ag, Al, As, Au, Ba, Be, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hg, Ho, K, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Rb, Sb, Sm, Sr, Tb, Th, Ti, U, V, Yb, Zn, Zr	Bačeva et al. (2012)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Thuidium tomentosum Besch., *Sematophyllum subpinnatum* (Brid.) E. Britton, *Helicodontium capillare* (Hedw.) A. Jaeger, *Schlotheimia jamesonii* (W.-Arnott) Brid., and *Meteorium deppei* (Hornsch. ex Müll. Hal.) Mitt.	Bryophytes	Brazil	6	AAS	Zn, Ni, Cd, Cr, Cu, Pb	Mazzoni et al. (2012)
Moss, soil	Bryophytes	Turkey	10	EDXRFA	Al, V, Cr, Mn, Fe, Ni, Cu, Zn, Hg, Pb	Koz et al. (2013)
Hypnum cupressiforme, *Homalothecium lutescens* (Hedw.) Robins., *Lencodon scinroides* (Hedw.) Schwaegr., *Brachythecium salebrosum* (Web & Mohr.) B. S. & G., *Scleropodium purum* (Hedw.) Limpr., *Homalothecium sericeum* (Hedw.) B. S. & G., *Brachythecium albicans* (Hedw.) B. S. & G., and *Brachythecium glareosum* (Spruce) B. S. & G.	Bryophytes	North Macedonia	53	ICP-MS, ICP-AES, cluster and factor analysis	Co, Cr, Fe, Sc, Li, V, Ga, Y, Ni, Mn, Al, La–Lu, Cu, Ge, Be, Bi, Hf, As, Tl, Sb, Mg, Rb, Cs, Mo, Sr, Ba, Hf, Zr, Bi, Cd, Zn, Ag, Cu	Bačeva et al. (2013)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Pseudoscleropodium purum	Bryophytes	Not specified	5	Reciprocal transplantation, monitoring concentrations	Cd, Cu, Hg, Pb, Zn	Boquete et al. (2015)
Dandelion (*Taraxacum officinale*)	Angiosperms	Czech Republic	3	AAS	Cd, Hg, Pb	Boquete et al. (2014)
Padus serotina, *Acer campestre*, *A. negundo*, *Quercus robur*, *Celtis occidentalis*	Angiosperms	Hungary	9	ICP-OES, SEM	Ba, Cu, Fe, Mn, Ni, Pb, S, Sr, Zn	Simon et al. (2014)
Hypnum cupressiforme	Bryophytes	Albania	11	Microwave digestion, ICP-AES, AAS, normalization	As, Cr, Cu, Ni, V, Zn, Al, Li, Fe, Cd, As	Bekteshi et al. (2015)
Spinach (*Spinacia oleracea* L.), kale (*Brassica oleracea* L.)	Angiosperms	Netherlands	Multiple	Biomonitoring over several years	Heavy metals, PAHs, dioxins/PCBs	van Dijk et al. (2015)
Moss (various species)	Bryophytes	Europe	Multiple	Biomonitoring, literature review, policy development	Ozone, nitrogen, Persistent Organic Pollutants (POPs), heavy metals	Harmens, Mills, et al. (2015)
Pseudoscleropodium purum	Bryophytes	Spain	Multiple	Factor analysis, biomonitoring	Heavy metals and metalloids (Cd, Pb, etc.)	Varela et al. (2015)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Moss (various species)	Bryophytes	Norway	3	Multivariate regression-kriging, generalized linear models, geostatistics	Cd, Hg, Pb	Nickel et al. (2014)
Homolothecium lutescens, *Hypnum cupressiforme*	Bryophytes	North Macedonia	47 elements (including Pb, Zn)	NAA, AAS, PCA	Pb, Zn, etc.	Barandovski et al. (2015)
Pseudoscleropodium purum	Bryophytes	Spain	5	Biomonitoring, growth measurement, concentration analysis	Cd, Cu, Hg, Pb, Zn	Boquete et al. (2014)
Plane tree (*Platanus orientalis* L.)	Angiosperms	Iran (Isfahan)	6	Dust sampling, metal concentration determination in leaves	Cu, Fe, Mn, Ni, Pb, Zn	Norouzi et al. (2015)
Moss samples	Bryophytes	Serbia (Bor)	1	Biomonitoring by moss, metal concentration analysis	S	Šerbula et al. (2015)
Moss (*Pseudoscleropodium purum*)	Bryophytes	Multiple sites (21 locations)	Trace metals (12)	Correlation with bulk deposition	Al, Fe, As, Cd, Cr, Cu, Ni, Mn, Pb, V, Zn, Li	Boquete et al. (2015)
Moss (*Hypnum cupressiforme*)	Bryophytes	Albania	12	Microwave digestion, ICP-AES, AAS	Al, Fe, As, Cd, Cr, Cu, Ni, Mn, Pb, V, Zn, Li	Qarri et al. (2015)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Pleurozium schreberi (Brid.) Mitt, *Hylocomium splendens* (Hedw.), *Hypnum cupressiforme* Hedw., *Pseudoscleropodium purum*, and other moss species	Bryophytes	Europe (multiple regions)	Multiple (varies by region)	Moss survey, comparison across regions	Pb, V, Cd, Cr, Zn, Ni, Fe, As, Hg, Cu	Harmens, Norris, et al. (2015)
Hypnum cupressiforme	Bryophytes	Albania	19	ICP-AES	Pb, Cd, As, Cu, Al, Cr, Ni, Fe, V, etc.	Qarri, Lazo, Stafilov, Frontasyeva, et al. (2014)
Moss species, including *Hypnum cupressiforme* and *Homalothecium lutescens*	Bryophytes	North Macedonia	60	ICP-MS, ICP-AES	As, Cd, Cu, Hg, Pb, Zn, etc.	Dimovska et al. (2014)
Hylocomium splendens, *Pleurozium schreberi*, and *Hypnum cupressiforme*	Bryophytes	Caucasus Mountains	23	NAA	Na, Mg, Al, Cl, K, Ca, Ti, V, Mn, Fe, Zn, As, Cd, I, Sb, Ba, La, Sm, W, Au, U	Shetekauri et al. (2015)
Hypnum cupressiforme	Bryophytes	Albania	6	ICP-AES	Al, Cr, Fe, Ni, V, Zn	Qarri, Lazo, Stafilov, Bekteshi, et al. (2014)
Sphagnum sp.	Bryophytes	Italy (Mt. Etna)	49	ICP-MS, ICP-OES	S, Tl, Bi, Se, Cd, As, Cu, B, Na, Fe, Al, etc.	Calabrese et al. (2015)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hylocomium splendens (Hedw.) Schimp	Bryophytes	Norway	Multiple (at least 7)	Statistical analysis of moss and soil samples, classification and regression trees	Pb, Cd, Zn, Cu, Ni, etc.	Meyer et al. (2015)
Pseudocleropodium purum, Hypnum cupressiforme	Bryophytes	Kosovo	9	AAS for metal detection, GIS for mapping	Cd, Cr, Cu, Fe, Hg, Ni, Mn, Pb, Zn	Maxhuni et al. (2016)
Hypnum cupressiforme	Bryophytes	Italy	13	ICP-OES	As, Ca, Cd, Cr, Cu, Fe, K, Mg, Na, Ni, Pb, V, Zn	Cortis et al. (2016)
Pleurochaete squarrosa, Hypnum cupressiforme	Bryophytes	Spain (Navarra)	14	Enrichment factor (EF) approach, N isotopic signatures, comparison of metal uptake patterns	N, Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sb, Ti, Zn	Izquieta-Rojano et al. (2016)
Phaeophyscia hispidula, *P. primaria*, and *P. constipate*	Bryophytes	India (Himalayas)	4	Analysis of lichenized fungi for heavy metal deposition	Fe, Zn, Cu, Ni	Gupta et al. (2017)
Moss bags of *Hypnum cupressiforme* Hedw.	Bryophytes	Italy (Campania)	39 elements (including rare earths and PAHs)	Active biomonitoring	Metals, metalloids, PAHs	Capozzi et al. (2016)
