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Heavy metal pollution in indoor dust of residential, commercial, and industrial areas: a review of evolutionary trends

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Abstract

Heavy metals (HMs) in indoor dust are among the most toxic micropollutants and have attracted mainly the attention of researchers in the last three decades concerning the environmental and human health perspectives. Hence, a thorough literature-based bibliometric analysis was inevitably needed to identify the research trend for the prevalence of HMs in indoor environments and their toxicological aspects. Accordingly, exploring publications on the Web of Science Core Collection database to identify the articles published on HM pollution in indoor dust environments revealed several peculiar findings. The review article indicates that the majority of studies conducted in this field are monitoring-based, utilizing "HMs (n = 79) ," "contaminations (n = 49) ," "lead (n = 49)," and "health" as primary keywords in the published articles. Among the countries, China emerged as the most active investigator in this area, followed by the USA, Middle East, Turkey, Korea, and India. Additionally, China has established collaborations with ~150 and >90 countries, respectively, solidifying its leading position in publications. Studies on HM pollution in indoor dust have evolved from initial exposure analyses in the 1990s to encompass bioavailability, bioaccessibility, exposure, risk assessment, speciation, and source apportionment assessments. Metal pollution in residential and commercial areas (schools/offices) primarily originates from in-house sources and vehicle emissions, while industrial areas, driven by anthropogenic activities (e-waste recycling/mining), face metal pollution from different sources. The analysis underscores that studies predominantly focus on risk assessment of significant metals, their bioaccessibility/bioavailability, and source apportionments. This study's exploration of HMs in indoor dust provides explicit content and trends, offering valuable insights for researchers delving into this field. It not only suggests remedial measures but also contributes to the development of forecasting models.

Keywords Indoor dust · Heavy metals · Contamination · Bibliometric analysis · Health risks

Introduction

The indoor environment, despite being considered a safe haven, exposes individuals of all age groups to a myriad of pollutants that can have detrimental effects on human health. With people spending an average of 95% of their time indoors, primarily in residential settings, the prolonged exposure to indoor pollutants raises concerns (Salthammer et al. 2018). The time spent inside could depend on factors such as seasonal and vocational activities (Park and Nagy 2018; Delgado-Saborit 2019; Doyi et al. 2020). Unlike the outdoors, where natural processes and agents aid in pollutant degradation, the indoor environment lacks such mechanisms, resulting in a higher concentration of pollutants and prolonged exposure duration. Degradation is facilitated in outdoor environments by ageing, biotic (microbiological),

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and abiotic (photolysis and hydrolysis) agents, as well as natural phenomena like wind and rain. Due to the absence of sunlight and microbial activity, the degradation of chemicals is prolonged in indoor environments compared to outdoors (Gunathilake et al. 2021).

Surprisingly, even though most of the time is spent inside homes and offices, the health risks associated with indoor chemical exposure have received limited research attention compared to outdoor pollutants (Cao et al. 2020; Shi and Wang 2021; Sahu and Gurjar 2021). Indoor dust serves as a major carrier of various chemicals, including heavy metals (HMs), volatile organic compounds (VOCs), flame retardants, and pesticides. These pollutants originate from numerous sources such as building materials, furnishings, cleaning products, and outdoor air pollution infiltrating indoor spaces. Due to their fine particulate nature, dust particles can easily become suspended in the air, making them readily inhalable, putting individuals at risk of respiratory issues, neurological disorders, allergies, and other adverse health effects.

Seven HMs namely, As, Cd, Cr, Cu, Ni, Pb, and Zn have been taken into consideration by the American Environmental Protection Agency (US EPA) as priority control pollutants because of their persistent and toxic nature (Luo et al. 2015; Huang et al. 2016; Jin et al. 2019; Khanoranga 2019). These metals, often referred to as HMs, have a high specific density (>5 g/cm^3) and can enter the body through inhalation, dermal contact, and ingestion (Lian et al. 2019; Sahu and Gurjar 2021). Inhalation occurs when fine dust particles become airborne and are inhaled into the respiratory system. Dermal contact can occur when individuals come into direct contact with contaminated surfaces or dust particles, allowing metals to penetrate the skin. However, ingestion, particularly through the accidental intake of dust-contaminated hands or objects, represents a significant pathway for HM exposure, especially for young children. HMs, once ingested, can bio-accumulate in the body over time (Yang et al. 2019; Obasi 2020; Zhang et al. 2020). This means that small amounts of metals are absorbed, stored in various organs, and can have cumulative toxic effects. Children between the ages of 1 and 8 years are particularly vulnerable to HM exposure through ingestion due to their hand-to-mouth behavior and exploratory nature. The duration and frequency of dust ingestion significantly impact the uptake of HMs, potentially leading to serious health risks.

These metals have vast and varied adverse effects on human health (Fig. 1). For instance, while Zn overdose causes nausea, vomiting, cramps, and fever (Jamal et al. 2019; Kan et al. 2021); Cr causes skin ulcers, kidney, liver, circulatory, and nervous tissue disorders; Pb damages nervous, enzymatic, skeletal, gastrointestinal, reproductive, and immune systems (Jamal et al. 2019). Further, Cu causes anemia, kidney damage, and stomach irritation; Cd ingestion results in pulmonary lesions, bone fractures, and kidney dysfunction; and As dust exposure causes skin cancers (Kumar et al. 2020; Gujre et al. 2021). HMs have the ability to accumulate in the body's internal organs and tissues, which can have severe consequences for human health (Zheng et al. 2010), disrupting the central nervous system and causing various disorders (Faiz et al. 2009; Kiran and Sharma 2021). Correspondingly, quantifying metals in the

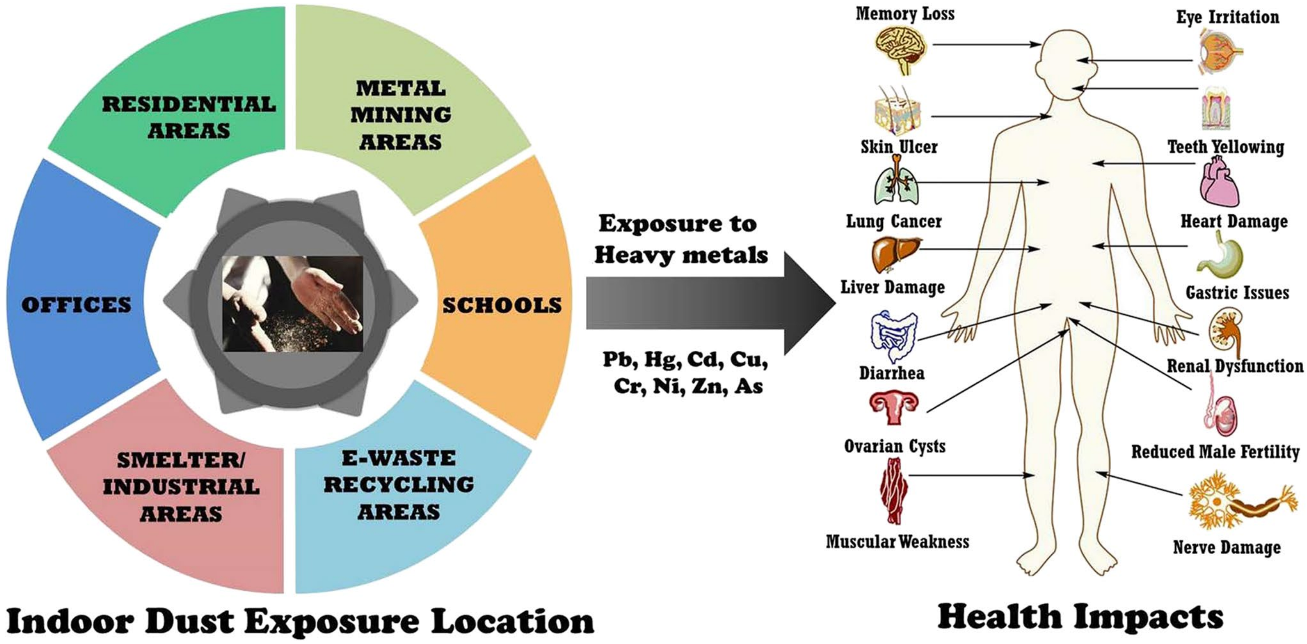

Fig. 1 Health effects from heavy metals

dust is critical for assessing and understanding the changes in the anthropogenic degradation of urban environmental quality. Moreover, quantitative measurements of HMs in dust provide a quantitative basis for understanding the potential health risks associated with exposure and guide effective pollution control measures (Dytłow and Górka-Kostrubiec 2021; Shi and Wang 2021).

A wide range of indoor sources contribute to the presence of HMs in indoor environments (Table S1), including Zn from electronic parts, ceramic glazes, cosmetics, pharmaceutical products, paint/dyes, lacquers, papers, oilcloths, glue, and wood preservatives; Cr from tobacco smoke, paints, and asbestos lining erosion; Pb from paints, ceramics, water pipes, cosmetics, colored pencils, canned foods, ayurvedic medicines, ceramics, leaded gasoline, solder, and crystals; and Cu from wiring, roofing, decorative art, pigments, wood preservatives, bacteriostatic agents, and fungicides (Marinho Reis et al. 2018; Manigrasso et al. 2019; Jha et al. 2020; Levin et al. 2021). Several studies have identified different physicochemical parameters influencing the HM concentrations in indoor dust (Pruvot et al. 2006; Yang et al. 2016). However, solely estimating total metal concentrations without pinpointing their sources falls short of providing a comprehensive understanding (Dytłow and Górka-Kostrubiec 2021; Jadoon et al. 2021; Shi and Wang 2021). Factors such as proximity to roads, the age of buildings, and household activities like smoking and pesticide use play a significant role in influencing the distribution of metals in residential areas (Isley et al. 2022). In commercial areas, the presence of metals can be affected by the use of commercial products like cleaning agents, cosmetics, and electronics, as well as foot traffic and the presence of metalworking shops or industries (Faisal et al. 2021). Furthermore, the presence of various metals in industrial areas is determined by processes such as mining, processing, manufacturing activities, and emissions from smokestacks (Haque et al. 2022; Zeng et al. 2023). Despite the adverse effects of HMs, surprisingly, the World Health Organization (WHO) has yet to establish prescribed permissible limits for indoor dust (Shi and Wang 2021). Hence, it is time to highlight the significance of indoor dust as a primary source of chemical exposure, especially HMs, and emphasize the need for further investigation and regulation in this domain.

In this context, the present study categorized indoor environments as residential, commercial (including schools and offices), and industrial (involving e-waste recycling and mining) areas. The study also conducted a comprehensive review and bibliometric analysis based on these foundational data, aiming to provide global-level solutions for existing issues. Furthermore, it is essential to raise public and government awareness about the seriousness of indoor air pollution. This study serves as a cornerstone for understanding current challenges and devising effective solutions on a global scale, promoting the adoption of safer alternatives in various industries, implementing stricter regulations on HM emissions, and encouraging the adoption of sustainable practices.

