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Original Article

창원 산업단지 도로먼지 내 잠재적 독성원소의 오염도, 생태 및 건강위험 평가

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Assessments of Pollution, Ecological and Health Risks of Potentially Toxic Elements (PTEs) in Road Dust from Changwon Industrial Complex

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요 약

산업활동은 주변 환경의 잠재적 독성원소(PTEs) 오염의 주요한 원인이며, 고농도의 독성원소에 오염된 도로먼지 입자는 대기 및 강우유출을 통해 해양환경으로 이동된다. 본 연구에서는 창원 산업단지 내 6가지 크기의 도로먼지의 잠재적 독성원소를 측정하여 오염 수준, 생태학적 및 건강 위험도를 평가하였다. 작은 입자의 도로먼지에서 상대적으로 독성원소의 농도가 높았다. 63 μm 이하의 도로먼지의 경우, Zn의 평균 농도가 3,999 mg/kg으로 가장 높았고, Cr>Cu>Pb>Ni>As>Cd>Hg의 농도순이었다. 오염평가지수(PLI) 역시 입자 크기가 감소함에 따라 증가했으며, 모든 입자크기가 1을 초과하였다. 마산만에 인접한 정점에서 독성원소의 오염도가 높은 것으로 나타났다. 작은 사이즈(63 μm 이하)의 도로먼지 입자에서 농집지수는 Zn과 Cd이 5를 초과하여 심각한 오염이 진행된 것으로 나타났다. 창원 산업지역 도로먼지 내 Cr, Zn 및 Cd의 심각한 오염도는 산업활동(기계제조, 전력, 철강, 조선 산업 및 자동체 제조산업)과 이와 관련된 교통활동의 영향을 크게 받고 있음을 알 수 있었다. 독성계수가 높은 Cd은 매우 높은 생태학적 위험이 있는 나타나, 강우유출을 통한 연안 환경으로의 이동 및 퇴적은 생태계에 해로운 영향을 미칠 우려가 높다. 또한 섭취를 통해 어린이가 고농도의Cr를 포함한 도로먼지에 노출되는 경우, 비발암성 위험이 발생할 가능성이 있는 결과를 보였다.

Abstract – Industrial activity is a major source of potentially toxic elements (PTEs) in the surrounding environment and small particles of road dust contaminated with high concentration of PTEs can be transported to the coastal environments through atmospheric deposition and rainfall runoff. PTEs concentrations in six different sizes of road dust were measured to evaluate pollution levels and ecological and health risks. PTEs con-

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centration in road dust of the study area was relatively high in small particles. In the case of road dust of less than 63 μm, the average concentration of Zn was the highest at 3,999 mg/kg, and the rest average concentrations were in descending order of Cr>Cu>Pb>Ni>As>Cd>Hg. PLI values increased as the particle size decreased, and exceeded 1 for all the particle size fractions of road dust, revealing overall high PTEs contamination in the study area, especially Cr and Zn. Machine manufacturing, electric power, steel and shipbuilding industries seem to be the sources of these PTEs accumulations. I_{geo} values exceeded 5 for Zn and Cd in road dust particles of less than 63 μm. It seems to be related to automobile manufacturing activities. Extremely high ecological risk was found for Cd, and non-carcinogenic health risk is possible in case of children's exposure to Cr-containing road dust, especially via ingestion.

Keywords: Potentially toxic elements(잠재적 독성원소), Road dust(도로먼지), Pollution assessment(오염도 평가), Health risk assessment(건강위해성 평가)

1. Introduction

Masan Bay was designated as a special management area for the first time in Korea to improve water quality as the marine environment continues to deteriorate due to rapid industrialization and urbanization. As a result of various environmental improvement efforts, the anaerobic environment of the bottom water has been improved. The inside of Masan Bay is still polluted with PTEs and the concentration of Cd is particularly high compared to other specially managed sea area of Korea (Ra *et al*.[2013]; Sun *et al*.[2014]; Lee *et al*.[2020a]). Because organic matter and nutrients are the main target substances for water quality improvement and non-point pollution management, there are almost no data on metal contamination sources in the terrestrial watershed that are the cause of metal contamination of sediments in Masan Bay. Changwon National Industrial Complex is located inside Masan Bay. About 2,700 industrial facilities are in operation and the total number of employees is about 0.12 million. The main industrial types are machinery, electricity and electronics, transportation equipment and machinery-related facilities account for more than half of the total.