Moss transplants of *Pseudoscleropodium purum*	Bryophytes	Spain (steelworks)	5	Active biomonitoring	Cd, Cu, Hg, Pb, Zn	Ares et al. (2015)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Oxyrrhynchium hians, *Eurhynchium angustirete*, *Orthotrichum speciosum*, *Brachythecium rutabulum*, *Atrichum undulatum*, *Brachythecium salebrosum*, *Abietinella abietina*, *Rhytidiadelphus triquetrus*, *Cirriphyllum piliferum*, *Pleurozium scheberi*	Bryophytes	Russia (Tula Region)	Multiple	ENAA	V, Fe, Zn, As, Cd, Cr, Pb, etc.	Gorelova et al. (2016)
Epiphytic plants (*Tillandsia* genus)	Angiosperms	Paraguay (Asunción)	3	Biomonitoring of air pollution	Pb, Hg, Cd	Sánchez-Chardi (2016)
Lichens (*Hypogymnia physodes*, *Parmelia sulcata*, *Flavoparmelia caperata*, *Parmelina tiliacea*, *Punctelia borreri*, *Hypotrachyna revoluta*, *Xanthoria parietina*, *Evernia prunastri*, *Pseudevernia furfuracea*, *Usnea* sp.) and mosses (*Hypnum cupressiforme*, *Pleurozium schreberi*, *Scleropodium purum*)	Lichens and bryophytes	France	17 metals/ metalloids	Biomonitoring	Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Zn, etc.	Agnan et al. (2015)
Fabriona ciliaris, *Leskea angustata*	Bryophytes	Mexico (Toluca Valley)	4	Metal concentration analysis (ICP-MS)	Zn, Pb, Cr, Cd	Macedo-Miranda et al. (2016)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Haplocladium microphyllum, H. angustifolium	—	China (Wuxi)	6	Metal concentration analysis, GIS	Cd, Cr, Cu, Ni, Pb, Zn	Yan et al. (2016)
Brassica oleracea var. *acephala* (collard greens), *Spinacia oleracea* (spinach), *Tillandsia usneoides*	Angiosperms	Brazil (Sao Paulo)	4	ICP-MS, PCA, GLMs	As, Cd, Cr, Pb	Amato-Lourenco et al. (2016)
Angiosperms (*Salix rehderiana*, *Populus purdomii*, *Betula albosinensis*), Gymnosperms (*Abies fabri*, *Picea brachytyla*), and mosses (*Pleurozium schreberi*, *Papillaria crocea*)	Angiosperms, gymno-sperms, and bryophytes	China (Eastern Tibetan Plateau)	6	Metal concentration analysis, Pb isotopic ratios	Cd, Cr, Cu, Ni, Pb, Zn	Bing et al. (2016)
Hypnum cupressiforme, Homolothecium lutescens	Bryophytes	North Macedonia (Bregalnica River basin)	7	ICP-AES, ICP-MS, PCA, FA, CA	Pb, Zn, Cu, and other elements from human activities	Balabanova et al. (2016)
Terrestrial moss, e.g., *Camptothecium lutescens, Hypnum cupresifforme, Scleropodium purum, Hylocomium splendens, Homalothecium lutescens, Lencodon scindroides*	Bryophytes	North Macedonia	22	ICP-AES, AAS	Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Rb, Sr, V, Zn	Stafilov et al. (2018)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hylocomium splendens (Hedw.) (Schimp.), *Pleurozium schreberi* (Mitt.) (Brid.), and *Hypnum cupressiforme* (Hedw.)	Bryophytes	Georgia	47	ENAA, SEM-EDX	Various (including clastic, anthropogenic, cosmic dust)	Shetekauri et al. (2018)
Chicken eggshell	Bird (eggshell)	India	5	Fine particulate sampler	Cd, As, Pb, Zn, Fe	Subpiramaniyam et al. (2018)
Hypnum cupressiforme, Pseudoschleropodium purum	Bryophytes	Albania	9	ICP-AES, ENAA	Cd, Cr, Co, Cu, Hg, Ni, Pb, Zn, As	Allajbeu et al. (2017)
Hypnum cupressiforme, Hylocomium splendens, Pleurozium schreberi	Bryophytes	Romania	9	AAS, NAA	Al, Cd, Cr, Cu, Fe, Pb, Ni, V, Zn	Stihi et al. (2017)
Evernia prunastri	Lichens	Slovakia (SW)	15	Transplantation of lichens and analysis of elements in various locations	Al, As, Ca, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, S, Ti, V, Zn	Paoli et al. (2017)
Moss samples	Bryophytes	Turkey (Istanbul)	12	ICP-ES for metal analysis and radionuclide activity measurements	Al, As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, Sb, V, Zn	Erenturk and Haciyakupoglu (2018)
Pleurozium schreberi, Hypnum cupressiforme, Pseudoscleropodium purum	Bryophytes	Europe (Germany focused)	Multiple	Statistical analysis of biomonitoring data and model calculations	Not specified	Nickel and Schröder (2017c)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hypnum cupressiforme, Pleurozium schreberi, and *Scleropodium purum*	Bryophytes	Germany	Multiple	Deposition modeling and biomonitoring network data	Cd, Pb, etc.	Nickel and Schröder (2017a)
Physcia adscendens	Lichens	Turkey (Istanbul)	10	Lichen biomonitoring, spatial distribution mapping	Al, As, Cd, Cr, Fe, Mn, Ni, Pb, V, Zn	Kurnaz and Cobanoglu (2017)
Moss (*Hypnum cupressiforme, Pleurozium schreberi, Scleropodium purum*), angiosperms (*Fagus sylvatica, Populus nigra*), gymnosperms (*Picea abies, Pinus sylvestris*)	Bryophytes, gymnosperms, and angiosperms	Germany, Europe	5	Modeling (LOTOS-EUROS), biomonitoring (moss survey)	Cd, Pb, etc.	Nickel and Schröder (2017b)
Pseudevernia furfuracea	Lichens	Italy	40	ICP-MS, multivariate analysis	Hg, P, Mg, Zn, etc.	Incerti et al. (2017)
Moss (*Hypnum cupressiforme, Pleurozium schreberi, Scleropodium purum*), angiosperms (*Fagus sylvatica, Populus nigra*), gymnosperms (*Picea abies, Pinus sylvestris*)	Bryophytes, gymnosperms, and angiosperms	Europe (multiple countries)	2	Geostatistical analysis, biomonitoring (moss)	Cd, Pb	Schröder et al. (2017)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Aesculus hippocastanum	Angiosperms	Bulgaria	7	Phytomonitoring (leaf analysis)	Pb, toxic elements	Chonova et al. (2019)
Hylocomium splendens	Bryophytes	Canada	13	Moss biomonitoring, ICP-OES	Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Pb	Cowden and Aherne (2019a)
Hypnum cupressiforme	Bryophytes	Albania	10	Moss biomonitoring, ICP-AES, ETAAS, CVAAS	Cr, Cu, Fe, Ni, Pb, V, Zn, As, Cd, Hg	Qarri et al. (2019)
Hylocomium splendens, Pleurozium schreberi, Isothecium stoloniferum	Bryophytes	Canada	13	Moss biomonitoring, ICP-OES	Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Pb	Cowden and Aherne (2019b)