The definite objectives of this review article include the following: (i) to structure a bibliographic (which can help in understanding the research activity of a topic) and scientific database, with the help of the VOSviewer, for the identification of the significant research developments in the area of different indoor environments contamination with HMs; (ii) to establish the concurrent knowledge of various research groups, countries, authors, universities, institutions, and journals, and collaborations among them for easy access to all the researchers/academicians/environmentalists; (iii) to identify the significant knowledge gaps in this particular field which enable active scientific groups to design the more relevant studies; and (iv) to provide the literature study-based future recommendations related to long-term monitoring of HMs in the different indoor environments to get an idea about the potential exposure implications.

Bibliometric studies help in understanding the research activity of a topic. The present investigation uses bibliographic and scientific databases, with the help of the VOSviewer, to identify significant research developments (Moed et al. 1995; Kostoff 2002; Waltman 2016; Aleixandre-Tudó et al. 2019). Further, the study shed light on various research groups, countries, authors, universities, institutions, and journals and collaborations among them (Rueda et al. 2007; Aleixandre-Tudó et al. 2019). Moreover, by utilizing research papers from reputable scientific databases, this bibliometric investigation enhances our understanding of HMs in indoor dust. It offers a comprehensive analysis of the current state of research, including the existing knowledge, research gaps, and scientific implications. By identifying the most influential studies, authors, and institutions, this analysis provides a valuable resource for researchers, policymakers, and stakeholders involved in addressing HM pollution in indoor environments. The findings of this study contribute to the scientific community's understanding of HMs in indoor dust. These findings not only enhance our understanding but also have the potential to shape future research agendas and inform policy interventions in this field.

Methodology

Literature search

Clarivate Analytics conducted a search on the Web of Science (WoS) Core Collection., on February 24th, 2023, with specific keywords (indoor dust metal OR house dust metal OR residen* dust metal OR apartmen* dust metal OR kitche* dust metal OR e-waste recycling metal indoor dust OR e-waste recycling metal house dust OR e-waste recycling metal residen*dust OR e-waste recycling metal kitchen dust OR e-waste recycling metal apartment dust OR e-waste recycling metal school dust OR e-waste recycling metal office dust OR smelting metal indoor dust OR smelting metal house dust OR smelting metal residen*dust OR smelting metal kitchen dust OR smelting metal apartment dust OR smelting metal school dust OR smelting metal office dust OR industr* metal indoor dust OR industr* metal house dust OR industr* metal residen*dust OR industr* metal kitchen dust OR industr* metal apartment dust OR industr* metal school dust OR industr* metal office dust OR school metal dust OR office metal dust) the link for which could be accessed using "https://www.webofscience.com/wos/woscc/summary/46d9bc0d-812f-4272-ab21-e744d7ed5fd0-732865ef/relevance/1".

Data extraction and analysis

The "full records and cited references" under the tab-delimited option were downloaded and transferred to version 1.6.16 of the VOSviewer program (van Eck and Waltman 2010). The primary analyses used the "Analyze" and "Create Citation Report" functions. The bibliometric analyses were performed to determine scientific collaborations among authors and countries. Further, keywords used in the publications were analyzed to get acknowledged the research direction through the years. In the analysis, the frequency of the usage of a term (author, country, or keyword) is reflected in its bubble size. The distance between the bubbles represented the frequency of collaboration between the terms.

Results and discussion

Residential areas

Due to its longer residence duration than the outside, the interior environment is a possible exposure pathway for numerous contaminants in all age groups. Paints for walls, pesticides, furniture-cleaning chemicals, tobacco, batteries, and wood burning can all be sources of metals in indoor environments. The earliest studies on HMs in house dust included "HMs in the street and house dust in Bahrain" (Salim Akhter and Madany 1993). The continuous automobile increase per 1000 population was responsible for elevated metal concentrations in street dust (Statistical Abstracts, 1990). Zn was associated with lubricating oils in automobiles, Ni and Cr with chrome painting of automobiles, Pb from petrol, and Cd from tire wear. Good correlation values of metals like Zn and Pb ($r = 0.4$; $P < 0.01$), Ni and Cr ($r = 0.6$; $P < 0.001$), and Cd and Pb ($r = 0.3$; $P < 0.01$); suggest automobile emissions as their common source of origin. Automobile emissions are the primary source of Pb, Zn, and Cd in house and street dust implying that these metals are brought into houses through wind-blown dust from the outside environment, which is particularly relevant in the arid environment of Bahrain. Elevated concentrations of Ni and Cr in low-trafficked, rural areas were from the smoke originating from burning oil fields of Kuwait. Street samples contained metal concentrations higher than indoors, while HMs levels were identical in different sites in Bahrain (Table 1). The burning oilfields of Kuwait resulted in elevated Ni concentrations in this city. Similar results were found 2 years later when the correlations between indoor and outdoor metals were studied (Madany et al. 1994). While house dust had lower metal concentrations (in µg/g), (Pb = 517, Zn = 202, Cd = 1.9, Cr = 11, Ni = 10) compared to the outdoors (Pb = 742, Zn = 67, Cr = 9.6, Ni = 12, Cd = 1.5). Automobiles were the major sources for metals in street dusts, and only Ni and Pb in indoors. For metals like Cd, Cr, and Zn indoor sources played a vital role in posing risks to children.

During a year-long investigation, (Park et al. 2008) monitored the levels of total suspended particulate (TSP), PM_{10}, and $PM_{2.5}$ in the ambient air of Seoul's residential area. Their concentrations were within the range of 71–158 µg/m^3, 40–106 µg/m^3, 28–43 µg/m^3, respectively. In addition, the authors conducted an analysis of HM components and calculated the excess cancer risk associated with carcinogenic metals like Cr, As, and Cd. They observed fluctuations in PM10 levels in different seasons, while a constant level of $PM_{2.5}$ was identified. In general, all the metals were detected in both $PM_{2.5}$ and PM_{10}. Specifically, Cr showed significant carcinogenicity compared to other $PM_{2.5}$-bound HMs in the studied region. The authors claimed that their findings offer valuable insights into the potential establishment of a $PM_{2.5}$ standard.

Indoor dust samples from 90 houses in six districts of Chengdu city, China were investigated for HM levels (Cr, Cd, Pb, Zn, Cu, Ni) (Cheng et al. 2018). The correlation of HMs in dust and house attributes was assessed. The concentration of metals (in mg/kg) (Cd = 2.37, Ni = 52.6, Cr = 82.7, Cu = 190, Pb = 123, and Zn = 675) in indoor dust was higher than that of street dust (except Cr). The elevated concentrations of metals were mainly contributed by the corrosion of alloys and different traffic sources. They found that HM concentrations and floor levels did not correlate well. Ingestion was established as a primary pathway for exposure to Pb, Zn, Cu, and Ni, while dermal contact for Cd and Cr in house dust. The non-carcinogenic hazards from HMs in household dust were insignificant in Chengdu residents.

In Nepal in 2019, researchers looked into source analysis, regional distribution, and health hazards associated with HMs in soil and household dust (Yadav et al. 2019). Soil and dust samples had higher median values (of Pb,

Table 1 Details and significant findings of the scientific publications dealing with heavy metal contamination from indoor dust

Study details	Reference	Journal	Findings and suggestions
Residential areas			
Street and house dust, Bahrain.	Salim Akhter and Madany (1993)	*Water, Air and Soil Pollution*	• Significant Cd, Pb, Cr, Zn, and Ni in indoor and street dust • Indoor dust metals- similar/lower than road dust • Motor vehicles were the primary source of Zn, Cr, Cd, and Pb smoke from Kuwait oil fields for Ni
Tobacco smoke, indoor air quality, USA	Landsberger and Wu (1995)	*Science of the Total Environment*	• Cd (maximum), K, Zn, Na, Cl, Br high indoors (due to smoking) • Risk of respirable diseases from long-term low-concentration exposure • Prohibit indoor smoking • Separate smoking and non-smoking areas
Street, indoor, and outdoor dust from Aswan, Egypt.	Rashed (2008)	*Clean-Soil Air Water*	• Mn, Fe, Pb- highest in the indoor, street, and outdoor fallen dust • Metal concentrations were highest for street dust and lowest for indoor dust. Outdoor fallen dust • Pb is present in all dust samples near traffic • Promote catalytic converters for reducing metals in street dust originating from vehicles
Household dust: a review, Plymouth, UK	Turner (2011)	*Environmental Geochemistry and Health*	• Soil, street dust, and paints as surrogates of household dust to be avoided • Metal bioaccessibility is variable in a household setting • Variation in bioaccessibility- due to the inherent heterogeneity of samples and differences in industrial emissions, geology, and domestic practices • Study effects of physicochemical variables and pH of stomach phase systematically- to factor algorithms into measures of bioaccessibility
Indoor dust, Istanbul, Turkey	Kurt-Karakus (2012)	*Environment International*	• Acceptable cancer risk from Cr in Istanbul • Metal exposure pathways-ingestion>inhalation>dermal • No potential health risks to the population from indoor dust • Heavy metal enrichment in different particle sizes in indoor dust is relevant for exposure via inhalation

Table 1 (continued)

Study details	Reference	Journal	Findings and suggestions
Indoor dust, Ahvaz city, Iran	Neisi et al. (2016)	*Toxin Reviews*	• No non-carcinogenic risks • Carcinogenic risks higher than acceptable levels in children • Biomarker studies (urine, blood) are needed to determine the adverse health effects of metals
Indoor dust and its health risks-review	Mas'udah et al. (2016)	*Reviews On Environmental Health*	• Urban areas- higher metal concentrations (compared to rural areas) • Focus on carcinogenic risks in children in indoor dust to deduce sources
Household dust (urban area) Chengdu, China	Cheng et al. (2018)	*Science Of the Total Environment*	• House dust- more metals (compared to street dust except for Cr) • Sources- traffic, alloy corrosion, in-house dust • Major pathway of exposure: Ingestion–Pb, Ni, Cu, Zn; Dermal contact–Cd, Cr • Minor carcinogenic and non-carcinogenic risks • The investigation of the health effects of metals in PM10 and $PM_{2.5}$ in the indoor environment
House dust and surface soil, Nepal, India	Yadav et al. (2019)	*Chemosphere*	• Median concentrations in dust and soil were 2–13 times higher than background; Zn was the prominent metal • Sources of metals- natural and anthropogenic • Metals pose significant cancer and non-cancer risks • Heavy metals assessment in the urban area suggested
Schools			
Elementary schools, Hermosillo, Sonora, Mexico	Meza-Figueroa et al. (2007)	*Atmospheric Environment*	• Metal contamination sources- natural and anthropogenic • Both topography and location of emission source- control metal distribution • Suggested atmospheric transportation modeling
Preschool children in Malaysia	Latif et al. (2014)	*Air Quality Atmosphere and Health*	• Anthropogenic factors caused Pb, Cd, Zn in indoor dust, Cd, Cr, and Zn in children's palms and indoor walls • Heavy metal investigation in and around schools, along with mitigation procedures

