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The concentration of potentially toxic elements (zinc, iron, manganese) bound $PM_{2.5}$ in the indoor air of urban schools: a global systematic review and meta-analysis

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Abstract

Exposure to potentially toxic elements (PTEs) bound to $PM_{2.5}$ can cause various health effects, including cardiovascular disease, allergies, and other related diseases. There have been several studies on the concentration of PTEs, including zinc (Zn), iron (Fe), and manganese (Mn) bound $PM_{2.5}$ in the indoor air of urban schools. In this study, the concentration of Zn, Fe, and Mn in the indoor air of schools bound $PM_{2.5}$ were meta-analyzed. PubMed and Scopus were used to retrieve papers related to the concentration of PTEs bound $PM_{2.5}$ in the indoor air of urban schools from January 1, 2000 to March 10, 2020. The concentration of PTEs in $PM_{2.5}$ was meta-analyzed based on the country subgroup in the random-effects model (REM). Thirty papers with 25 data reports were included in the study. The rank order of PTEs bound $PM_{2.5}$ was Zn (17.32 ng/m^3) > Fe (14.49 ng/m^3) > Mn (7.40 ng/m^3). The rank order of countries based on the concentration of Fe-bound $PM_{2.5}$ in the indoor air of urban schools was China > Poland > Italy > Spain > Taiwan > Turkey > Iran) > Chile; Zn, Poland > Iran > Taiwan > Turkey > Spain > Italy > Chile; and for Mn, Poland > China > Iran > Taiwan > Spain > Italy > Chile. The pooled concentration of PTEs (Fe, Mn, and Zn) bound $PM_{2.5}$ in the indoor air of urban schools in Poland and China was higher than in other countries, hence, therefore, it is recommended to carry out a $PM_{2.5}$ concentration reduction program in the indoor air of schools in these countries.

Keywords Air pollution, $PM_{2.5}$ · Indoor air · Potentially toxic elements · Meta-analysis

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Introduction

Chemical and microbial contamination of the environment, including water(Wang et al. 2022; Yang et al. 2021; Yu et al. 2022), food(Liu et al. 2022a; Sun et al. 2022; Wang et al. 2022), soil (Liu et al. 2022b), and air (Quan et al. 2022) can endanger human health. Air pollution in urban environments is one of the leading causes of health concerns, especially for sensitive people, especially children (Raysoni et al. 2017a). Ambient airborne particles are one of the main components of air pollutants that have significant adverse effects on human health (Chen et al. 2022b; Fang et al. 2018; Ghozikali et al. 2018; Liu et al. 2022c; Shang et al. 2021; Tian et al. 2022; Wang et al. 2022; Zhang et al. 2021). The presence of airborne particles in school classrooms is one of the primary pollutants affecting students' health and indoor air quality (Di Gilio et al. 2017b). Various studies have shown that particulate matter of different sizes, such as PM_{10} and $PM_{2.5}$, are associated with decreased lung function indices so that $PM_{2.5}$ particles can penetrate deep into the lungs and lead to inflammation of the alveoli (Ghozikali et al. 2018).

Also, PTEs s are among the most harmful toxins in the environment, particularly airborne dust (Chen et al. 2022a; Gao et al. 2022; Huang et al. 2018; Wu et al. 2021; Yin et al. 2021; Zhang et al. 2021; Zoghi et al. 2022). The presence of trace metal elements in and on fine particles ($PM_{2.5}$) is one of the main components that determine the toxicity of $PM_{2.5}$ (Bi et al. 2018).

$PM_{2.5}$ particles are produced by physical and mechanical processes and mainly originate from combustion (Ghozikali et al. 2018).In addition, these particles are produced from other sources such as traffic and various industries and natural resources such as dust storms (Hassanvand et al. 2015a). In general, indoor sources of $PM_{2.5}$ emissions include cooking, combustion heat, and smoking, which are not present in school buildings. However, classroom indoor air pollution depends on various factors such as ventilation system, activities, number of occupants, concentration, and composition of outdoor $PM_{2.5}$ (Di Gilio et al. 2017b). However, the sources of $PM_{2.5}$ in the classroom may differ from elsewhere, and the metal compositions of $PM_{2.5}$ may also be different (Bi et al. 2018). These trace elements may originate from various urban and industrial sources (Di Gilio et al. 2017b).