Haplocladium angustifolium	Bryophytes	China	10	Moss biomonitoring, ICP-MS	As, Cd, Co, Cr, Cu, Mn, Ni, V, Pb, Zn	Jiang et al. (2020)
Achillea wilhelmsii, Cardaria draba	Angiosperms	Iran	5	Soil and plant sample analysis along highways	Cd, Cu, Pb, Ni, Zn	Hosseini et al. (2020)
Evernia prunastri (L.)	Lichens (transplants used)	Not specified	Multiple	Atmospheric deposition via lichen transplants	Not specified, focuses on assessment method	Loppi et al. (2019)
Pseudoscleropodium purum, Sphagnum denticulatum	Bryophytes	Spain	3	Analysis of moss tissues and bulk deposition	Cd, Hg, Pb	Boquete et al. (2020)
Arctic char (*Salvelinus alpinus*)	Fish	Canada (Cornwallis Island, Nunavut)	1	Mercury concentrations in muscle tissue	Hg	Hudelson et al. (2019)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Pleurozium schreberi	Bryophytes	Poland	5	Moss biomonitoring for atmospheric deposition	Cd, Pb, Fe, Cu, Zn	Kapusta et al. (2019)
Hypnum cupressiforme, Homalothecium lutescens, H. sericeum	Bryophytes	North Macedonia	41	NAA, AAS, ICP-AES	Geogenic (e.g., Al, Fe, Cr), anthropogenic (e.g., Cd, Pb, Zn, Ni)	Barandovski et al. (2020)
Pleurosium shreberi	Bryophytes	Russia (Vladimir, Yaroslavl)	30+	NAA, AAS	As, Sb, Pb, V, Cd, W, Fe, Cr, Ni, Co, etc. (anthropogenic sources)	Vergel et al. (2020)
Hylocomium splendens, Hypnum cupressiforme, Pleurozium schreberi	Bryophytes	Georgia	41	INAA, AAS	Geogenic (e.g., Th, Zr), anthropogenic (e.g., As, Cd)	Chaligava et al. (2021)
Hypnum cupressiforme	Bryophytes	Bulgaria	34+	NAA, AAS, ICP-AES	Pb, Cd, Cu, etc. (transport, industry sources)	Hristozova et al. (2020)
Hyophila involuta	Bryophytes	Sri Lanka	7	AAS	Fe, Zn, Cu, Pb, Ni, Cr, Cd (petroleum-based sources)	Jayalath et al. (2021)
Haplocladium microphyllum	Bryophytes	China (Yancheng, Jiangsu Province)	7	Positive Matrix Factorization (PMF), Pb isotopic ratios	Cd, Cr, Pb, Zn, V, Ni, Cu	Zhou et al. (2021)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Hypnum cupressiforme, Brachythecium rutabulum, Hylocomium splendens, Cirriphyllum piliferum, Calliergonella cuspidata, Rhytidiadelphus squarrosus, Atrichum undulatum, Eurhinchium hians	Bryophytes	Czech Republic (Moravian-Silesian Region) and Poland (Silesian Voivodship)	38	INAA, statistical analysis (PCA, factor analysis)	Sm, W, U, Tb, Th (anthropogenic emissions), various elements related to natural background and anthropogenic activity	Krakovská et al. (2020)
Hypnum cupressiforme Hedw., *Pleurozium schreberi*	Bryophytes	Switzerland	4	Statistical estimation (moss survey)	Cd, Cu, Pb, Zn	Loppi et al. (2021)
Cedrus atlantica	Gymnosperms	Turkey (Kastamonu)	2	Analysis of atmospheric deposition in tree rings	Pb, Cd	Isinkaralar (2022)
Chamaecyparis lawsoniana	Gymnosperms	Turkey (Urban parks)	3	Comparison of heavy metal accumulation in leaves	Cr, Cd, Zn	Isinkaralar et al. (2022)
Pleurozium schreberi	Bryophytes	Azerbaijan	44	NAA	Na, Mg, Al, Si, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, Rb, Sr, Mo, Ag, Cd, In, Sb, I, Cs, Ba, La, Ce, Nd, Sm, Eu, Tb, Tm, Yb, Hf, Ta, W, Au, Th, U	Madadzada et al. (2022)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Pleurozium shreberi	Bryophytes	Crimea (Crimean Mountains)	34	NAA	Na, Mg, Al, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, As, Se, Br, Rb, Sr, Sb, I, Cs, Ba, La, Ce, Nd, Sm, Eu, Tb, Yb, Ta, Th, U	Nekhoroshkov et al. (2022)
Racomitrium lanuginosum	Bryophytes	Japan (mountainous areas)	4	Trace metal analysis (Pb isotope ratios)	Pb, Zn, As, V	Oishi (2022)
Pleurozium schreberi, Sphagnum fallax, Dicranum polysetum	Bryophytes	Urban area (unspecified)	7	Moss-bag method, vitality parameter (photosystem II)	Cu, Zn, Cd, Pb, Mn, Fe, Hg	Świsłowski et al. (2022)
Atrichum angustatum	Bryophytes	India (Brahmaputra Valley)	5	Biomonitoring using moss, PCA	Cr, Zn, Cu, Ni, Pb	Hussain and Hoque (2022)
Homalothecium sericeum, Hypnum cupressiforme, Pseudoscleropodium purum	Bryophytes	Kosovo	8	Statistical analysis, Contamination Factor (CF), Pollution Load Index (PLI)	Al, Cd, Cr, Cu, Fe, Ni, Pb, Zn	Sopaj et al. (2022)
Camptothecium lutescens, Hypnum cupressiforme, Homalothecium sericeum, Sceropodium purum, Plagiothecium silvaticum, Hylocomium splendens	Bryophytes	North Macedonia	51	ICP-AES, ICP-MS, R-mode factor analysis	As, Co, Cr, Fe, K, Li, Mg, Ni, Pb, Ti, Zn, etc.	Stafilov et al. (2022)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Taxiphyllum taxirameum	Bryophytes	China (Xichang)	Multiple (22 sampling sites)	Biomonitoring using moss bags, seasonal analysis	Various heavy metals (no specific list)	Mao et al. (2022)
Hypnum cupressiforme	Bryophytes	Albania	3	Geochemical normalization, factor analysis	Co, Cr, Ni	Qarri et al. (2023)
Cinnamomum camphora (tree leaf and ring)	Angiosperms	China (near Cu smelter)	2	Atmospheric deposition monitoring, spatial analysis	Cu, Cd	Cui et al. (2023)
Saxicolous lichens (*Umbilicaria phaea*, *Rhizoplaca melanophthalma*, *Letharia vulpina*)	Lichens	USA (Southern Sierra Nevada, San Bernardino Mountains)	23 elements (including N, S)	PCA, cluster analysis	N, S, etc.	Kovasi et al. (2022)
Haplocladium microphyllum	Bryophytes	China (Huai'an)	12	Nemerow index, ecological risk index, PMF model	Al, Fe, Zn, Mn, Ba, Cu, V, Cr, Pb, Ni, Co, Cd	Zhou et al. (2023)
Tawny owl (*Strix aluco*) feathers	Bird (feathers)	Norway	5 toxics (Al, As, Cd, Hg, Pb), 5 essential/beneficial (B, Co, Cu, Mn, Se)	Elemental concentrations in feathers	Al, As, Cd, Hg, Pb, B, Co, Cu, Mn, Se	Devalloir et al. (2023)
Mosses, including *Hypnum plumaeforme* Wilson, *Abietinella abietina* (Hedw.) M. Fleisch., and *Hylocomium splendens* (Hedw.) Schimp	Bryophytes	China (Qinghai-Tibet Plateau)	4	Concentration measurement in mosses, spatial distribution	Zn, Pb, Cd, Cu	Lv et al. (2023)