Table 1 (continued)

Study details	Reference	Journal	Findings and suggestions
Primary school (Sri Serdang, Malaysia)	Praveena et al. (2015)	*Environmental Forensics*	• Windows had the highest quantities of metal, while fans had the lowest percentages • The metal concentrations ranged as follows: Cd=1.73–7.5 µg/g, Pb=34.17–101.87 µg/g, and Cu=20.27–82.13 µg/g • Only Pb posed significant non-carcinogenic risks.
Schools across Lagos, Nigeria	Famuyiwa and Entwistle (2021)	*Environmental Science Processes & Impacts*	• Indoor dust samples were mostly uncontaminated except for only two samples. • The trend of enrichment factors was as: - Al< Ni<Cd<As<V<Mn<Ba<Cu<Cr<U<Zn<Pb • Ni, Mn, U, Fe, Al, and As were influenced by lithogenic factors; Cu, Pb, and Cd were affected by anthropogenic sources; V, Zn, and Cr had mixed source origins • The bioaccessibilities of different metals were Fe (7%), Cr(10%), Ni(28%), Cu(36%), As (37%), Al(41%), Ba (48%), Pb (48%) and Mn (57%) • Human health risks were within acceptable levels from bioaccessible fractions
Saudi Arabia's Riyadh Elementary School environments: indoor and outdoor dust	Alotaibi et al. (2022)	*Atmosphere*	• Indoor dust was shown to have higher metal concentrations of Ni, Co, Zn, Pb, Cd, and Cu than outdoor dust • Pb, Cd, and moderate amounts of Cu and Zn were strongly present in indoor and outdoor dust • Potential ecological risks from heavy metals were lower • Health risks for children were maximum and least in adults
Offices			
Toxic metals in vacuum-cleaner collected indoor dust	Lisiewicz et al. (2000)	*The Science of the Total Environment*	• Higher metal concentrations were found in finer fractions (8–50 µm) • Only Pb concentrations of 120 µg/g were comparatively low in finer 63–125 µm fractions and 210 µg/g for 8–32 µm fractions • The high Zn 1020–1070 µg/g content and Cr 90-100 µg/g were found • Strong correlations were found between Fe-Cr, Pb-Zn, and Pb-Cu • Working environments had higher concentrations of Zn, Pb, Ni, Cu, and Br

Table 1 (continued)

Study details	Reference	Journal	Findings and suggestions
Fine particles and implications for workers' health in dental offices	Olujimi et al. (2015)	*Sustainability*	• Review on dental workers' health and dental medicines • Fine particle exposure must be minimized using gloves, eyeglasses, and masks • Indoor air must be kept clean using air filters, ventilators, and efficient air conditioning systems
Particulate matter (PM2.5, PM10) in indoor and outdoor in Doha, Qatar	Saraga et al. (2017)	*Aerosol and Air Quality Research*	• 100% of the outdoor measurements exceeded the WHO guideline values • Outdoor- crustal matter derived from the surrounding crustal material has elevated quantities of carbonate carbon • OC/EC readings indicate that secondary organic aerosol, sources from traffic, and resuspended dust may have contributed together • The predominance of nitrate and sulphate ions, which account for a sizeable amount of the particle mass, suggests the anthropogenic influence • Infiltration had a significant role in the higher enrichment of Pb, Zn, Cu, As, and Cd in outdoor and indoor environments • The indoor-outdoor relationship is significantly impacted by particle infiltration and penetration into the building, mainly through the ventilation system and, to a lesser extent, through windows or breaches in the building shell • Although the low interior-to-exterior ratio makes outdoor levels dominate compared to internal ones, there is a positive relationship between indoor and outdoor PM on days when the building was open to the public and employees
Smelter/industrial area			
Households near a lead smelter, Lhota village, Czech Republic	Rieuwerts et al. (1999)	*Environmental Monitoring and Assessment*	• Localized sources, associated with soil heaps-sources of Cd, Cu, and Zn • Strong correlation of metal concentrations with house age, distance from smelter against metals in garden soils

Table 1 (continued)

Study details	Reference	Journal	Findings and suggestions
Heavy metal leaching, spent household batteries, municipal solid waste, Thailand	Karnchanawong and Limpiteeprakan (2009)	*Waste Management*	• The type of battery influences metals in leached solutions • Low pH leaches more metals than high pH • Disposal of spent batteries from households in landfills increases metals in leachate
Indoor/outdoor relationship of metals in particulate matter, industrial area, Pakistan	Nazir et al. (2011)	*Atmospheric Research*	• Outdoor particles have high Zn, Co, Fe, Cr, and Mn concentrations • High Pb and Cu concentrations in indoor particles • Sources identified - automobile emissions, soil-derived dust, and industrial activities • Cd, Sb, Zn, Pb, Co highly enriched in PM
E-waste recycling area			
Southeast China	Leung et al. (2008)	*Environ. Sci. Technol.*	• Metal concentrations at workshop (Cu=8360, Ni=1500, Pb=110000, Zn=4420) and roads Cu=6170, Ni=304, Pb=22600, Zn=2370) were analyzed • Compared to non-e-waste locations, Cu and Pb concentrations were higher at e-waste sites • The food market and schoolyard were adversely affected • Cu and Pb originated majorly from recycled circuit boards • Uncontrolled e-waste recycling in Guiyu that was not under control was endangering people's health
Food, household dust, and water from a South China e-waste recycling facility	Zheng et al. (2013)	*Ecotoxicology And Environmental Safety*	• Vegetables, rice, and house dust- most significant contributors to non-carcinogenic risks from heavy metal exposure • Oral exposure risks more than inhalation and dermal contact
Hong Kong, China	Lau et al. (2014)	*Environ Sci Pollut Res*	• Elevated Pb concentrations were found in the dismantling and desoldering • Carcinogenic risks were posed to the workers in the dismantling and desoldering areas • Blood lead levels from exposure to the floor dust in these two places were estimated by the Adult Lead Model (USEPA) to be 10 and 39.5 μg/dl

Table 1 (continued)

Study details	Reference	Journal	Findings and suggestions
E-waste workshop indoor and outdoor dust, Wenling city, China	Xu et al. (2015)	*Environmental Science And Pollution Research*	• The chronic risk from Pb through on-site exposure • Outdoor-BDE dust underwent a more physico-chemical process • Debromination of deca BDE (brominated diphenyl ethers) formed a higher percentage of non-BDE during e-waste recycling • Despite the low deleterious risks of BFRs (brominated flame retardants), give concern to DBDPE (deca bromo diphenyl ethane), as its toxicity is unknown.
Heavy metal inhalation from size-fractionated, particle-bound trash in a recycling area of electronic waste, Qingyuan, China	Huang et al. (2016)	*Journal Of Hazardous Materials*	• Finer particles- anthropogenic origins • Coarser particles- crustal origins • Significant carcinogenic risks via inhalation in both adults and children
E-waste recycling area, indoor dust, South China	He et al. (2017)	*Ecotoxicology And Environmental Safety*	• E-waste recycling areas had higher metal concentrations compared to other regions (except Cr) • Toddlers exposed to Pb and BDE, 209 in e-waste recycling need serious attention
Health risks for children from exposure to trace elements in recycling area dust.	Xu et al. (2021)	*Science of the Total Environment*	• Higher metal concentrations were found in kindergartens, house dust, and road dust of Guiyu compared to Shantou and Haojiang • Similar distribution patterns were seen in road dust and house dust • Close relationships were found of trace elements, as per Spearmanns correlation • Houses with indoor shoe cabinets and open windows had higher trace metal concentrations • Higher Ba concentrations were found in children having airway inflammations. • Higher exposure was found through the ingestion route, while acceptable exposure risks were found in children through inhalation • Significant health risks are posed by exposure to trace elements to children in e-waste recycling areas
Metal mining areas			

Table 1 (continued)

Study details	Reference	Journal	Findings and suggestions
Korea's Goseong is home to abandoned metal mines	Ji et al. (2013)	*Environmental Pollution*	• Soil, crop, and rice samples near mines exceeded permissible levels • The predicted daily intake of metals was lower than the permissible daily intake at the time • Metal contamination in soil and rice from metal mine areas needs focus
Mining city of Oruro, Bolivia	Barbieri et al. (2014)	*Science Of The Total Environment*	• There were still substantial correlations between non-essential metallic elements (As, Cd, Pb, Sb, and Sn) in dust and hair after accounting for children's habits, but not for essential elements (Cu and Zn) • Children who played in the dirt had higher Pb, Sb, and Cu dust-hair correlations ($P =$ 0.006, 0.022, and 0.001, respectively), whereas children who put their hands or toys in their mouths had higher Cd dust-hair correlations ($P = 0.011$) • In the suburbs, neither the gender nor the behavior of the children affected the lack of a connection between metallic dust particles and children's hair • As a result of children's playing behavior, indoor dust exposure becomes a significant channel for exposure for them
Phosphorus mining, Guizhou Province, China	Yang et al. (2015)	*Archives of Environmental Contamination and Toxicology*	• In indoor dust, mining activities contributed to Pb, Hg, As, and Mndust • Vehicular emissions contributed to Cd and Mn indoors • The separation from the mining region and the predominant wind direction were crucial factors in the distribution of the components • Even though Pb and As's carcinogenic and non-carcinogenic risks were within tolerable ranges, these metals required special consideration regarding their potential health hazards

Table 1 (continued)

Study details	Reference	Journal	Findings and suggestions
As Cd, Cu, and Pb were found near a copper smelter in central Chile	Berasaluce et al. (2019)	*Journal of Trace Elements in Medicine and Biology*	• The amount of trace elements found in hair and toenails and the estimated chronic daily indoor and outdoor dust intake are strongly correlated • With high concentrations and prolonged residence times at their homes, humans in Puchuncav were exposed to trace metals in interior dust at higher levels than in soil • No non-carcinogenic risks were associated with the exposure to indoor dust and soil • In all analyzed locations, including the control, only As posed a significant carcinogenic risk (1.0E−04) to young children (between 1 and 5 years old) and children between 6 and 18 years in the exposed area.
Xinqiao mining area, Tongling, China	Li et al. (2020)	*Human and Ecological Risk Assessment: An International Journal*	• Indoor dust was enriched in heavy metals (Cd>Zn>Cu>Pb), except for Co • Metals except Co originated from mining activities. • Despite this, no other elemental concentrations (apart from Cu) demonstrated a significant regional difference ($P > 0.05$) • Neither adults nor children faced any non-cancer health risks. • The risks of Ni, Cr, Cd, Ni, Co, and Cr causing cancer were within tolerable limits • Only Pb's noncarcinogenic risk and Cd's and Cr's carcinogenic danger require consideration

Zn, Cr, Cd, Cu, Co, Ag, Mn, and Sb) than the background in Nepal's four major urban areas. Higher spatial variability was found when comparing the concentrations of Cu, Pb, Zn, Cd, and As. Soil and dust showed maximum Zn concentration in dust (59%) and soil (55%). The metal sources were evaluated using principal component analysis (PCA) applied to the whole metal data set of soil. Four major factors were extracted, with eigen values greater than 1, accounting for 81.7% of total variance. A poor correlation was found between metal concentrations, total organic carbon, and black carbon. In soil and dust, anthropogenic sources like industrial and traffic emissions were Pb, Cu, Zn, Cr, Sb, Ni, and Ag. In contrast, natural sources contributed to metals like Mn, Fe, As, Cd, Co, and Fe. The carcinogenic risks from metals in soil and dust were beyond the permissible limits.