In general, particle exposure is widely associated with various cardiovascular, respiratory, and immunological health problems. These effects would be exacerbated by potentially toxic elements (PTEs) adsorbed on $PM_{2.5}$ particles (Mesías Monsalve et al. 2018a). The trace metals zinc and manganese are carcinogenic and mutagenic (Raysoni et al. 2017a). These consequences are even more harmful to children's health because their respiratory system is not yet fully developed (Di Gilio et al. 2017b).

Various toxicological studies have shown that metal components in or on $PM_{2.5}$ particles produce reactive oxygen species through the Fenton reaction, which in turn causes damage to cell DNA, lipids, and proteins (Gali et al. 2015). Furthermore, numerous studies have shown that particle-bound metals are involved in causing oxidative stress and mitochondrial damage, leading to increased mortality and cardiovascular disease (Di Gilio et al. 2017b).

It is estimated that adults spend approximately 60 to 80% of their time indoors and children at least 50% of their time in school. Thus, a significant portion of exposure to air pollutants occurs in school environments (Viana et al. 2014b), and exposure to fine particles and trace elements in the classroom can lead to health threats for children (Bi et al. 2018). Therefore, understanding the composition and concentration of suspended particles and trace elements and their relationships is important for evaluating personal exposure (Hassanvand et al. 2015a).

Although there are several investigations on the concentration of $PM_{2.5}$ and PTEs bound in $PM_{2.5}$ in the indoor air of urban schools (Abdel-Salam 2019, Bi et al. 2018, Chithra and Nagendra 2014, Ekmekcioglu and Keskin 2007, Ghozikali et al. 2018, Halek et al. 2009, Mohammadyan et al. 2017, Mohammadyan et al. 2013), a meta-analysis has not been conducted. The main aim of the current study was to meta-analysis the concentration of Zn, Fe, and Mn bound $PM_{2.5}$ in the indoor air of urban schools.

Material and method

Searching strategy

PRISMA guidelines were used to retrieve papers (Higgins and Green 2011) (Fig. 1). PubMed and Scopus were used to retrieve papers related to the concentration of PTEs bound $PM_{2.5}$ in the indoor air of urban schools from January 1, 2000 to March 10, 2020. Keywords were "air pollution" OR "Particulate Matter" OR "$PM_{2.5}$" OR "PM_{10}" AND "toxic element" OR "trace element" OR "heavy metal" OR AND "residential" OR "school" OR "university." Disagreement between two authors regarding excluding and select of papers was resolved by the final decision of the corresponding author(Aranega and Oliveira 2022, De Souza et al. 2021).

Inclusion and extraction of data

Our criteria measured Zn, Fe, Mn bound $PM_{2.5}$ in indoor air; available full text; descriptive study; and presented mean and standard deviation PTEs in $PM_{2.5}$ and investigation performed in school and urban areas. Extracted data from each paper included country, sample duration, mean and standard

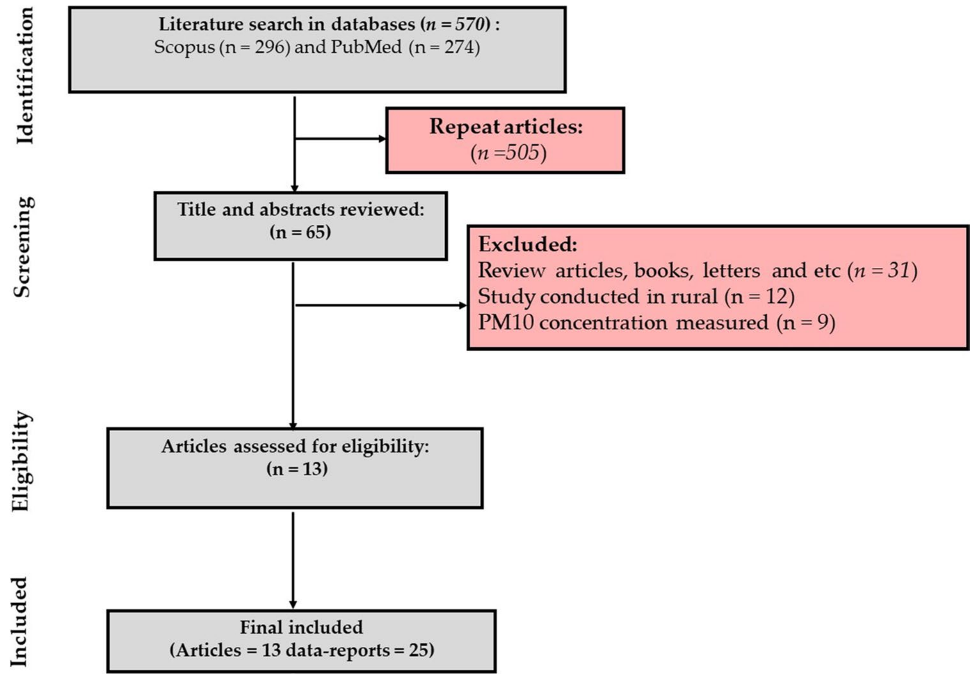

Fig. 1 Process of selection papers based on PRISMA

deviation concentration of heavy metal bound $PM_{2.5}$, and measurement method.