Continuation of Table S1.

Species	Group of organisms	Countries studied	Number of heavy metals detected	Methods of heavy metal analysis	Types of heavy metals detected	Reference
Pleurozium schreberi, *Ptilium crista-castrensis*	Bryophytes	Canada (Quebec)	18 elements	Sampling and statistical analysis	Various elements, including metals	Michel et al. (2024)
Hypnum cupressiforme	Bryophytes	Karabük, Turkey	6	ICP-MS	Cr, Cu, Cd, Ni, Pb, Co	Isinkaralar O. et al. (2024)
Pleurozium schreberi (Brid.) Mitt.	Bryophytes	Southwestern Europe	Multiple	Enrichment Rate (ER)	Ni, Pb, Zn	Vázquez-Arias et al. (2024)
Evernia mesomorpha	Lichens	Tangshan, China	49	ICP	Ag, Al, As, Cd, Co, Cr, Cu, Fe, Li, Mg, Mn, Mo, Ni, Pb, Sb, Se, Sn, Sr, Ti, Zn, etc.	Lin et al. (2024)
Echeveria elegans	Angiosperms	Mexico (semiurban soils)	Multiple	XRF, gamma spectrometry	Metals, radionuclides	Ortiz-Oliveros et al. (2024)
Pinus pinaster, *Cupressus arizonica*, *Picea orientalis*, *Cedrus atlantica*, *Pseudotsuga menziesii*	Gymnosperms	Unknown	1	Analysis of bismuth accumulation in tree species	Bi	Isinkaralar K., Isinkaralar O., Koç İ., et al. (2024)
Picea orientalis, *Cedrus atlantica*, *Pinus pinaster*, *Cupressus arizonica*, *Pseudotsuga menziesii*	Gymnosperms	Unknown	4	Biomonitoring of atmospheric pollution	Cu, Mn, Ni, Zn	Isinkaralar K., Isinkaralar O., Koc I., et al. (2024)