Such industrial activities are prone to emit potentially toxic elements (PTEs) such as Cr Ni, Cu, Zn, and Pb to the surrounding areas (Hao *et al*.[2020]). PTEs concern to the environment and human health due to their toxicity, persistency and bioaccumulation potential (Tabrez *et al*.[2021]). In urban areas, PTEs emitted from industrial sources can accumulate in road dust through atmospheric deposition (Bi *et al*.[2018]). The pollution of PTEs in road dust is greatly affected by traffic activities related to industrial activities. Because heavy-duty vehicles transport a large amount of raw materials and final products in industrial areas, the wear of tires and brake pads is more severe than those of light-duty vehicles in urban environments, resulting in a high PTEs concentration (Lee *et al*.[2020b]; Jeong *et al*.[2020a]; [2020b]). Also, discharging to the road surface during raw material transport is one of the causes of contamination of PTEs in road dust (Jeong *et al*.[2021]).

The finer-size fractions of road dust particles can be resuspended and transported to the atmosphere or water bodies such as the ocean through runoff (Sharma *et al*.[2021]). In these environments, road dust with high concentrations of PTEs can affect benthic organisms. Moreover, road dust may also pose a risk to human health through the ingestion, inhalation, and dermal contact of contaminated particles (Wang *et al*.[2019]). Hence, environmental quality assessments through road dust in the Changwon National Industrial Complex are useful instruments for pollution control that ensures both the human and environment well-being in the Masan Bay.

The main purpose of the present study is to evaluate the PTEs pollution level in size-fractionated road dust deposited in the Changwon National Industrial Complex as a potential source of metal pollution in Masan Bay. The ecological risk of metal pollution from road dust and the health risk to industrial employees and surrounding citizens were also evaluated in this study.

2. Materials and methods

2.1 Road dust sampling

Road dust samples were collected from 15 sites using a cordless vacuum cleaner (DC-35, Dyson, Co., UK) along an area of 0.25 m^2 (0.5 m×0.5 m) around the road curb side in December 2013 from the Changwon National Industrial Complex (Fig. 1). After sampling road dust in each sampling site, the vacuum cleaner was cleaned to prevent cross-contamination and samples were stored in zipper bags. The road dust samples were dried in an oven at 40 °C and then weighted. About 100 g of dried road dust were separated into 6 different sizes (>1000 μm, 500-1000 μm,