Meta-analysis of data

The concentration of Zn, Fe, and Mn bound $PM_{2.5}$ was meta-analyzed based on mean and standard deviation. Cochran's *Q* test calculated the I^2 index (heterogeneity statistic). As the I^2 index was higher than 50%, heterogeneity was considered high (Higgins et al. 2008). Therefore, the random-effects model (REM) was used to estimate pooled effect size in the country subgroup. REM is a statistical model where the parameters of the model are random variables(Higgins et al. 2008). The concentration of PTEs bound to $PM_{2.5}$ converted to ng/m^3. Meta-analysis was conducted using Stata software (version 14; STATA Corp., College Station, TX).

Results

Five hundred and seventy articles were found in the initial search, and 505 were excluded due to duplicates in the databases. Then, in the screening step, 52 articles were excluded for reasons such as review articles, measurement of PM_{10}, and measurement in rural areas. Finally, 13 articles with 25 data reports were included in the meta-analysis (Fig. 1 and Appendix 1). The "Results" revealed that the rank order of PTEs in bound $PM_{2.5}$ based on overall concentration in the indoor air of urban school Zn (17.32 ng/m^3) > Fe (14.49 ng/m^3) > Mn (7.40 ng/m^3). High concentrations of metals such as Zn and Fe in $PM_{2.5}$ are mostly related to busy streets and high-traffic areas (areas that experience more than 20 vehicles from 2 or more axle vehicles). On high-traffic streets, vehicles are frequently stopped. Intermittent movement and stopping cause these metals to be released into the air from the exhaust and brake linings, the tires wear, and brake wear (Pastuszka et al. 2010). Also, many studies have stated that the reason for the high concentration of Zn compared to other metals in indoor air is the high use of,this metal in the following cases: as a coating to protect metals and wood from corrosion and UV rays; as a protector in paints to prevent mildew, the UV-protection of coatings, and zinc-rich coatings (Canha et al. 2014; Slezakova et al. 2011).

The rank order of countries based on concentration of Mn bound $PM_{2.5}$ in indoor air of urban school was Poland (46.00 ng/m^3) > China (26.56 ng/m^3) > Iran (15.25 ng/m^3) > Taiwan (6.49 ng/m^3) > Spain (5.90 ng/m^3) > Italy (4.93 ng/m^3) > Chile (1.49 ng/m^3) (Table 1).

Studies have shown that the release of Mn into the atmosphere depends more on natural resources (such as Earth's crust erosion, excavation, volcanic activity, and mining). However, Ahmadi cited brake pads as the primary source of manganese emissions (Pastuszka et al. 2010, Rogula-Kozłowska et al. 2008). Similar to Pb emission, an abundance of Mn bound to $PM_{2.5}$ was observed in March and April. Analysis of data in Chinese studies showed that two factors cause the presence of Mn on particulate matters in the atmosphere; one is the burning of coal as fuel in the cold seasons and the second is the re-suspension of dust on the dirt road and unpaved areas (Wang et al. 2020). Fang et al. (Fang et al. 2018) reported that the difference in the $PM_{2.5}$ concentration and metals adsorbed on the $PM_{2.5}$ surface in

Table 1 Meta-analysis of concentration of Mn bound $PM_{2.5}$ in indoor air of urban school (ng/m^3)

County	Number study	ES[1]	Lower	Upper	Weight (%)	Heterogeneity statistic	Degrees of freedom	p value	I^2
Iran	1	15.25	2.70	27.80	4.48	0	0		.%
Chile	2	1.49	0.13	3.12	29.36	2.21	1	0.137	54.70%
China	9	26.56	12.28	40.84	10.78	12.79	8	0.119	37.40%
Spain	1	5.90	1.04	10.76	11.23	0	0		.%
Taiwan	3	6.49	3.38	9.61	31.29	0.28	2	0.871	0.00%
Italy	1	4.93	0.87	8.99	12.2	0	0		.%
Poland	1	46.00	8.13	83.87	0.67	0	0		.%
Overall	18	7.40	4.24	10.56	100	66.02	17	0	74.20%

[1]Effect size (average concentration)

Taiwan is related to seasonal changes and weather conditions (temperature, humidity, wind speed). According to the findings, the $PM_{2.5}$ concentration was highest in August and October, which coincided with school reopening. The concentration of Mn adsorbed on the $PM_{2.5}$ was highest in August and September, attributed to the higher temperature in these months. The presence of low amounts of manganese-associated particles in the indoor air of Italian schools was attributed to its crustal origin (Cesari et al. 2012; Contini et al. 2014).