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Table S2. Most-cited countries in atmospheric heavy metal studies.

Country	Total citations	Average article citations
China	20 681	42.10
USA	3782	51.80
United Kingdom	3471	102.10
France	2898	76.30
Italy	1840	40.90
Spain	1724	44.20
India	1594	37.10
Germany	1469	28.80
Australia	1413	58.90
Norway	1241	82.70
Sweden	1168	77.90
Belgium	1027	68.50
Canada	1002	33.40
Poland	949	25.60
Czech Republic	795	49.70
Switzerland	702	63.80
Finland	638	45.60
Turkey	612	23.50
Japan	594	49.50
Jordan	521	104.20
Argentina	451	90.20
New Zealand	430	61.40
Hong Kong	421	140.30
Croatia	419	139.70
Austria	418	46.40
Serbia	399	44.30
Iran	390	21.70
Hungary	338	42.20
North Macedonia	298	27.10
Chile	292	48.70
Albania	242	22.00
Bangladesh	235	47.00
Netherlands	208	29.70
Sri Lanka	187	37.40
Korea	169	16.90
Lithuania	164	54.70
Pakistan	152	19.00
Slovakia	152	12.70
Denmark	144	24.00
Greece	144	24.00
Mexico	135	16.90
Brazil	129	12.90
Saudi Arabia	120	24.00
Slovenia	113	22.60

Continuation of Table S2.

Country	Total citations	Average article citations
Portugal	112	18.70
Ireland	104	20.80
South Africa	99	14.10
Romania	87	8.70
Ghana	86	28.70
Kuwait	69	69.00
Singapore	61	30.50
Malaysia	57	11.40
Cyprus	48	48.00
Bulgaria	45	6.40
Morocco	40	40.00
Nigeria	40	4.00
Monaco	37	37.00
Tunisia	37	37.00
Latvia	34	11.30
Iraq	33	16.50
Egypt	31	10.30
Syria	28	28.00
Kazakhstan	27	27.00
Algeria	26	8.70
Israel	25	25.00
Vietnam	18	9.00
Colombia	15	5.00
Thailand	14	4.70
Zimbabwe	9	9.00
Estonia	8	8.00
United Arab Emirates	6	6.00
Belarus	4	4.00
Bosnia	4	4.00
Peru	4	4.00
Azerbaijan	3	3.00
Georgia	1	0.50
Ethiopia	0	0.00

Table S3. Collaboration between countries based on publication frequency.

From	To	Frequency
China	USA	38
North Macedonia	Slovenia	21
Germany	Norway	17
Albania	North Macedonia	14
Norway	Austria	14
United Kingdom	Sweden	14
Romania	Slovenia	13
United Kingdom	Norway	13
China	Australia	12
China	Canada	12
France	Belgium	12
France	Switzerland	12
Germany	Belgium	12
Italy	France	12
Italy	Germany	12
Italy	United Kingdom	12
Norway	Sweden	12
Spain	France	12
USA	Canada	12
Czech Republic	Slovakia	11
France	Austria	11
France	Norway	11
Germany	Austria	11
Italy	Switzerland	11
Norway	Belgium	11
Norway	Finland	11
Poland	Norway	11
Romania	North Macedonia	11
United Kingdom	Czech Republic	11
United Kingdom	Germany	11
United Kingdom	North Macedonia	11
United Kingdom	Poland	11
Austria	Slovenia	10
Belgium	Austria	10
China	Germany	10
China	Hong Kong	10
Finland	Switzerland	10
France	Poland	10
Germany	Finland	10
Germany	Poland	10
Italy	Slovakia	10
North Macedonia	Croatia	10
Norway	North Macedonia	10
Poland	Austria	10
Poland	Finland	10
Spain	Italy	10

Continuation of Table S3.

From	To	Frequency
Spain	Norway	10
Spain	Poland	10
Sweden	Finland	10
United Kingdom	Estonia	10
United Kingdom	Switzerland	10
Austria	Estonia	9
Austria	Slovakia	9
Belgium	Estonia	9
Belgium	Finland	9
Belgium	Slovakia	9
Belgium	Slovenia	9
China	Korea	9
Czech Republic	Austria	9
Czech Republic	Estonia	9
Finland	Austria	9
Finland	Estonia	9
Finland	Slovakia	9
Finland	Slovenia	9
France	Estonia	9
France	Finland	9
France	Slovakia	9
France	Slovenia	9
Germany	Slovakia	9
Germany	Switzerland	9
Italy	Austria	9
Italy	Norway	9
Italy	Sweden	9
Norway	Croatia	9
Norway	Estonia	9
Norway	Romania	9
Norway	Slovakia	9
Norway	Slovenia	9
Poland	Belgium	9
Poland	Czech Republic	9
Poland	Estonia	9
Poland	Slovakia	9
Poland	Slovenia	9
Slovakia	Estonia	9
Slovakia	Slovenia	9
Slovenia	Croatia	9
Slovenia	Estonia	9
Spain	Austria	9
Spain	Belgium	9
Spain	Estonia	9
Spain	Finland	9
Spain	Slovakia	9

Continuation of Table S3.

From	To	Frequency
Spain	Slovenia	9
Spain	United Kingdom	9
Sweden	Austria	9
Sweden	Switzerland	9
United Kingdom	Albania	9
United Kingdom	Austria	9
United Kingdom	Belgium	9
United Kingdom	Finland	9
United Kingdom	France	9
United Kingdom	Slovakia	9
United Kingdom	Slovenia	9
Austria	Croatia	8
Austria	Iceland	8
Austria	North Macedonia	8
Austria	Ukraine	8
Belgium	Croatia	8
Belgium	Iceland	8
Belgium	North Macedonia	8
Belgium	Switzerland	8
Belgium	Ukraine	8
China	Pakistan	8
Czech Republic	Belgium	8
Czech Republic	Finland	8
Czech Republic	Slovenia	8
Czech Republic	Ukraine	8
Estonia	Croatia	8
Estonia	Iceland	8
Estonia	Ukraine	8
Finland	Croatia	8
Finland	Iceland	8
Finland	North Macedonia	8
Finland	Ukraine	8
France	Croatia	8
France	Czech Republic	8
France	Germany	8
France	Iceland	8
France	North Macedonia	8
France	Sweden	8
France	Ukraine	8
Germany	Estonia	8
Germany	Netherlands	8
Germany	Slovenia	8
Germany	Sweden	8
Italy	Belgium	8
Italy	Estonia	8
Italy	Finland	8
Italy	Iceland	8
Italy	Poland	8

Continuation of Table S3.