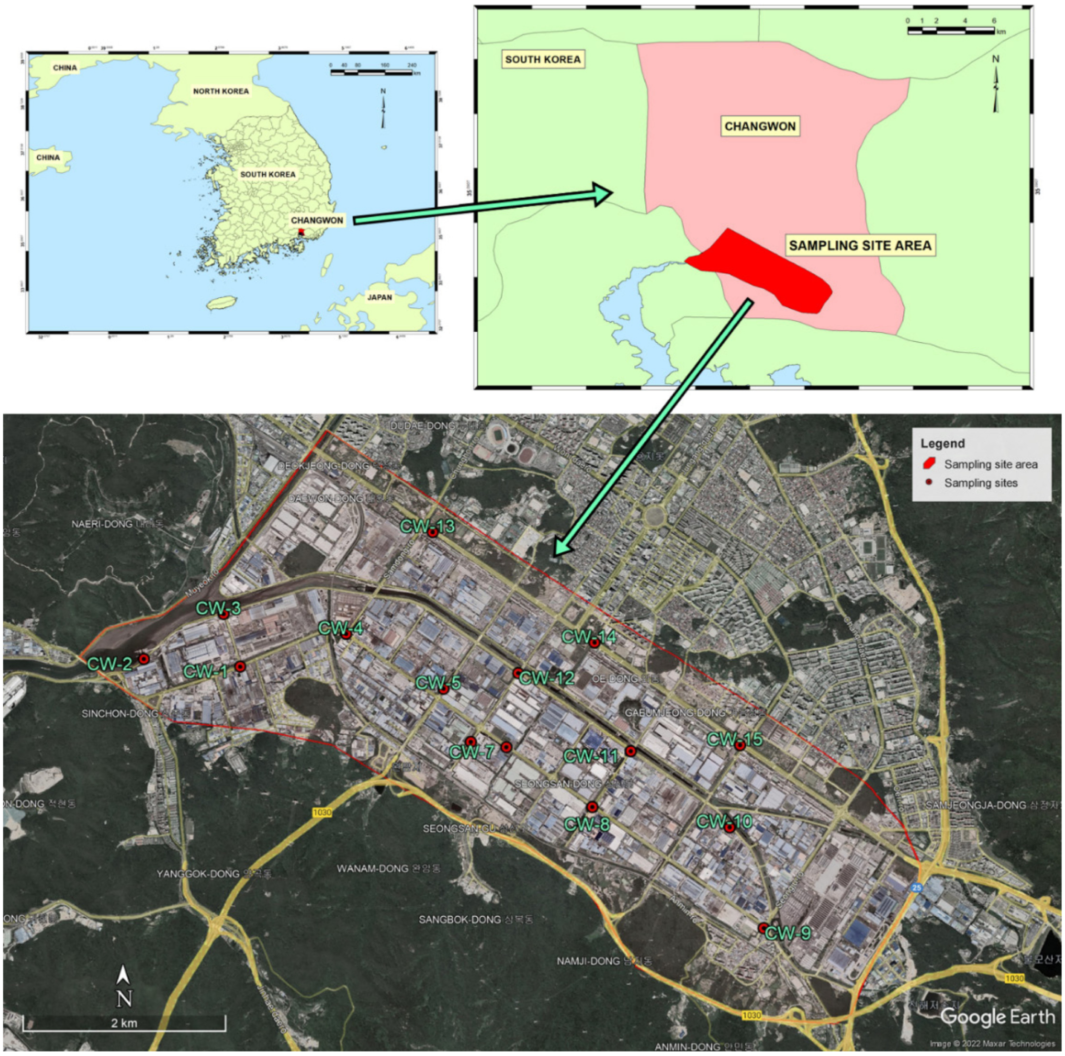

Fig. 1. Sampling sites for road dust in the Changwon industrial complex of South Korea (base map from Google Earth).

250-500 μm, 125-250 μm, 63-125 μm, <63 μm) using a vibrating sieve shaker (Analysette 3 pro, Fritsch Co., Germany) (Wentworth [1992]; Jeong *et al*.[2021]). Road dust samples separated into different sizes were weighed, pulverized and homogenized using a planetary mono mill grinder (Pulverisette 6, Fritsch Co., Germany), and stored in pre-acid cleaned PE bottles.

2.2 PTEs analysis

About 100 mg of the pulverized sample was weighed in a PFA digestion vessel, and after adding high-purity (supragrade for Merck, ultra-100 grade for Kanto) mixed acid (HF, HNO_3, and $HClO_4$), it was completely decomposed at 185 °C for 36 hours on a heating plate (OD-98-002, ODLAB Co., Korea). The completely decomposed sample was almost evaporated to dryness and re-dissolved with 2% HNO_3 to dilute differently depending on the trace elements. PTEs including Cr, Ni, Cu, Zn, As, Cd, and Pb were analyzed with an inductively coupled plasma mass spectrometry (ICP-MS, iCAP-Q, Thermo Scientific Co., Germany) at the Korea Institute of Ocean Science and Technology (KIOST). The mercury (Hg) concentration in road dust samples was analyzed using a direct mercury analyzer (DMA-80, Milestone Inc., Italy). Certified reference materials of sediment (PACS-3, NRCC, Canada) and road dust (BCR-723, IRMM, Belgium) were used to validate the PTEs data. Recoveries for reference materials ranged from 94.6% to 104.7%.

2.3 Pollution and ecological risk assessments

Geo-accumulation, pollution load and potential ecological risk indices were used to evaluate the degree of anthropogenic pollution and ecological risk for individual PTEs (Muller [1969]; Hakanson[1980]; Tomlinson *et al*.[1980]; Jeong *et al*.[2021]).

Geo-accumulation index (Igeo) was calculated by the following equation:

$$I_{geo} = \log_2(C_n/1.5 \times B_n)$$

The total pollution level for each sampling point in the study area was evaluated using the pollution load index (PLI):

$$PLI = (PI_1 \times PI_2 \times PI_3 \ldots \times PI_n)^{1/n}$$

Where, PI is the ratio between the concentration of PTEs (C_n) in road dust divided by the background value (B_n). n represents the number of PTEs analyzed in the study. There is contamination in the sites where PLI values are greater than 1.