Soleimani et al. (Soleimani et al. 2018) reviewed the PTEs in the indoor air of Iran. They predicted that the Mn concentration associated with the particulate matter was higher in summer, fall, and winter. According to this research, high levels of manganese in the air were related to seasonal dust storms and strong monsoon winds. In contrast, Naderizadeh et al. (Naderizadeh et al. 2016) and Hassanvand et al. (Hassanvand et al. 2015b) reported sources of Mn emission in the air anthropogenic activities such as metal mining, industries that are metal-based, and vehicles. Numerous researchers in Chile have ascribed Mn emission in the atmosphere to erosion of the Earth's surface, mining activities, and the distribution of their waste by wind (Castilla and Nealler 1978, Medina et al. 2005, Mesías Monsalve et al. 2018b, Neary and Garcia-Chevesich 2008, Ramirez et al. 2005). Steel, ferroalloy, and manganese manufacturing plants are the major industrial processes leading to high Mn loadings on particulate matter in the Spanish atmosphere (Arruti et al. 2010).

The rank order of countries based on concentration of Fe-bound $PM_{2.5}$ in indoor air of urban school was China (1334.81 ng/m^3) > Poland (567.80 ng/m^3) > Italy (212.00 ng/m^3) > Spain (200.00 ng/m^3) > Taiwan (192.26 ng/m^3) > Turkey (156.85 ng/m^3) > Iran (102.20 ng/m^3) > Chile (1.62 ng/m^3) (Table 2).

Studies conducted in Poland have shown that the proximity of schools to crossroads and traffic sites can be the primary cause of high levels of Fe associated with fine particles (Pastuszka et al. 2010, Rogula-Kozłowska et al. 2008). Specific research in Italy has shown that iron-bound particles in indoor air are due to the activity of industries (especially steelmaking and metal smelting) near the city. These studies showed that when wind speeds are high in autumn and winter, wind blow lead to re-suspension and transfer of

Table 2 Meta-analysis of concentration of Fe-bound $PM_{2.5}$ in indoor air of urban school (ng/m^3)

County	Number study	ES[2]	Lower	Upper	Weight (%)	Heterogeneity statistic	Degrees of freedom	p value	I^2
Iran	1	102.20	44.11	160.29	2.34	0	0		.%
Turkey	1	156.85	67.70	246.00	1.02	0	0		.%
Chile	2	1.62	0.20	3.04	92.84	3.54	1	0.06	71.70%
China	6	1334.81	242.53	2427.08	0.44	28.78	5	0	82.60%
Spain	1	200.00	86.32	313.68	0.63	0	0		.%
Taiwan	3	192.26	128.66	255.86	2.02	0.56	2	0.755	0.00%
Italy	1	212.00	91.50	332.50	0.57	0	0		.%
Poland	2	567.80	321.34	814.26	0.14	0.25	1	0.618	0.00%
Overall	17	14.49	5.37	23.60	100	165.75	16	0	90.30%

[2]Effect size (average concentration)

dust-containing metal to indoor air (Di Gilio et al. 2017a). It has been reported that the presence of Fe production industries and the re-suspension of dust and soil are responsible for the high level of this metal on $PM_{2.5}$ in urban air. Hassan et al. (Hassanvand et al. 2015b) reported that since industries in Iran are located outside the city, the main reason for iron-on $PM_{2.5}$ in indoor air is the re-suspension of dust from roads. Studies in Taiwan have reported that the average concentration of Fe-bound $PM_{2.5}$ is highest in summer when temperatures are high (Fang et al. 2003, 2018, 2014). The proximity of schools to dirt roads, unpaved streets and playgrounds, and sweeping the street was reported by Amato et al. (Amato et al. 2014) as the leading cause of the release of Fe into the indoor air of Spanish schools. In research papers conducted in Spain, dust re-suspension through solid wind, moving vehicles, and playing with children were reported to cause iron release into the indoor air. Raysoni et al. (Raysoni et al. 2017b) attributed the Fe contents associated with $PM_{2.5}$ emitted from non-anthropogenic sources such as erosion of the Earth's crust, volcano eruption, and excavation to heavy traffic and metallurgical industries. In addition, Monsalve et al. (Mesías Monsalve et al. 2018b) and Amato et al. (Amato et al. 2014) revealed that Fe's presence in $PM_{2.5}$ in the air had been caused due to natural sources, urbanization activities, and natural crustal elements. They discussed that Fe emissions in the air were not associated with industrialization.