Doyi et al. (2019) studied exposure risks from metal concentrations in indoor dust of 224 homes in Sydney, Australia. The metal levels (in mg/kg) were as follows: As = 20.2, Cr = 99.8, Cu = 298, Mn = 247, Ni = 56.7, Pb = 364, Zn = 2437. Pb values were higher in the older part of the city, that were 60 years old on average (20.6% ≥100 years old), compared to the newer buildings were <50 years old. There may be non-carcinogenic risks from exposure to Pb and Cr. However, only Cr poses a risk for cancer in youngsters. According to the Integrated Exposure Uptake Biokinetic (IEUBK) model, 5.80% of people had blood Pb levels over 10 μg/dL, and 19.2% had levels over 5 μg/dL. Hence, levels of Cr and Pb in indoor dust posed the most adverse health effects in children. Later in 2020, he published his findings on the bioavailability and metal bioaccessibility in dust and potential health hazards. They discovered that As, Cu, Ni, Pb, and Zn are most prevalent in the 90–150 μm fraction, while Cr and Mn predominate in the <45 μm fraction. In vitro bioaccessibilities (gastric phase alone) were analyzed for dust particles of the following sizes: <45 μm, 45–90 μm, 90–150 μm, and 150–250 μm. IEUBK children's model estimated Pb exposure. The mean bioaccessibilities of lead in percentage were as follows: <45 μm = 59.6%, 45–90 μm = 42%, 90–150 μm = 62%, 150–250 μm = 62.2%. Dust size of 90–150 μm posed the highest risk in young children, with children (<3 years) likely exceeding Pb criteria blood of 5 μg/dL.

In Puchuncaví Valley (Valparaíso, Chile), indoor dust had higher elemental concentrations than soil (Berasaluce et al. 2019). However, there were no non-carcinogenic risks, and As posed considerable (>1.0E−04) carcinogenic risks to youngsters. Thus, some target intervention was suggested. In Kharagpur, four important sampling locations were selected: residential area, moderately trafficked area, heavily trafficked area, and near a petrol pump. Significant enrichment of Pb (Igeo=2.01, EF = 41.79) and Cr (Igeo=1.6, EF=4.39) were found (Rani et al. 2019) (1.0E−06 to 1.0E−04).

In Lanzhou City, China, indoor dust metal concentrations variations were measured with seasonal scale and floor heights (Bao et al. 2019). The winter season recorded higher metal concentrations (Cu, Cd, Ni, Pb, and As) than in summer. Hg present in dust was mainly derived from anthropogenic activities indoors. Hg concentrations on upper floors (9th–16th) were higher than on lower ones (1st–8th). However, for Mn and As, the concentrations were higher on lower floors (1st–8th) and allowed on upper floors (9th–16th). Cu and Cd concentrations increased with height. Indoor and outdoor dust posed potential health risks to both children and adults.

In the Lagos State of Nigeria, metal levels (mg/kg) followed the trend: As (57.76–111.93) > Pb (13.81–116.60) >Zn (22.73–224.2) > Cu (8.27–228.75) > Cr (2.53–22.60) (Bamidele et al. 2020). The highest exposure dose was through the ingestion pathway. Although there were no non-carcinogenic risks, the total lifetime cancer risk was slightly higher in Lagos Mainland children (1.02E−04) and Shomolu (1.03E−04). This indicated that the risk of a carcinogenic effect in children exposed to As was prevalent here.

According to Ali et al. (2021), household dust from floors and air conditioner filters in Saudi Arabia's rural and urban areas included high amounts of As and Pb. Pb concentrations were more significant in rural AC filter dust (775 mg/kg compared to 167 mg/kg in urban AC dust). Socioeconomic factors did not influence the concentration of these metals. Cumulative lifetime cancer risk was within the tolerable range (USEPA = 1.0E−05 to 5.0E−07). Pb exposure resulted in considerable non-cancerogenic hazards in young children in urban areas.

In Bahrain, industrial metal emissions were negligible, with metal concentrations in line with or lower than those found in road dusts (Salim Akhter and Madany 1993). Pb was the dominant metal in Bahrain, both indoors and in street dust (Madany et al. 1994). Automobile activities primarily contributed to Pb in street dust, while Ni and Pb in indoor dusts originated from street dust. Both studies lacked information on the primary sources of metals within the households. In Seoul, Korea, only Cr in $PM_{2.5}$ fractions posed carcinogenic risks to residents (Park et al. 2008). In Chengdu, indoor metal concentrations were influenced by specific sources (paint, old building materials and alloy corrosion) and activities such as smoking (Cheng et al. 2018), with no associated health risks but, a recommendation for future investigations on HMs in PM_{10} and $PM_{2.5}$. In Lanzhou city of China, elevated indoor mercury (Hg) levels indicated a source from building materials, while other metals had higher concentrations outdoors. The winter season had increased metal concentrations, with children being particularly vulnerable to health risks from metal exposure. In Nepal, a similar monitoring study found higher metal concentrations in dust compared to soil (Yadav et al. 2019), with total organic carbon (TOC) and black carbon (BC) having no influence on metal concentrations. Different metals posed non-carcinogenic (Pb, Cr) and carcinogenic risks (Cd, Ni, Pb), prompting future assessments of HMs in various environmental matrices. In Australian homes, elevated blood lead levels in children were found to affect their IQ, posing potential non-carcinogenic risks from Pb and Cr but no carcinogenic risks (Doyi et al. 2019). Limited studies focused on metal bioavailability through chemical speciation, including one in Malaysian classrooms using PBET. Although no association was found between HM concentrations and children's respiratory systems, continuous monitoring was recommended to safeguard children from long-term HM exposure (Tan et al. 2018).

The number of publications in this field increased dramatically from 2 in 1990 to 19 in 2001, 38 in 2012, 86 in 2017, and 148 in 2021. In 2023, 19 documents have already been released. The author with the most publications on this subject is Pat E. Rasmussen (19), who is followed by Mohd Talib Latif (16) and Xinwei Lu (15). China has published the most articles globally (374), followed by the USA (325) and India (96). Most studies on the topic of HMs in indoor dust of residential areas have been published in *Science of the Total Environment* (120), *Environmental Science and Pollution Research* (120), and *Environmental Geochemistry and Health* (62), and together they account for 62. Analysis of the keywords (Figure S8) indicated studies on indoor/in-house/household dust with a greater focus on lead apart from metals like cadmium, copper, and zinc. The studies also focused on identifying metals in children by analyzing their blood samples. At the same time, indoor air environments were also investigated, where source apportionment, health risk assessment, and human exposure were assessed along with particulate matter studies.

Commercial areas

Schools

A considerable amount of their time is spent in kindergartens/schools. High respiration rates, physical activity, and behavioral and physiological characteristics of children make them vulnerable to dust exposure. Due to their small body weight, children have higher oxygen demand, hence high respiration rates (Praveena et al. 2015). The location of schools near busy-trafficked roads can contribute significantly to higher metal exposure from dust in schools. Physical activities, like sucking hands/fingers and consuming non-food items, expose them to toxins in indoor dust via dermal and ingestion routes (Meza-Figueroa et al. 2007; Chen et al. 2014). The higher absorption rate of HMs in the gastrointestinal tract and increased hemoglobin sensitivity are other behavioral and developmental characteristics affecting children (Tong and Lam 1998; Meza-Figueroa et al. 2007). Once HMs are absorbed, they can lead to stunted growth and decreased physical, mental, and neuropsychological abilities (Faiz et al. 2009). Even lower doses over more extended periods can cause metal poisoning due to their non-degradable nature (Tong and Lam 1998; Meza-Figueroa et al. 2007; Chen et al. 2014). Elevated metal concentrations were discovered in soil and dust samples from Xi'an, China (Chen et al. 2014). Dust samples showed higher metal concentrations compared to soil (except Mn, As, V, Ni). The campus dust was not contaminated with As, Ni, Mn, and V, moderately contaminated with Ba, Cr, and highly contaminated with Zn, Pb, Co, and Cu (Table 1). Nemerow synthesis pollution indices indicated HM contamination in dust samples suggesting the need for more attentiveness in schools of Xi'an, China. Metal concentrations (mg/kg) in ten preschools in Selangor, Malaysia, showed the following trend: Fe (4,801 ± 1,873) > Pb (253.5 ± 83.2) > Zn (144.9 ± 73.4) > Cr (11.9 ± 6.8) > Cd (0.23 ± 0.10) (Latif et al. 2014). Fe concentration was highest in soil dust (8225 ± 6,800), children's palms (3882 ± 3401), and interior walls (1865 ± 756). Indoor dust had high quantities of Cd, Pb, and Zn, while Cr, Cd, and Zn were found in indoor walls and palms of children predominantly from anthropogenic origins.

Latif M T primarily studied indoor environments of schools (Latif et al. 2014), university buildings (Sulaiman et al. 2017), particulate matters (Srithawirat et al. 2016; Latif et al. 2018), and metal compositions during renovation (Othman et al. 2018). The metal concentrations were studied in Anhui rural areas of China (Lin et al. 2015), indoor dust in Huainan (Lin et al. 2016), scalp hair of Huainan urban areas (Fang et al. 2019), Xinqiao mining area and rural kitchen dust (Lei et al. 2020), and driving schools of Wuhu (Lin et al. 2021). Lin Y. S and Fang F. M had similar research areas and co-authored most papers. Among the top 5 articles, Mai BX has studied e-waste recycling areas since 2011. One of her publications on scalp hair was recently published in 2021 (Kogianni et al. 2021). Samara C. worked chiefly on metals in particulate matters of indoor environments.