Potential ecological risk index (RI) was also calculated by the following equation:

$$E_r^i = T_r^i \times (C_n/B_n)$$

$$RI = \sum_{i=1}^{n} E_i^i$$

Where, C_n is the PTEs concentrations in road dust of the present study. B_n indicates the geochemical background values (mg/kg) which were 92, 47, 28, 67, 4.8, 0.09, 17, and 0.05 for Cr, Ni, Cu, Zn, As, Cd, Pb, and Hg, respectively (Rudnick and Gao[2003]). E^i_r means the single factor ecological risk degree for each PTE. T^i_r values are the toxic response factor (Hg=40, Cd=30, As=10, Cu=Ni=Pb=5, Cr=2, Zn=1). Geo-accumulation index (Igeo) and single factor ecological risk degree (E^i_r) were classified into seven and five grades, respectively. The potential ecological risk (RI) values, which combines the potential toxicity of individual PTEs, are divided into four classes: low risk (RI<150), moderate risk (150<RI<300), severe risk (300<RI<600), and serious risk (RI>600).

2.4 Health risk assessments

Average daily intake doses of PTEs in the finest size of road dust (<63 μm) and exposure through ingestion (ADD_{ing}), dermal contact (ADD_{derm}), and inhalation (ADD_{inh}) were calculated to evaluate non-carcinogenic risks for adults and children living in industrial areas and the surrounding city using USEPA based on exposure factors (USEPA[2000]; [2001]; [2005]; [2011]).

$$ADD_{ing} = C_n \times \left(\frac{\mathrm{Ing}R \times EF \times ED}{BW \times AT}\right) \times 10^{-6}$$

$$ADD_{inh} = C_n \times \left(\frac{\mathrm{Ing}R \times EF \times ED}{PEF \times BW \times AT}\right)$$

$$ADD_{derm} = C_n \times \left(\frac{SL \times SA \times ABS \times EF \times ED}{BW \times AT}\right) \times 10^{-6}$$

Where C_n indicates the concentration of PTEs in the finest road dust (<63 μm). For all parameters used for calculating health risk assessment, data arranged by Jeong *et al.*[2022] were used.

The hazard index, HQ, was also calculated by the following equation using the ratio of the reference dose for each exposure pathway to evaluate the non-carcinogenic risk posed by PTEs in road dust.

$$HQ_i = \frac{ADD_i}{RfD_i}$$

Where, RfD represents oral reference dose, dermal reference dose, and inhalation reference concentration. Since values of some parameters do not exist in Korea, reported values for all parameters were used in this study (Ferreira-Baptista and de Miguel[2005]; Ma *et al.* [2019]; USEPA[2011]).

The hazard index, HI, for each PTE was also calculated using the following equation:

$$HI = HQ_{ing} + HQ_{inh} + HQ_{derm}$$

If HQ and HI values are greater than 1, potentially adverse health effect and non-carcinogenic effects may occur.

3. Results and Discussion

3.1 Spatial distribution of PTEs in road dust

Table 1 represents the average values of Cr, Ni, Cu, Zn, As, Cd, Pb, and Hg concentrations according to each size of road dust. Road dust showed the highest average concentration in the [<63 μm] particle size, and these values were 1.0 (As and Pb) to 14.0 (Hg) times higher than that of the [>1000 μm] particle size. Similar to other industrial areas in Korea, PTEs in the fine particles of road dust were characterized by the highest average concentration (3,999 mg/kg) for Zn. The average concentration of Cr was the second-highest at 2,057 mg/kg, followed by Cu (666 mg/kg), Pb (557 mg/kg), Ni (498 mg/kg), As (18.9 mg/kg), Cd (5.3 mg/kg), and Hg (0.28 mg/kg). The average concentrations of PTEs in the [<63 μm] particle size of the study area were higher than in urban (Ansan and Busan) and industrial region (Daebul industrial complex) of Korea (Table 1). Cu and Pb had lower average concentration in Changwon industrial complex than in Shiwa industrial complex.