From	To	Frequency
Italy	Slovenia	8
North Macedonia	Estonia	8
Norway	Czech Republic	8
Norway	Iceland	8
Norway	Switzerland	8
Norway	Ukraine	8
Poland	Croatia	8
Poland	Iceland	8
Poland	North Macedonia	8
Poland	Netherlands	8
Poland	Sweden	8
Poland	Switzerland	8
Poland	Ukraine	8
Slovakia	Croatia	8
Slovakia	Iceland	8
Slovakia	North Macedonia	8
Slovakia	Ukraine	8
Slovenia	Iceland	8
Slovenia	Ukraine	8
Spain	Croatia	8
Spain	Czech Republic	8
Spain	Germany	8
Spain	Iceland	8
Spain	North Macedonia	8
Spain	Sweden	8
Spain	Switzerland	8
Spain	Ukraine	8
Sweden	Belgium	8
Sweden	Czech Republic	8
Sweden	Estonia	8
Sweden	Iceland	8
Sweden	Slovakia	8
Sweden	Slovenia	8
Switzerland	Austria	8
Switzerland	Estonia	8
Switzerland	Iceland	8
Switzerland	Slovakia	8
Switzerland	Slovenia	8
Switzerland	Ukraine	8
United Kingdom	Croatia	8
United Kingdom	Iceland	8
United Kingdom	Ukraine	8
Austria	Belarus	7
Austria	Bulgaria	7
Belarus	Iceland	7
Belgium	Belarus	7
Belgium	Netherlands	7
China	Japan	7

Continuation of Table S3.

From	To	Frequency
China	United Kingdom	7
Croatia	Iceland	7
Croatia	Ukraine	7
Czech Republic	Croatia	7
Czech Republic	Iceland	7
Czech Republic	North Macedonia	7
Czech Republic	Switzerland	7
Estonia	Belarus	7
Finland	Belarus	7
France	Belarus	7
Germany	Croatia	7
Germany	Czech Republic	7
Germany	Iceland	7
Germany	North Macedonia	7
Germany	Ukraine	7
Italy	Belarus	7
Italy	Croatia	7
Italy	Czech Republic	7
Italy	North Macedonia	7
Italy	Ukraine	7
North Macedonia	Iceland	7
North Macedonia	Ukraine	7
Norway	Belarus	7
Poland	Belarus	7
Romania	Austria	7
Romania	Czech Republic	7
Slovakia	Belarus	7
Slovenia	Belarus	7
Spain	Belarus	7
Sweden	Belarus	7
Sweden	Croatia	7
Sweden	North Macedonia	7
Sweden	Ukraine	7
Switzerland	Belarus	7
Switzerland	Bulgaria	7
Switzerland	Croatia	7
Switzerland	North Macedonia	7
Ukraine	Iceland	7
United Kingdom	Belarus	7
Albania	Croatia	6
Albania	Slovenia	6
Belarus	Ukraine	6
Belgium	Albania	6
Croatia	Belarus	6
Czech Republic	Belarus	6
Czech Republic	Bulgaria	6
France	Romania	6
Germany	Belarus	6

Continuation of Table S3.

From	To	Frequency
Germany	Romania	6
Italy	Romania	6
North Macedonia	Belarus	6
Norway	Albania	6
Norway	Bulgaria	6
Poland	Lithuania	6
Poland	Romania	6
Romania	Belgium	6
Romania	Estonia	6
Romania	Finland	6
Romania	Slovakia	6
Serbia	North Macedonia	6
Serbia	Slovenia	6
Slovenia	Bulgaria	6
Spain	Romania	6
Turkey	Bulgaria	6
United Kingdom	Bulgaria	6
United Kingdom	Romania	6
USA	France	6
Albania	Estonia	5
Austria	Albania	5
Belgium	Bulgaria	5
Belgium	Serbia	5
Bulgaria	Estonia	5
Bulgaria	Iceland	5
Bulgaria	Ukraine	5
China	France	5
Czech Republic	Lithuania	5
Egypt	Saudi Arabia	5
Finland	Albania	5
Finland	Bulgaria	5
Finland	Lithuania	5
France	Albania	5
France	Bulgaria	5
Germany	Bulgaria	5
Italy	Bulgaria	5
Netherlands	Austria	5
Norway	Lithuania	5
Norway	Turkey	5
Poland	Albania	5
Poland	Bulgaria	5
Poland	Turkey	5
Romania	Albania	5
Romania	Belarus	5
Romania	Croatia	5
Romania	Iceland	5
Romania	Sweden	5
Romania	Switzerland	5

Continuation of Table S3.

From	To	Frequency
Romania	Ukraine	5
Slovakia	Albania	5
Slovakia	Bulgaria	5
Spain	Albania	5
Spain	Bulgaria	5
Sweden	Bulgaria	5
Sweden	Lithuania	5
Turkey	Austria	5
United Kingdom	Serbia	5
USA	Austria	5
USA	Italy	5
Albania	Belarus	4
Albania	Iceland	4
Albania	Ukraine	4
Austria	Latvia	4
Austria	Lithuania	4
Austria	Serbia	4
Belgium	Latvia	4
Belgium	Lithuania	4
Bulgaria	Belarus	4
Bulgaria	Croatia	4
Bulgaria	Latvia	4
Bulgaria	Lithuania	4
China	Egypt	4
Czech Republic	Albania	4
Czech Republic	Latvia	4
Czech Republic	Serbia	4
Czech Republic	Turkey	4
Estonia	Latvia	4
Estonia	Lithuania	4
Finland	Latvia	4
Finland	Serbia	4
France	Denmark	4
France	Korea	4
France	Latvia	4
France	Lithuania	4
France	Serbia	4
France	Turkey	4
Germany	Albania	4
Germany	Latvia	4
Germany	Lithuania	4
Germany	Serbia	4
Germany	Turkey	4
Italy	Albania	4
Italy	Canada	4
Italy	Latvia	4
Italy	Lithuania	4
Italy	Serbia	4

Continuation of Table S3.