The order of metal concentrations in indoor dust of Universiti Teknologi MARA (UiTM) in Malaysia were as follows: As < Pb < Cu < Zn < Fe (Sulaiman et al. 2017). According to PCA results, the sources of these metals are mixed for Fe and Cu and anthropogenic for As, Pb, and Zn. Although no non-carcinogenic risks were found, elevated concentrations in the long term might pose risks to adults. Dust, automobiles, plantations, and industrial activity were the main contributors to HM pollution in Malaysian schools (Tan et al. 2018). The mean bioavailable metal concentrations followed the order: Pb < Cd < As < Co < Cr < Ni < Cu < Zn. Apart from Cu, there was no direct connection between bioavailable HMs and respiratory symptoms (odds ratio = 0.03). The existing metal concentrations posed no health risks (carcinogenic or non-carcinogenic). In the schools of Lahore, Pakistan (Rehman et al. 2020)**,** strong contamination of Cd and Zn and moderate contamination of Pb, Cr, and Cu were found. The hazard indices followed the order: Cr (4.61E−01) in industrial > Pb (4.30E−01) in roadside > Pb (4.30E−01) in residential. Ingestion was the prominent pathway of metal exposure. Cr had the most major carcinogenic risk (1.53E−06) in the industrial school area. Hence, metals pose health risks via the ingestion pathway in children. In Toronto (Al Hejami et al. 2020)**,** indoor dusts from laboratory dusts of Ryerson University **r**ecorded the highest (0.5–0.67 × indoor dusts from households, offices and classrooms) metal concentrations (in mg/kg) (Ba = 152; Cd = 12; Cr = 87; Cu = 411; Mn = 216; Ni = 146; Pb = 86; Zn = 3571). EF for Cd, Cu, Pb were >1, whereas that of Zn ranged from 15–554, indicating anthropogenic internal sources of metal pollution. Zhao studied the contamination degrees and health risks from three university libraries in Qingdao and found Pb, Cd, Cu, Zn, Ni, and As concentrations in the dust to be higher than the soil background values (Zhao et al. 2021). The enrichment factors revealed severe enrichment of Cd (39.61), Zn (39.76), and Cu (15.27); moderate enrichment of Pb (8.14) and Ni (3.25); and minor enrichment of Cr (2.30) and Mn (1.38) in the dust. There were no non-carcinogenic risks posed by these metals. As and Cd posed significant carcinogenic risks (>1 × E−06). However, as the summation of total risks did not exceed 1.0E−05, the carcinogenic risks were acceptable. Hence, there were no immediate health risks, even after Cd posing potential ecological risks.

The proximity of schools to heavily trafficked roads significantly influenced indoor metal concentrations. For instance, Chen's research in Xi'an, China revealed higher metal concentrations in dust near kindergartens compared to the soil (Chen et al. 2014). Metal concentration studies extended beyond school indoor dust to include particulate matters, university buildings, rural areas, laboratory dust, and scalp hair. While most studies identified distinct metal sources and associated health risks (Sulaiman et al. 2017), only a limited number explored the link between bioavailable HMs and respiratory symptoms (Tan et al. 2018).

Research on HM analysis in indoor dust of schools began in 1992 with 2 publications, and 198 articles have been observed. While 0–6 documents were published till 2013, a maximum of 28 publications was recorded in 2021. Among the authors, Mohd Talib Latif published the most significant number of documents (8), followed by Xinwei Lu (7), Diana Meza-Figueroa (6), and Hao Chen (6). Among countries, China topped the publication list (50), followed by the USA (36) and Malaysia (12). *Science of the Total Environment*, *Environmental Geochemistry and Health*, and *Environmental Science and Pollution Research* were the journals involved in maximum publications with 17, 14, and 12 articles, respectively. Examining the keywords revealed studies being done on health risk assessment and spatial dispersion (Fig. S9), bioaccessibility, and pollution caused because of HMs (like Pb and Cd) apart from focusing upon health risks in schools (especially nursery and elementary schools) and air pollution in the indoor atmosphere.

Offices

Office environments are potent targets of metal exposure for workers (Zhang and Reynolds 2019). Often, metal concentrations in office dust are higher than in house dust (Xiang et al. 2016). The indoor dust of homes and offices was measured in Istanbul, Turkey, and their metal concentrations (mg/kg) were as Ni = 120–2600, Mn = 8–1300, Co = 2.4–25, Zn = 210–2800, Cr = 2.8–460, Cu = 62–1800, Pb = 3–200, and Cd = 0.4–20 (Kurt-Karakus 2012) (Table 1). The ingestion route posed the maximum carcinogenic risks. Compared to ingestion and inhalation pathways, the dermal way posed negligible risks. Among metals, Cr posed carcinogenic risks (children = 2.7E−05, adult = 3.7E−05) within permissible limits of EPA (1.0E−04 to 1.0E−06). These metals posed no non-carcinogenic risks.

In Ogun State, Nigeria, metal concentrations were measured in the indoor dust of living rooms, offices, and classrooms (Olujimi et al. 2015). The geo-accumulation index followed the trend: As (1.64) < Ni (2.48) < Pb (2.61) < Cr (3.28) < Cd (4.84). Among different exposure routes, health risks were posed by ingestion. The inhalation of Hg vapor in children posed the highest non-carcinogenic risks (0.13). Only Cr posed significant carcinogenic risks in adults and children, while all other metals like Co, Pb, Cr, Ni, Cd, and As were within acceptable ranges. Metal concentrations were measured in indoor environments, like offices, homes, laboratories, and classrooms in Canada (Al Hejami et al. 2020). Offices, homes, and classrooms had metal concentrations almost 0.5−0.67 times lower than in laboratory dust values. The enrichment factors of metals like Zn, Cu, Cd, and Pb ranged from 15 to 554, signifying internal anthropogenic metal sources. While in Iran, metal concentrations in offices, schools, houses, and labs were measured (Ardashiri and Hashemi 2018). In offices, the hazard indices were as Pb < Zn < Cu < Ni < Cd < Cr. Children were found to be more vulnerable to toxic substances compared to adults.

Metal concentrations in offices were compared to that of homes in Istanbul, Turkey (Kurt-Karakus 2012). Although no significant risks of cancer were posed from Cr in Istanbul, it was not representative of other heavily industrialized cities. Also, as only dusts of <100 μm particle sizes were considered, particle sizes of <10 μm, are bound to be more enriched with metals. Future studies on wider particle fractions and larger datasets are recommended for accurate extrapolation. Laboratory dusts were found to have higher metal concentrations, in both Toronto, Canada and Bushehr, Iran (Ardashiri and Hashemi 2018; Al Hejami et al. 2020). Metal concentrations in dusts from offices, houses and classes of Toronto were almost similar (except Zn and Mn) (Al Hejami et al. 2020). It is noteworthy that sources contributing to metals in indoor dusts exhibited variations both between and within different indoor environments, underscoring the presence of distinct sources within these settings. Lastly, a comparison was made between dust samples collected from various indoor environments, including offices, classrooms, and living rooms (Olujimi et al. 2015). Ingestion emerged as the primary route of exposure, and carcinogenic effects remained within acceptable limits.

Research on HM analysis in indoor dust of offices began in 1994. Only 0–7 documents were published yearly, a maximum of 7 in 2019 (55 publications). Among authors, Susana Marta Marta Almeida, Cristiana Franco, and Ping Xiang published a maximum of two documents each. At the same time, among countries, the USA reported the maximum number of articles published (15), followed by China (9), England (5), and South Africa (5). Concerning journals, *Science of the Total Environment*, *Environmental Research*, *Environment International*, and *Environmental Science and Pollution Research* published 5, 4, 3, and 3 documents, respectively. Analysis of the keywords (Figure S10) denoted a prominence of studies on health risk assessment, occupational exposure, biomonitoring, bioaccessibility, source apportionment, diseases, and mortality caused by HMs apart from indoor air pollution assessment.

Industrial areas

Manufacturing areas, smelters, and repairing workshops

Workplace environments also play a critical role in metal exposure and its consequent derogatory health effects (Sadovska and Matter 2012). At times, even the metal concentrations in workplaces can be more than outdoors, especially in industries (Myers and Maynard 2005) (Table 1). In Pakistan, Sialkot, health risks from HMs in leather manufacturing industries were studied (Junaid et al. 2017). Cr was highly enriched here, and Cr (VI) posed higher carcinogenic risks than Cd. Leather manufacturing activities like cutting, shivering/crusting, and stitching were the primary sources of these metals. The bio-monitor samples like blood, urine, and hair samples also showed significant contamination from HMs.

In Durgapur, West Bengal (Pal et al. 2018), a wide range of bio-accessible Pb concentrations in indoor dust. The highest Pb concentration was in residential areas with industrial activities at Sagarbhanga (157±45.8 mg/kg). Nevertheless, it was found safe for children and adults. Indoor dust samples were collected from Chengdu, machinery, automobile, food, medicine, various construction sites, and vehicles. A negative correlation was found between floor height and metal concentrations in Chengdu, China (Cheng et al. 2018). Interestingly, higher metal concentrations were found indoors than outdoors (except Cr). This might be due to the corrosion of alloys indoors. For metals like Pb, Cu, Ni, and Zn, ingestion was the primary exposure route, while for Cd and Cr, dermal contact was the main route. However, the overall non-carcinogenic and carcinogenic risks were the only minors. In Russia, indoor dust samples were collected from Chelyabinsk, a major industrial center. There were negligible non-carcinogenic risks (Krupnova et al. 2019). Carcinogenic risks from As and Cr were within acceptable levels for adults (1.0E−06 to 1.0E−04) and harmful to children (>1.0E−04) as they used carcinogenic risk of 1.36E−04, while Cr posed 2.81E−04 in children.

Metal concentrations were 30 times greater in the proximity of a smelting area in another Chinese city than in the surrounding environment (Cao et al. 2020). The Hazard index values from As and Pb were more significant than 1. Hg contributed to 73.44 of the total hazard indices, among other metals like Cr, Zn, and Mn. Non-carcinogenic risks were mainly from exposure to indoor dust. Floor dust from mechanical repair workshops (MRWs) and battery repair workshops (BRWs) in the Iranian industrial city of Yazd revealed elevated amounts of Cd, Zn, Pb, and Cu (Sabouhi et al. 2020). Principal component analysis and Pearson's correlation indicated that workshop activities were the sources of these metals. Considerable non-carcinogenic risks were posed by Pb (HQ_{ing} mean = 2.91, HI_{mean} = 3.03), while carcinogenic risks for Cd and Cr were below safe limits (1.0E−06). The blood lead levels of BRWs were almost seven times that of MRWs (MRW = 3.33 µg/dL, BRW = 21.4 µg/dL), indicating severe Pb exposure in BRWs. This might have been due to the unavoidable use of Pb in battery workshops. Rahman et al. studied indoor dust from windows of industrial buildings in Dhaka, Bangladesh. Higher concentrations were observed for Cu, Zn, Pb, Fe, and Sr (Rahman et al. 2021). Only Pb (HI =1.9) posed a significant non-carcinogenic risk in children, while As posed carcinogenic risks ranging from 5.02E−07 to 1.21E−05. Non-cancer risks for As, Mn and Zn posed hazard index.

In Chelyabinsk area of Russia, the carcinogenic risks were within acceptable limits in adults, As and Cr posed significant carcinogenic risks to children (Krupnova et al. 2019). In Yazd city, Iran only Pb and Cu posed potential non-carcinogenic risks from BRWs (Sabouhi et al. 2020). There was an overestimation of risk, as the parameters were calculated assuming 100% intake from dust. The blood lead levels of on-site workers surpassed 5 µg/dL, indicating detrimental health effects. Thus, constant monitoring through toxicological and epidemiological parameters was suggested. In southwest China, the average daily dose of

Pb was 1.51 times more than FAO/WHO limits (Cao et al. 2020) . Even significant non-carcinogenic risks were posed by Pb (60%) and As (24%), while carcinogenic risks were insignificant. The non-carcinogenic risks were explicitly attributed to Cr, Zn, Hg, Cu, and Mn. Ingestion was the primary pathway of exposure. In Dhaka, both natural and anthropogenic sources were responsible for metal contamination (Rahman et al. 2021). The ingestion pathway was the primary route for posing non-carcinogenic risks in the population. Although there were no significant carcinogenic risks, regular monitoring in the future was suggested.