The spatial distribution of PTEs in the [<63 μm] particle size fraction of road dust in the study area is presented in Fig. 2. Sampling site CW-2 had the highest concentration values of Cr (5,888 mg/kg), Cu (1,314 mg/kg), Pb (940 mg/kg), and Hg

Table 1. Comparison of mean values for PTEs concentrations (mg/kg) in road dust in this study and those in the other published data of Korea

Size	Cr	Ni	Cu	Zn	As	Cd	Pb	Hg	Reference
>1000 μm	943	64	200	1,275	19.8	1.61	541	0.02	This study
500-1000 μm	590	86.5	226	968	23.7	1.37	318	0.02	This study
250-500 μm	765	125	364	1,249	20.2	1.45	236	0.04	This study
125-250 μm	1,088	253	610	1,787	15.8	2.14	280	0.07	This study
63-125 μm	1,723	393	595	3,110	18	3.96	419	0.24	This study
< 63 μm	2,057	498	666	3,999	18.9	5.3	557	0.28	This study
< 63 μm	769	312	1,810	3,605	24	3.5	1,438	0.24	Lee *et al.*[2020b], Industrial, Shihwa IC
< 63 μm	125	41	246	2,236	7.9	1.1	117	0.04	Jeong *et al.*[2020a], Industrial, Daebul IC
< 63 μm	467	50.3	160	907	15.7	1.4	207	0.04	Jeong *et al.*[2020b], Urban, Ansan
< 63 μm	531	139	559	2,511	17.2	4.1	385	0.38	Jeong and Ra[2022], Urban, Busan

(0.82 mg/kg), which makes it the sampling site with the highest concentration of PTEs in the [<63 μm] particle size fraction of road dust. Sampling site CW-3 had the second-highest concentration of PTEs, especially Zn (6,998 mg/kg), which was the PTE with the highest concentration in the study. Site CW-3 also contained the highest concentration of Cd (8.63 mg/kg). The highest concentration of Ni was found in CW-4 (1767 mg/kg), and the highest concentration of As was found in CW-6 (45.9 mg/kg). The lowest PTEs concentration in road dust in the [<63 μm] particle size fraction was found in CW-15 and CW-14, in the northeast part of the study area. While there was a relatively lower concentration of PTEs in the central and eastern zones of the study area, there was a significant accumulation of PTEs in the western part, especially of Cr and Zn. In this region, industries related to machine accessories manufacturing, electric power plants, shipbuilding and repair and iron and steel companies are located. Manufacturing of electric batteries and fuel-burning engines and turbines has been reported as potential sources of Zn and Pb (Rehman *et al.*[2021]). Furthermore, Fe-Cr-Ni stainless steel has been widely used for the manufacturing of 3D solid parts (Heidarzadeh *et al.*[2021]). Next to the industries around sampling sites CW-2 and CW-3, there is a stream that directly disembogues into the Yellow Sea. Then, PTEs emissions are likely to reach the ocean through the transportation of road dust in the course of water bodies in this area. Moreover, near CW-4, where the highest accumulation of Zn was found, industries related to automobile parts and manufacturing are located. In the automobile manufacturing process, casting is required, which is commonly done with aluminum and zinc, as they are lighter and cheaper than iron for die casting (Goenka *et al.* [2020]).

The mean PLI values for each particle size fraction were found in decreasing order as the particle size increases: [<63 μm] (17.55) > [63-125 μm] (14.05) > [125-250 μm] (8.28) > [250-500 μm] (5.86) > [500-1000 μm] (4.79) > [>1000 μm] (4.67). Thus, the highest PLI value was found in the smallest particle size fraction of road dust ([<63 μm]). Nonetheless, the smallest PLI value found in the study (4.67) in the [>1000 μm] particle size fraction, was still larger than 1, which means that PTEs contamination was prevalent in all the particle size fractions of road dust. Moreover, Fig. 3 shows the spatial distribution of the pollution load index (PLI) for every particle size fraction of road dust. The sampling site CW-2 had the largest average PLI value for the particle sizes [>1000 μm], [250-500 μm], [63-125 μm], and [<63 μm]. For the particle size fraction [500-1000 μm], CW-1 was the sampling site with the highest PLI value, and CW-3 for the [125-250 μm] particle size fraction. Hence, the highest PTEs pollution was found in the western part of the sampling site, specifically around the sampling sites CW-2, CW-3, and CW-1. Manufacturing activities are dominant in this area, which could be the main source of PTEs emissions and contamination in road dust. Large PLI values were also found around CW-8, especially for the coarser particle size fractions of road dust. Textile and machine manufacturing industries are present in this area, which could be responsible for the elevated PLI values found. The lowest PLI values were found around CW-14 and CW-15, with values as low as 1.58 for the [>1000 μm] particle size fraction, and as high as 8.95 for the [<63 μm] particle size fraction. Therefore, PTEs contamination should be addressed integrally along the Changwon National Industrial Complex, with especial attention to dust found on roads surrounding small- and large-sized industries.