From	To	Frequency
Italy	Turkey	4
Latvia	Iceland	4
Latvia	Ukraine	4
Lithuania	Iceland	4
Lithuania	Latvia	4
Lithuania	Ukraine	4
North Macedonia	Bulgaria	4
Norway	Latvia	4
Norway	Netherlands	4
Norway	Serbia	4
Pakistan	Saudi Arabia	4
Poland	Denmark	4
Poland	Latvia	4
Poland	Serbia	4
Romania	Bulgaria	4
Serbia	Croatia	4
Serbia	Estonia	4
Serbia	Iceland	4
Serbia	Ukraine	4
Slovakia	Latvia	4
Slovakia	Lithuania	4
Slovakia	Serbia	4
Slovenia	Hungary	4
Slovenia	Latvia	4
Slovenia	Lithuania	4
Spain	Latvia	4
Spain	Lithuania	4
Spain	Netherlands	4
Spain	Serbia	4
Spain	Turkey	4
Sweden	Albania	4
Sweden	Latvia	4
Sweden	Serbia	4
Sweden	Turkey	4
Switzerland	Albania	4
Switzerland	Latvia	4
Switzerland	Lithuania	4
Switzerland	Serbia	4
Turkey	Belgium	4
Turkey	Estonia	4
Turkey	Finland	4
Turkey	Iceland	4
Turkey	Latvia	4
Turkey	Lithuania	4
Turkey	Slovakia	4
Turkey	Slovenia	4
Turkey	Switzerland	4
Turkey	Ukraine	4

Continuation of Table S3.

From	To	Frequency
United Kingdom	Latvia	4
United Kingdom	Lithuania	4
United Kingdom	Netherlands	4
United Kingdom	Turkey	4
USA	Australia	4
USA	Germany	4
Australia	New Zealand	3
Australia	Sri Lanka	3
Austria	Hungary	3
Belgium	Hungary	3
China	Italy	3
China	Sweden	3
Czech Republic	Netherlands	3
Denmark	Lithuania	3
Finland	Denmark	3
Finland	Netherlands	3
France	Canada	3
France	Hungary	3
France	Netherlands	3
Germany	Brazil	3
Hungary	Bulgaria	3
India	Korea	3
Italy	Netherlands	3
Italy	Portugal	3
Latvia	Belarus	3
Latvia	Croatia	3
Lithuania	Belarus	3
Lithuania	Croatia	3
Netherlands	Estonia	3
Netherlands	Slovakia	3
Netherlands	Slovenia	3
Netherlands	Ukraine	3
North Macedonia	Latvia	3
North Macedonia	Lithuania	3
Romania	Netherlands	3
Serbia	Belarus	3
Serbia	Bulgaria	3
Serbia	Latvia	3
Serbia	Lithuania	3
Spain	Canada	3
Spain	Colombia	3
Spain	Greece	3
Sweden	Portugal	3
Switzerland	Netherlands	3
Turkey	Belarus	3
Turkey	Croatia	3
Turkey	North Macedonia	3
Turkey	Serbia	3

Continuation of Table S3.

From	To	Frequency
United Kingdom	Hungary	3
United Kingdom	India	3
United Kingdom	Ireland	3
United Kingdom	Portugal	3
USA	Spain	3
Albania	Serbia	2
Australia	Bangladesh	2
Australia	Egypt	2
Australia	Greece	2
Australia	Ireland	2
Austria	Denmark	2
Austria	Portugal	2
Bangladesh	Saudi Arabia	2
Belgium	Denmark	2
Belgium	Korea	2
Belgium	Portugal	2
Bulgaria	Portugal	2
Canada	Ghana	2
Canada	Iran	2
Canada	Norway	2
China	Denmark	2
China	Greece	2
China	Malaysia	2
China	Nepal	2
China	Netherlands	2
China	Norway	2
China	Saudi Arabia	2
China	Turkey	2
Czech Republic	Denmark	2
Czech Republic	Hungary	2
Czech Republic	Portugal	2
Denmark	Belarus	2
Denmark	Bulgaria	2
Denmark	Estonia	2
Denmark	Iceland	2
Denmark	Latvia	2
Denmark	Ukraine	2
Finland	Hungary	2
Finland	Portugal	2
France	Algeria	2
France	Lebanon	2
France	Portugal	2
France	Tunisia	2
Germany	Argentina	2
Germany	Canada	2
Germany	Denmark	2
Germany	Hungary	2
Germany	Korea	2

Continuation of Table S3.

From	To	Frequency
Germany	Portugal	2
Greece	Egypt	2
Hungary	Estonia	2
Hungary	Iceland	2
Hungary	Latvia	2
Hungary	Lithuania	2
Hungary	Portugal	2
Hungary	Ukraine	2
India	Saudi Arabia	2
India	Sri Lanka	2
Italy	Denmark	2
Italy	Hungary	2
Korea	Egypt	2
Korea	Hong Kong	2
Netherlands	Albania	2
Netherlands	Belarus	2
Netherlands	Bulgaria	2
Netherlands	Croatia	2
Netherlands	Iceland	2
Netherlands	North Macedonia	2
Nigeria	Malaysia	2
Nigeria	Saudi Arabia	2
Norway	Denmark	2
Norway	Hungary	2
Norway	Portugal	2
Poland	Hungary	2
Poland	Portugal	2
Portugal	Estonia	2
Portugal	Iceland	2
Portugal	Latvia	2
Portugal	Lithuania	2
Portugal	Ukraine	2
Romania	Hungary	2
Romania	Turkey	2
Slovakia	Denmark	2
Slovakia	Hungary	2
Slovakia	Portugal	2
Slovenia	Denmark	2
Slovenia	Portugal	2
Spain	Denmark	2
Spain	Hungary	2
Spain	Iran	2
Spain	Portugal	2
Sweden	Denmark	2
Sweden	Hungary	2
Sweden	Netherlands	2
Switzerland	Denmark	2
Switzerland	Hungary	2

Continuation of Table S3.