Research on HM analysis in indoor dust has observed 280 publications beginning from 1994, with 1–7 documents followed till 2010; 15 were published in 2015, 21 in 2018, and 30 in 2021. Among authors, Joachim Heinrich published the most documents (5) among the authors, followed by Yves Noack (4) and Guijian Liu (4). Among countries, China released the most documents overall (67), followed by the USA (58), Iran (23), England (21), and Australia (20). Among journals, *Science of the Total Environment*, *Environmental Geochemistry and Health*, *Environmental Science and Pollution Research*, and *Environmental Pollution* published 21, 19, 15, and 12 documents, respectively. Analysis of the keywords (Fig. S12) indicated studies on health risk assessment, source identification, bioaccessibility, exposure, speciation, and ecological risks caused by HMs in indoor dust, focusing on children, toxic metals, and indoor environments. Proper scientific disposal of electronic instruments and batteries can reduce the metal concentrations in leachate.

E-waste recycling areas

Electronic waste (e-waste) recycling activities include various electronic items like computers, mobile phones, televisions, refrigerators, video cameras, audio recorders, and printers (Suzuki et al. 2018). Recycling of these goods emits various toxic metals (Guo et al. 2009) and gases. Even non-intensive recycling activities like collection, storage, transport, and manual dismantling may have serious health concerns (Suzuki et al. 2018). The paper titled “HMs in food, house dust, and water from an e-waste recycling area in South China and the potential risk to human health” received 143 citations where food, house dust, and water samples were tested for their metal contents, along with health risks in South China (Zheng et al. 2013) (Table 1). Although non-carcinogenic risks in adults were majorly attributed to diet (rice = 3.3, vegetables = 2.2, house-dust = 1.9), children were predominantly exposed to house dust (HI = 15). Groundwater posed more significant risks than the residents' drinking water supply. Considering the carcinogenic risks in adults and children, Pb posed the maximum risks from oral intake in adults (8.0E−05) and children (3.0E−04) compared to inhalation or dermal contact.

In southern China, indoor dust from e-waste recycling in rural and urban areas was measured (He et al. 2017). The E-waste recycling area recorded higher metal values (except Zn) than other areas. The median values of their concentrations (mg/kg) were as the following: - Cd = 2.46 to 40.4, Pb = 206–1380, Cu = 217–1200, Cr = 25.3–134, Zn =176–212. Except Zn, all other metals had higher concentrations in this e-waste recycling area. Metals like Pb and Cd had sources from e-waste recycling activities, while Cr, Zn, and Cu originated from household products. The estimated daily intake of Pb was 18 times higher than reference in toddlers, indicating their higher exposure risks.

In the Guangdong province of China, a former e-waste recycling area was evaluated for HMs in PM_{10}, dust, soil, and crops (Yu et al. 2019). Metals in PM_{10} dust were lower than reported previously, whereas vegetables and soils recorded higher metal concentrations. Soil played a critical role in high metal concentrations in crops of this region. HM concentrations in crops followed the order Pb < Cu < Ni < Cd < Zn. For metals like Cu, Zn, Ni and Cd rice consumption was the primary route of exposure, where the average daily doses varied from 78 to 91.7% in adults and 75.2–86.7% in children. While for Pb, soil ingestion was the primary route of exposure in adults (ADD = 48.9%); and ingestion of rice (28.6%), dust (23.7%), and vegetables (44.7%) in children. Consumption of crops contributed majorly (99.9%) to health risks in adults and children. The carcinogenic risks from Pb had exceeded the acceptable levels.

The sources of HMs posing health risks to the population varied. Like, in South China, house dust in children and diet in adults were the primary sources posing non-carcinogenic risks (Zheng et al. 2013). In South China, Pb derived from e-waste recycling activities, posed the highest carcinogenic risks in toddlers (He et al. 2017). In Guangdong, crop consumption was the primary route of exposure to metals, posing various health risks. In Guangdong province soil repair could reduce the risks from metals to the locals (Yu et al. 2019). Pb was the primary metal of concern in most of these studies.

With 29 publications in this area, the 1st article was reported in 2011, and 0–5 documents have been published since then, with a maximum of 5 articles reported in 2016. Among authors, Xia Huo and Ming Hung Wong have published 3 articles each, while among countries, China has topped the publications list (18 documents), followed by the USA (7) and Canada (4). Among journals, *Science of the Total Environment*, *Environmental Science and Pollution Research*, and *Environmental Science Technology* have published 8, 5, and 4 documents, respectively. Analysis of the keywords (Fig. S11) suggested studies being carried out related to risk assessment, occupational exposure, spatial distribution, and bioaccessibility of HMs in e-waste recycling locations and on printed circuit boards.

Metal mining areas

Mining is a widely known anthropogenic activity that leads to HM pollution in air, water, and soil. Mining activities emit metals that are easily carried into the atmosphere and deposited in soils, streets, and indoors of neighboring areas of mines (Li et al. 2020). Population residing in these areas are easily exposed to these metals via ingestion, inhalation, or dermal contact (Kurt-Karakus 2012; Rasmussen et al. 2013). Occupational hazards like pneumoconiosis and malfunctions in the immune, physical, mental, and endocrine systems are common in coal miners (Wang et al. 2022a).

In Istanbul, Turkey, eight metal concentrations were measured in dust from residences and workplaces. The concentration ranges (mg/kg) were Ni = 120–2600, Co = 2.4–25, Cr =2.8–460, Mn =8–1300, Pb =3–200, Cd = 0.4–20, Cu = 62–1800, and Zn = 2.8–460 (Kurt-Karakus 2012) (Table 1). Carcinogenic risks from Cr for adults (3.7E−05) and children (2.7E−05) were within an acceptable range of EPA (1.0E−06 to 1.0E−04). Among the three exposure pathways, maximum non-carcinogenic risks were the following: the ingestion route posed significant non-carcinogenic effects, followed by the dermal and inhalation routes. When compared to ingestion and dermal routes, neglect was posed from the inhalation route. The hazard index values were below 1, suggesting no potential risks to the population.

Mining activities also affected the indoor homes of Oruro, Bolivia (Barbieri et al. 2014). Non-essential metals (Pb, Sb, Cd, As, Sn) in hair samples of children were correlated with that of metals in dust, whereas no correlation was found with essential elements like Zn and Cu. Different behaviors of children (pica) modified the exposure to various metals.

In the Greece mining village of Stratoni, researchers looked at the links between household dust and garden soil for the uptake of Pb in 2014. (Argyraki 2014). Household dust was discovered to be an essential indicator for assessing health risks, and the influence of outdoor and interior settings on the destiny of Pb in the environment of Stratoni was underlined. The highest Pb concentrations (mg/kg) in soil and house dust were 2040 and 7000, respectively. The highest concentrations of Pb (mg/kg) in house dust samples were almost 3.5 times that of soil (2040 mg/kg). The closest homes to the ore-processing facility, 300–600 m away, had the most unique Pb contents. In dust samples, Pb was predominantly available in the fine grains of size (<10–20 µm diameter), while in soil samples, it was enriched in the Fe-Mn oxide forms. According to the integrated exposure uptake biokinetic model, more than 61% of blood lead levels were higher than 10 µg/dL.

Characterization and metal composition of house dust were collected from residential homes, entranceways, and trafficked areas (low and high) in Canada (Dingle et al. 2021). The metal concentrations of outdoor soils resembled entranceways, mainly from crustal origins. While Zn, Pb, and Cu concentrations inside the houses were almost six times higher than outside, depicting their in-house origins. Pb concentrations were elevated in low-traffic areas.

In a pioneering study from the past, (Argyraki 2014) assessed total and bioaccessible lead (Pb) levels for the first time in garden soil and house dust in Stratoni village, Greece. This study played a crucial role in risk assessment and hazard characterization in sulfide-ore processing areas, shedding light on the contributions of indoor dust and soil to metal exposure. These databases proved valuable for decision-makers and public health professionals, enabling them to identify and address persistent pollution levels effectively. In Oruro, it was observed that children's playing behavior significantly influenced their exposure to indoor metals. Consequently, recommendations included the improvement of household conditions, along with implementing social, educational, and cultural campaigns. Furthermore, a study conducted in Canada by (Dingle et al. 2021) revealed significant differences in metal concentrations between dust in heavy traffic areas and entranceways. Specifically, Zn, Cu, and Pb concentrations were higher in trafficked areas compared to entranceways. To enhance the accuracy of health risk assessments for Cu, Pb, and Zn, the characterization of $PM_{2.5}$ and PM_{10} was suggested. Additionally, concurrent indoor and outdoor sampling was recommended to gain a better understanding of exposure and transport routes.

With a total of 88 publications, 0–14 articles have been reported since 1995, with the maximum number of publications observed in 2016 (14 documents). Among authors, Joachim Heinrich published the most significant number of articles (4), followed by Rosalind Schoof, Inke Meyer, and Eduardo Saez, who published 3 documents each. Among countries, the USA published the maximum number of documents (32), followed by China (17) and England (10). Among journals, *Environmental Geochemistry and Health*, *Science of the Total Environment*, *Applied Geochemistry*, and *Environment International* published 9, 8, 4, and 4 documents, respectively. The keywords (Fig. S13) indicated studies on risk assessment, source apportionment, bioaccessibility, bioavailability, and exposure to young children concerning HMs (especially Pb and As) in smelter and mining areas.

Control measures

As metal exposure in today's indoor environments has become inevitable, one can adapt to various control measures to reduce their metal exposure through indoor environments like:

- Adapting to air pollution control measures, especially in transportation and industrial exhausts.
- Regular wet cleaning or/and efficient vacuum cleaners indoors (Ogilo et al. 2017).
- Removal of shoes at entryway.
- Renovating old homes of poor hygienic conditions.
- Use vacuum cleaners to remove indoor dry dust.
- • Routinely removing interior dust and avoiding using products with HMs (Latif et al. 2014; Tashakor et al. 2022).
- Use clean fuels in cooking and installing cleaning equipment like chimneys to capture gases produced from various cooking activities (Chu et al. 2020).
- Cost-effective air filtering systems are efficient in particulate matter removal from indoor air (Tan and Zhang 2004; Kim et al. 2018; González-Martín et al. 2021; Wang et al. 2022b).
- Improving the air tightness of buildings is an excellent option to limit the incoming outdoor pollutants (Bone et al. 2010; Wu et al. 2018; Toyinbo 2019).
- Use mechanical ventilation with efficient air purification systems (Polidori et al. 2013; Cui et al. 2017; Ji et al. 2021; Aldekheel et al. 2022).
- Installation of low-cost sensors to provide real-time pollutant measurements (Lambrou et al. 2014; Kumar et al. 2015).
- Source identification and spatial distribution patterns in industrialized and traffic-affected areas.