The rank order of countries based on concentration of Zn-bound $PM_{2.5}$ in indoor air of urban school was Poland (267.00 ng/m^3) > Iran (68.90 ng/m^3) > Taiwan (57.29 ng/m^3) > Turkey (48.54 ng/m^3) > Spain (42.10 ng/m^3) > Italy (15.50 ng/m^3) > Chile (1.41 ng/m^3) (Table 3).

Studies in Iran have shown that zinc emissions in the air are related to heavy traffic, brake wear, and vehicle tire wear. Also, because zinc is an additive in engine oil, this metal can be released into the environment (Hassanvand et al. 2015b; Norouzi et al. 2017; Soleimani et al. 2018). Studies in Taiwan have shown that the highest concentration of zinc-bound particles was associated with late summer, which was related to high temperature and the reopening of schools (Fang et al. 2003, 2018, 2012). Viana et al. (Viana et al. 2014a) and Querol et al. (Querol et al. 2004) attributed the release of Zn-bound particulate matter in indoor air in Spain to vehicle emissions wall painting, painting colors, and the presence of metal furniture in the classroom. Most studies in Poland have attributed identified heavy traffic that causes abrasion of car's internal components (such as pad, brake, engine, and tires) as the leading cause of Zn-$PM_{2.5}$ emission into the air (Pastuszka et al. 2010, Rogula-Kozłowska et al. 2008, Zwoździak et al. 2013). Studies reviewed in Chile reported that Zn could be released into the atmosphere due to smelting and mining activities, extraction of ores, natural oxidation of minerals, and Cu ore processes (Gidhagen et al. 2002, Jorquera and Barraza 2013, Mesías Monsalve et al. 2018b). Ekmekcioglu and Keskin (Ekmekcioglu and Keskin 2007) reported the Automotive Industry as a significant source of airborne Zn due to its use in many auto parts. Ergenekon and Ulutas (Ergenekon and Ulutaş 2014) have stated that emission of anthropogenic sources such as application in building materials, burning heavy oil, motor oil, generator activities, and power plants was associated with the Zn-$PM_{2.5}$ emission in indoor dust. Contini's study in Italy reported that Zn emissions were caused by sintering processes and heavy traffic (Contini et al. 2014).

Conclusion

In the current study, the concentration of Zn, Fe, and Mn in the indoor air of schools bound $PM_{2.5}$ were meta-analyzed. The concentration of Zn bound to PM in schools' indoor air was higher than in other PTEs. Therefore, it is recommended to carry out plans to identify zinc emission sources and reduce its emission. The pooled concentration of PTEs (Fe, Mn, and Zn) bound $PM_{2.5}$ in the indoor air of urban schools in Poland and China was higher than in other

Table 3 Meta-analysis of concentration of Zn-bound $PM_{2.5}$ in indoor air of urban school (ng/m^3)

County	Number study	ES[3]	Lower	Upper	Weight (%)	Heterogeneity statistic	Degrees of freedom	*p* value	I^2
Iran	1	68.9	29.738	108.062	1.65	0	0		0%
Turkey	1	48.54	20.95	76.13	3.12	0	0		0%
Chile	2	1.41	0.731	2.089	50.98	1.3	1	0.255	23.00%
Spain	1	42.1	18.171	66.029	3.99	0	0		0
Taiwan	6	57.29	30.149	84.431	25.37	30.21	5	0	83.40%
Italy	1	15.5	6.69	24.31	14.78	0	0		0
Poland	1	267	115.24	418.76	0.12	0	0		0
Overall	13	17.32	12.12	22.51	100	146.88	12	0	91.80%

[3]Effect size (average concentration)

countries. Hence, it is recommended to perform $PM_{2.5}$ concentration control plans in schools' indoor air, especially in these countries.

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Data availability Data openly available in a public repository.

Declaration

Ethics approval Ethical approval was approved from Tobacco and Health Research Center, Hormozgan University of Medical Sciences, Bandar Abbas, Iran (IR.HUMS.REC.1399.415).

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Conflict of interest The authors declare no competing interests.

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