From	To	Frequency
Switzerland	Portugal	2
Turkey	Denmark	2
Turkey	Hungary	2
Turkey	Portugal	2
United Kingdom	Australia	2
United Kingdom	Canada	2
United Kingdom	Denmark	2
United Kingdom	Malaysia	2
United Kingdom	Nigeria	2
United Kingdom	Saudi Arabia	2
USA	Belgium	2
USA	Brazil	2
USA	Chile	2
USA	Czech Republic	2
USA	India	2
USA	Netherlands	2
USA	New Zealand	2
USA	Norway	2
USA	Sweden	2
USA	United Kingdom	2
Albania	Bulgaria	1
Australia	Chile	1
Australia	Denmark	1
Australia	Korea	1
Australia	Malaysia	1
Australia	Nigeria	1
Australia	Saudi Arabia	1
Australia	Singapore	1
Australia	Sweden	1
Australia	Switzerland	1
Austria	Brazil	1
Austria	Georgia	1
Bangladesh	Fiji	1
Bangladesh	Thailand	1
Belgium	Mexico	1
Brazil	Bulgaria	1
Brazil	Cuba	1
Brazil	Ecuador	1
Canada	Australia	1
Canada	Austria	1
Canada	Brazil	1
Canada	Czech Republic	1
Canada	Ecuador	1
Canada	Jordan	1
Canada	Netherlands	1
Canada	Serbia	1
Canada	Sweden	1
Canada	Uganda	1

Continuation of Table S3.

From	To	Frequency
Chile	Colombia	1
Chile	Indonesia	1
China	Brazil	1
China	Chile	1
China	Czech Republic	1
China	Ghana	1
China	Hungary	1
China	India	1
China	Indonesia	1
China	Iran	1
China	Iraq	1
China	Ireland	1
China	Kenya	1
China	New Zealand	1
China	Qatar	1
China	Slovakia	1
China	Spain	1
China	Sri Lanka	1
China	Switzerland	1
Czech Republic	Ireland	1
Denmark	Croatia	1
Denmark	Egypt	1
Denmark	Ghana	1
Denmark	Lebanon	1
Denmark	Portugal	1
Denmark	Tunisia	1
Egypt	Georgia	1
Estonia	Ireland	1
Finland	Ireland	1
France	Australia	1
France	Bolivia	1
France	Brazil	1
France	Egypt	1
France	India	1
France	Mexico	1
France	Morocco	1
France	South Africa	1
France	United Arab Emirates	1
Germany	Australia	1
Germany	Egypt	1
Germany	Greece	1
Germany	Hong Kong	1
Germany	Nigeria	1
Germany	Uzbekistan	1
Greece	Bulgaria	1
Greece	Denmark	1
Greece	Kazakhstan	1
Hungary	Belarus	1

Continuation of Table S3.

From	To	Frequency
Hungary	Croatia	1
Hungary	Denmark	1
Hungary	Thailand	1
India	Australia	1
India	Bangladesh	1
India	New Zealand	1
India	Romania	1
India	Thailand	1
India	Turkey	1
India	United Arab Emirates	1
Iran	Korea	1
Israel	Uzbekistan	1
Italy	Argentina	1
Italy	Australia	1
Italy	Chile	1
Italy	Iran	1
Italy	Korea	1
Italy	Saudi Arabia	1
Japan	Bangladesh	1
Japan	Ghana	1
Japan	South Africa	1
Korea	Denmark	1
Korea	Greece	1
Korea	Pakistan	1
Korea	Saudi Arabia	1
Lithuania	Ireland	1
Malaysia	Bangladesh	1
Malaysia	Chile	1
Malaysia	Indonesia	1
Malaysia	Saudi Arabia	1
Malaysia	Singapore	1
Mexico	Egypt	1
Netherlands	Brazil	1
Netherlands	Denmark	1
Netherlands	Hungary	1
Netherlands	Iran	1
Netherlands	Latvia	1
Netherlands	Lithuania	1
Netherlands	Portugal	1
Netherlands	Serbia	1
New Zealand	Sri Lanka	1
New Zealand	Thailand	1
Nigeria	Bangladesh	1
North Macedonia	Denmark	1
North Macedonia	Hungary	1
North Macedonia	Portugal	1
Norway	Brazil	1
Pakistan	Chile	1

Continuation of Table S3.

From	To	Frequency
Pakistan	Indonesia	1
Pakistan	Malaysia	1
Poland	Kazakhstan	1
Poland	Korea	1
Poland	United Arab Emirates	1
Portugal	Belarus	1
Portugal	Croatia	1
Romania	Bangladesh	1
Romania	Denmark	1
Romania	Egypt	1
Romania	Georgia	1
Romania	Latvia	1
Romania	Lithuania	1
Romania	Portugal	1
Romania	Serbia	1
Romania	Thailand	1
Serbia	Denmark	1
Serbia	Hungary	1
Serbia	Portugal	1
Singapore	Thailand	1
South Africa	Ghana	1
Spain	Australia	1
Spain	Chile	1
Spain	Japan	1
Spain	Kenya	1
Spain	Mexico	1
Spain	Monaco	1
Spain	Tunisia	1
Sweden	Pakistan	1
Sweden	Saudi Arabia	1
Tunisia	Lebanon	1
Turkey	Egypt	1
Turkey	Greece	1
Turkey	Iraq	1
Turkey	Korea	1
Turkey	Netherlands	1
Turkey	Nigeria	1
Turkey	Thailand	1
United Kingdom	Bangladesh	1
United Kingdom	Brazil	1
United Kingdom	Greece	1
United Kingdom	Singapore	1
United Kingdom	South Africa	1
United Kingdom	Sri Lanka	1
United Kingdom	Uganda	1
USA	Bangladesh	1
USA	Ecuador	1
USA	Greece	1

Continuation of Table S3.

From	To	Frequency
USA	Hong Kong	1
USA	Iran	1
USA	Japan	1
USA	Kazakhstan	1
USA	Malaysia	1
USA	Mexico	1
USA	Morocco	1
USA	Poland	1
USA	Saudi Arabia	1
USA	Singapore	1
USA	Sri Lanka	1
USA	Turkey	1
USA	United Arab Emirates	1
USA	Venezuela	1

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