Laws and regulations; control standards and exposure risk assessment

Various countries have implemented a range of laws, regulations, pollution control standards, and exposure risk assessment methods to effectively manage HM contamination in indoor dust. Each country may have its own specific set of regulations and guidelines tailored to address these issues based on their unique environmental and public health concerns. These regulations aim to establish permissible limits for HMs in indoor dust, provide guidelines for sampling and measurement techniques, and prescribe mitigation strategies to reduce exposure risks. They often involve collaboration between governmental bodies, environmental agencies, health organizations, and industry stakeholders to ensure comprehensive management of heavy metal pollution in indoor environments. Furthermore, exposure risk assessment methods are employed to evaluate the potential health risks associated with HM exposure in indoor dust. These assessments consider factors such as individual exposure routes (ingestion, inhalation, dermal contact), exposure durations, and body weight to estimate the potential health impacts on different population groups. By quantifying exposure risks, policymakers and regulatory bodies can make informed decisions and implement appropriate measures to safeguard public health.

International

Pollution control standards, such as LEED (Leadership in Energy and Environmental Design), play a crucial role in guiding the design and management of sustainable buildings (Chi et al. 2020; Liu et al. 2022). These standards promote the use of low-emission materials and set restrictions on various HMs in construction materials. International Organization for Standardization (ISO) standards, such as ISO 14001, also address indoor pollution reduction, including HMs (Sartor et al. 2019; Camilleri 2022). The World Health Organization (WHO) standards for Indoor Air Quality establish guidelines for various indoor air contaminants to protect public health. Moreover, the ISO 16000 series has established appropriate sampling and measurement standards for HMs in dust (Motalei 2014; Volland 2021). To evaluate potential health concerns associated with HM exposure, toxicity reference values established by the Environmental Protection Agency (EPA) or WHO are used. These values aid in determining exposure risks. Exposure models like the Integrated Exposure Uptake Biokinetic Model (IEUBK) assist in calculating potential intake of HMs through ingestion, inhalation, and dermal routes over a specific exposure duration (Argyraki 2014; Doyi et al. 2019).

United States

The guidelines set forth by the US Environmental Protection Agency (EPA) address requirements for door air quality, hazardous chemicals, and concentration limits for HMs in indoor environments (Motalei 2014). The EPA's Indoor Air Quality (IAQ) guidelines also provide recommendations for addressing dust sources and implementing solutions such as ventilation to minimize indoor dust levels (Saini et al. 2020). The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 62.1 focuses on ventilation strategies for achieving acceptable indoor air quality and includes measures for managing dust (Li 2020). Furthermore, the Occupational Safety and Health Administration (OSHA) establishes regulations to protect workers from occupational exposure to HMs in various industries (Johnson 2020). These standards aim to safeguard workers and promote safe practices in relation to HM exposure.

European Union

The European Union Reference Laboratory for Indoor Air Quality (EU-RL-IAQ) has established reference values for HMs in indoor dust (Malings et al. 2020). In addition, building standards within the European Union focuses on addressing indoor air quality and implementing dust control measures in buildings. Green building rating systems, such as the one mentioned by (Sánchez Cordero et al. 2020) and (Zhang et al. 2019), promote the use of sustainable materials and practices to prevent indoor dust pollution. These initiatives aim to improve indoor air quality and minimize the presence of HMs in indoor environments.

India

While there are no specific pollution control standards for indoor dust in India, certain regulations indirectly contribute to the control of dust in indoor environments. The National Ambient Air Quality Guidelines (NAAQS) provide guidelines for various pollutants that help regulate outdoor pollution, consequently influencing the presence of metals in indoor dust. The Environmental Protection Act (EPA 1986) empowers both state and central pollution control boards to regulate and mitigate indoor air pollution caused by dust. The Ministry of Labour and Employment establishes norms and laws for workplace occupational safety and health, which also have implications for controlling indoor dust pollution. Although there is no specific framework solely dedicated to indoor dust control in India, these regulations and norms serve as important measures in addressing indoor air quality concerns, including dust-related pollution.

Bibliometric observations

A total of 1594 articles were observed during the search (including 76 review articles and 1507 research articles). The research in this area began in 1990 (2 publications). It grew exponentially from 24 publications during 1990–1994 (Phase 1), 58 during 1995–1999 (Phase 2), 110 during 2000–2004 (Phase 3), 151 during 2005–2009 (Phase 4), 267 during 2010–2014 (Phase 5), 536 during 2015–2019 (Phase 6), and 447 during 2020–2023 (till February 24th) (Phase 7) (Fig. 2). Such a research trend suggests an increasing interest among research communities in many regions of the world, possibly due to the increase in pollution and associated risks caused by HMs in indoor dust. The list of most prolific authors includes Pat E Rasmussen (19), Xinwei Lu (17), and Latif Mohd Talib (16) (Fig. 3a). In terms of citations received, Behnam Keshavarzi was the most cited author (588), followed by Xinwei Lu (568) and Farid Moore (562). Among countries, China published the highest number of documents (396), followed by the USA (342), India (97), England (95), and Australia (81) (Fig. 3b). However, the USA received more citations (15023) when compared to China (14858). China has been the front-runner in publishing articles, possibly due to the intensively active Chinese scientific programs and the large amount of investment put by the Chinese government in research and development. Concerning funding agencies, the National Natural Science Foundation of China (241), the US Department of Health and Human Services (57), and the National Institute of Health (54) were the most active, which was in line with the maximum

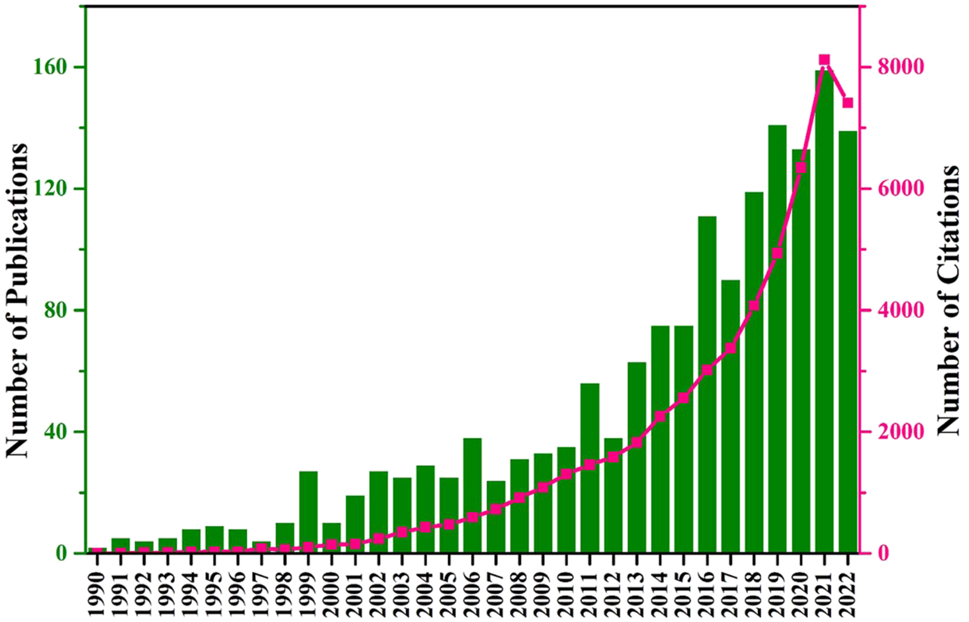

Fig. 2 Evolutionary trend of publications on heavy metals in indoor dust

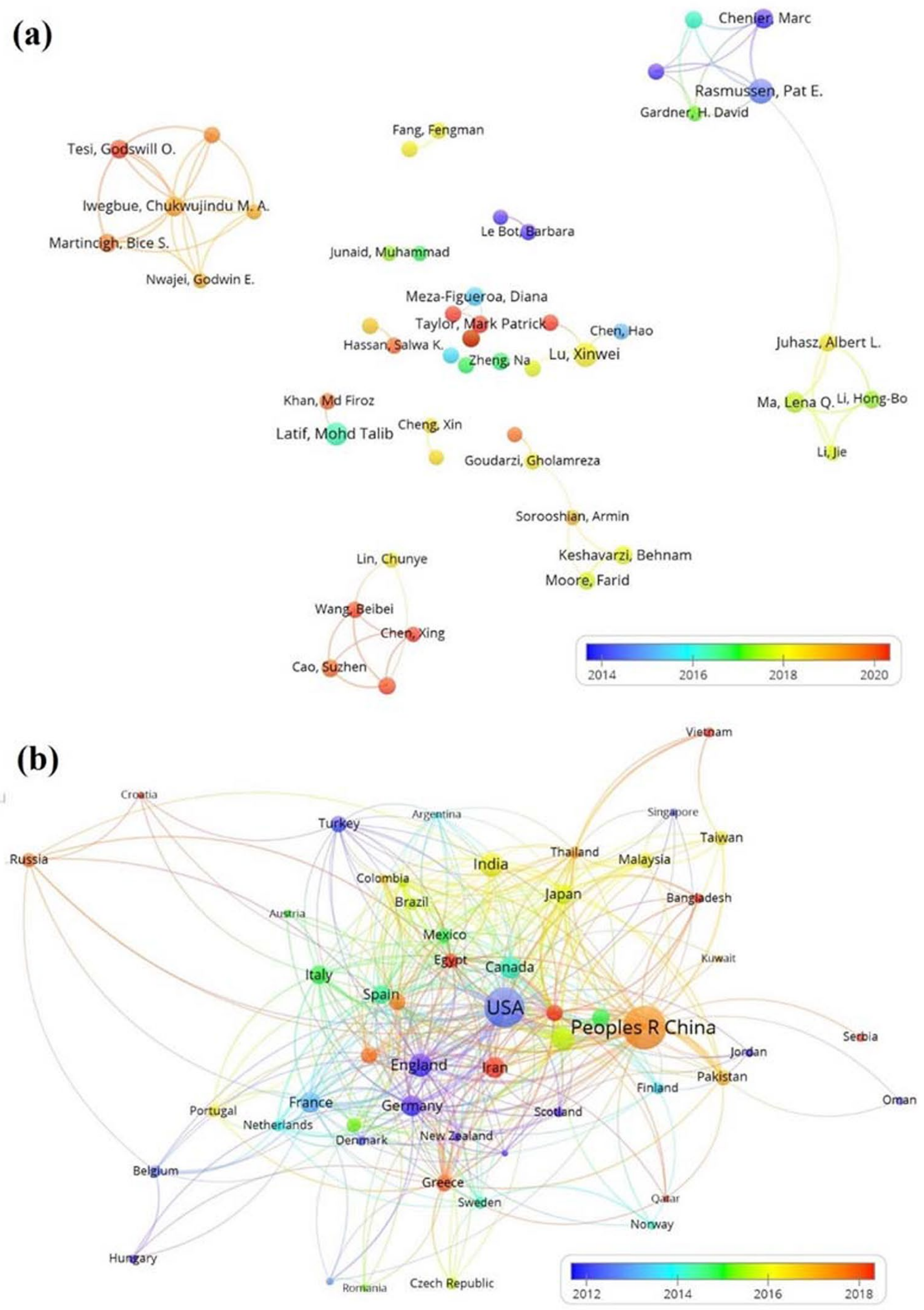

Fig. 3 Bibliometric maps of networks between **a** authors and **b** countries (with minimum five publications) on heavy metals in indoor dust

number of documents published by China and the USA. The list of most productive journals is given in Table S2.

The research areas in HMs of indoor dust varied from Environmental Science Ecology (1142), Public Environmental Occupational Health (296), Engineering (253), Toxicology (155), Water Resources (120), Meteorology Atmospheric Sciences (113), and Chemistry (71). Journals publishing large number of articles on HMs in indoor environments include *Science of the Total Environment* (127 documents) followed by *Environmental Science and Pollution Research* (93), *Environmental Geochemistry and Health* (68), *Environmental Pollution* (56), *Environmental Monitoring and Assessment* (48), *International Journal of Environmental Research and Public Health* (46), *Chemosphere* (45), *Environmental Research* (41), *Atmospheric Environment* (37), and *Environment International* (33). However, when sorted based on citations per article (CPA), *Atmospheric Environment* tops the list (83.32 CPA and 3083 citations), followed by *Environment International* (71.18 CPA and 2349 citations), *Science of the Total Environment*

(59.98 CPA and 7618 citations), *Chemosphere* (41.91 CPA and 1886 citations), *Environmental Pollution* (40.02 CPA and 2241 citations), *Environmental Research* (36.95 CPA and 1515 citations), *Environmental Monitoring and Assessment* (25.42 CPA and 1220 citations), *Environmental Geochemistry and Health* (24.47 CPA and 1664 citations), and *Environmental Science and Pollution Research* (15.4 CPA and 1432 citations).

In the articles on HMs in indoor environments, 137 keywords showed a minimum of 20 occurrences (Fig. 4). The words with more than 200 occurrences included HMs (469), dust (292), lead (271), exposure (271), contamination (269), street dust (261), pollution (241), source appointment (233), particulate matter (230), and metals (209). The keywords indicated studies on indoor/in-house/household dust where lead was the most observed HMapart from cadmium, copper, and zinc. The studies focused on identifying metals in children and young individuals by analyzing their blood samples, while vegetables were also analyzed for metals. The keywords also showed an evolving pattern (Fig. 5) where (i) during 1990–1999 the studies involved analysis of heavy/trace metals in dusts and aerosols, exposure of HMs to children, air pollution, and indoor dust studies in addition to bioavailability and mortality caused due to HMs (Fig. S1 and S2); (ii) during 2000–2009 the number of studies, which increased significantly, involved analyses of bioavailability, risk assessment, geochemistry and speciation of HMs, reports on polycyclic aromatic hydrocarbons, and articles on air pollution, asthma, allergy sensitization, aerosols, and particulate matter in indoor urban environments (Figure S3 and S4); and lastly (iii) during 2010–2023 the number of studies, which increased exponentially, involved analyses of speciation, bioavailability, bioaccessibility, exposure, risk evaluation, geographic distribution, and source attribution of polycyclic aromatic hydrocarbons and potentially hazardous substances in household dusts apart from studies on aerosols, PM_{10}, and $PM_{2.5}$ in indoor environments (Fig. S4, S5 and S6).

Fig. 4 Keyword co-occurrence map for heavy metals in indoor dust (minimum 20 occurrences)

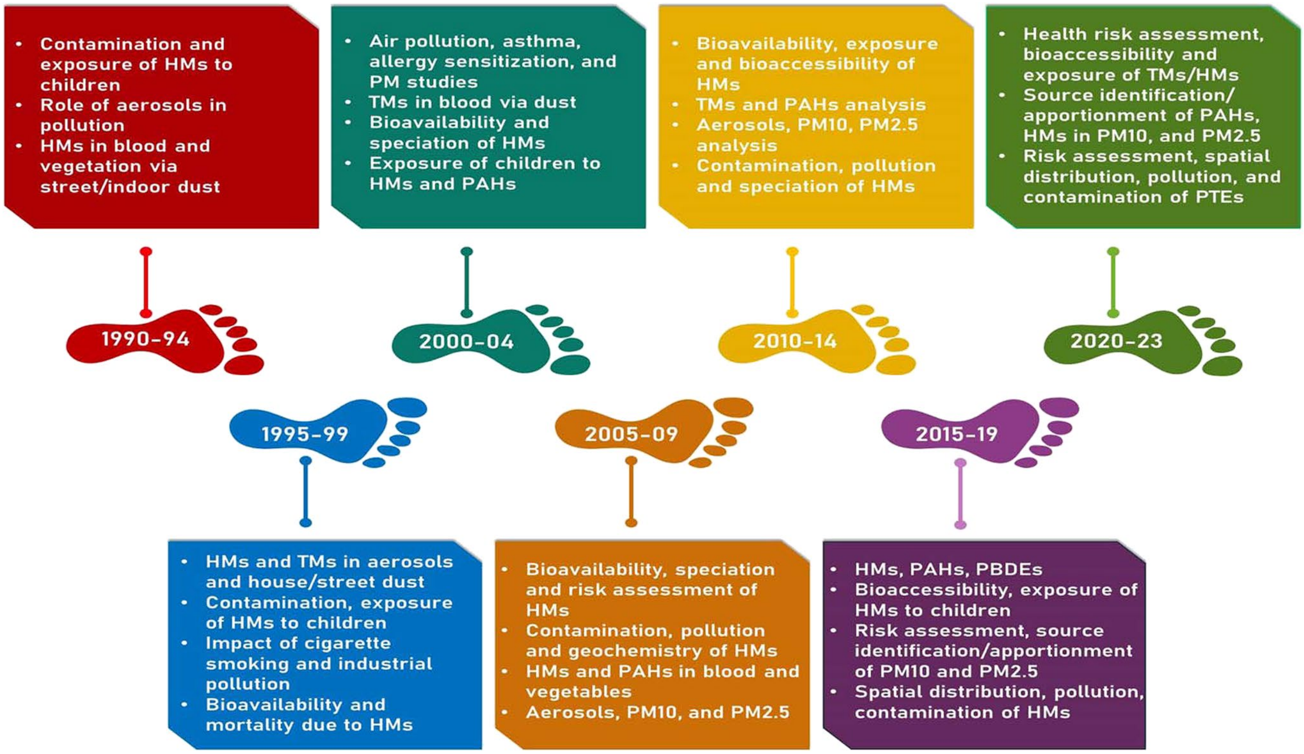

Fig. 5 The evolution of studies on heavy metals in indoor dust as suggested by the keyword co-occurrence analysis for different time. TM, total metal; HM, heavy metal; PTEs, potentially toxic elements; PAHs, polyaromatic hydrocarbons; PBDE, polybrominated diphenyl ether

Knowledge gaps, conclusions, and future scope

Although various reviews have been conducted on HMs in indoor dust, this work is the first systematic review of indoor environments. Stress should be given on time spent in various microenvironments along with daily activity patterns for more precise estimations of exposures in real-time scenarios. This will be fruitful in designing applications by which an individual can monitor their metal exposures. Further, potential sources and spatial characteristics in different microenvironments for exposure to multiple contaminants must be investigated. Also, very few studies have worked on the statistical significance of metal concentrations in indoor environments concerning human bio monitors like nails, hair, blood, or saliva. The quantification and health impact assessment of HMs in indoor dust receives vast scientific attention considering their overall toxic effects on the environment and occupational health. Hence, a bibliographic analysis was performed using the WoS to understand the current research trend in the toxicology of indoor dust-contributed HMs. The present review article suggested that most of the studies conducted in this field were monitoring-based studies, where "HMs (n = 79)," "contaminations (n = 49)," "lead (n = 49)," and "health" were used as the primary keywords of the published articles. Regarding scientific publications among countries, one of the most striking observations in the study shows that China is leading in publishing papers (twice of the second-placed country, the USA). Also, the results indicate the emergence of Iran (third-placed), India (fourth-placed), South Korea, and Brazil in this area of research. The free flows of funds and stronger international collaborations have helped China in publishing the maximum number of scientific articles in Science Citation Index (SCI)-indexed journals. China has partnered and cooperated with ~150 and >90 countries, respectively, which has helped it reach the top spot in publications. The analysis of the co-occurrence of keywords revealed wide usage of terms like "contamination," "area," "size distribution," "dust," "in-house dust," and less use of terms like "HMs," "bioaccessibility," and "health risk" indicating the scope of future research in these areas.

The domain seems to have enough international and institutional collaboration networks as interpreted through cooperation among the authors. Collaboration among authors, institutions, and countries exponentially grew in 2021. These collaborations helped broaden knowledge, research facilities, ideas, experiences, and resources. Authors from European countries such as France, Germany, and the UK showed substantial international co-authorships. In contrast, Iran did not show significant collaboration with international researchers. China has established well research collaborations with over 150 countries in recent years. Significantly fewer studies have considered the time spent in indoor environments, which is crucial in influencing exposure to HMs. India needs more funding for research in this domain, especially post-COVID times, as work-from-home culture has spiked up.

More exhaustive reviews in the present times are hence a necessity for identifying knowledge gaps on a global level. Further, socio-economic surveys, including the daily habits and status of buildings, have been under-reported. Although local or temporal studies have been done, there is much scope for large-scale epidemiological studies. In addition, the importance of discussing HM's chemical speciation and its impact on mobility and resulting toxicity in the indoor environment should be more extensively explored. The plantation of pollution-tolerant trees like *Mangifera indica*, *Psidium guajava*, or *Azadirachta indica* can be a sustainable solution for controlling air pollution levels. Human biomonitoring studies using nail or hair are also minimal. Metal bioaccessibility studies should also be paid more attention to estimating the real exposure scenarios.

Moreover, there is a need to standardize acceptable limits for HMs in indoor dust, and organizations like WHO and USEPA should be more proactive in this regard. This research could construct models to predict HM concentrations and the associated toxicity for a sustainable and safe future. Finally, this review and bibliometric analysis will help the researchers to identify the research gaps in the field of HM pollution in indoor dust and design comprehensive research on remediation, control, and chemical source apportionment.

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Author contribution AR: conceptualization, investigation, resources, data curation, writing—original draft preparation

AKJ: methodology, software

AK: methodology, writing—review and editing

TB: supervision, conceptualization, resources, writing—review and editing

SC: visualization, writing—review and editing

NPR: data curation, writing—review and editing, revision

MK: visualization, writing—review and editing

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Data Availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

Ethics approval This study does not require any ethics approval.

Consent to participate As this work did not involve any human participant, no consent of participation is required

Consent for publication This manuscript does not contain any person's data in any form, thus no consent to publish has been received.

Competing interests The authors declare no competing interests.

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