3.2 Pollution assessment of PTEs

PTEs pollution of road dust is greatly affected by particle size and pollution sources. It has been reported that small particles of road dust have a high concentration of PTEs and account for a large portion of the total PTEs pollution. The

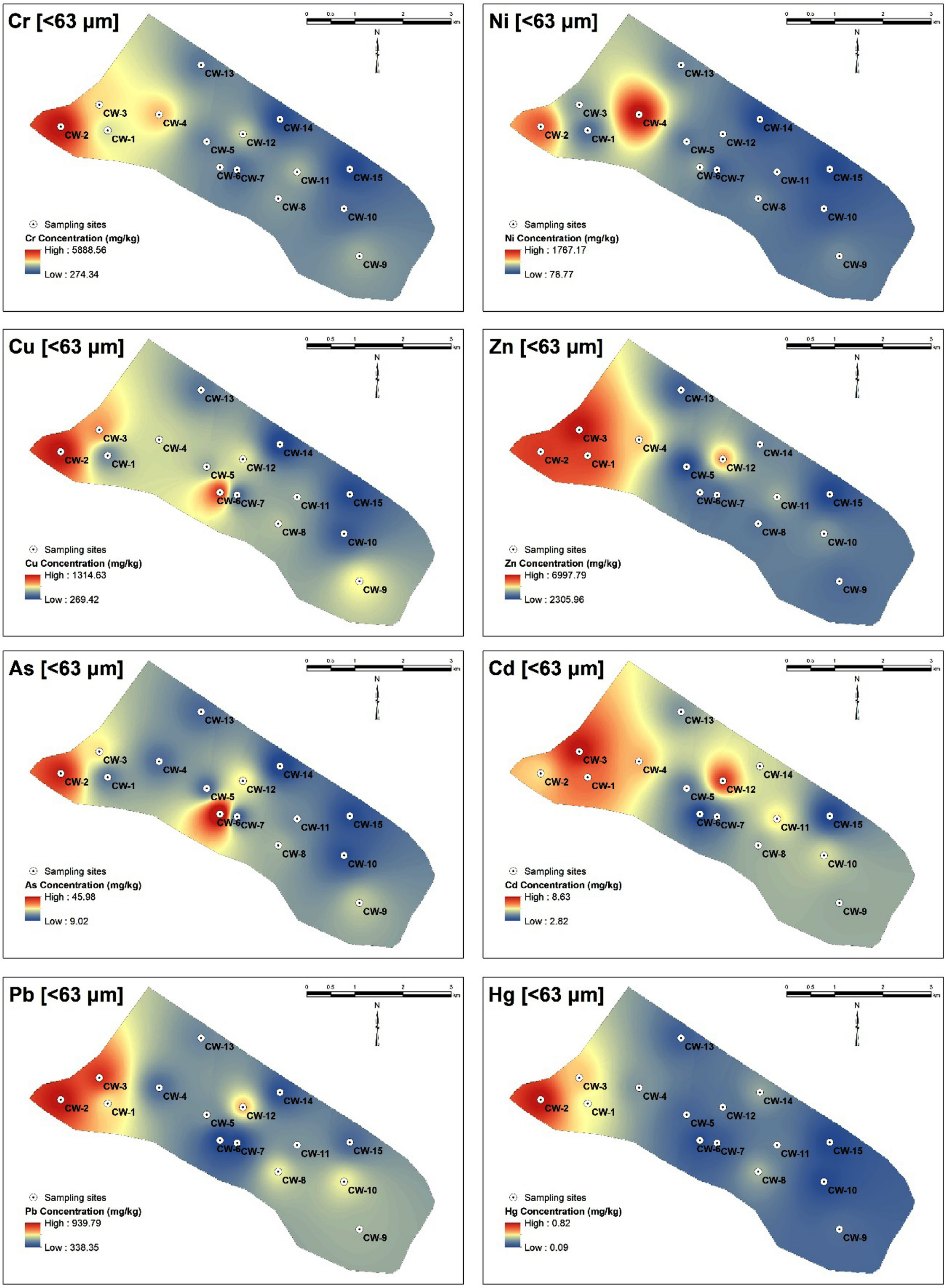

Fig. 2. Spatial distributions of PTEs in the finest particle size fraction of road dust (<63 μm).

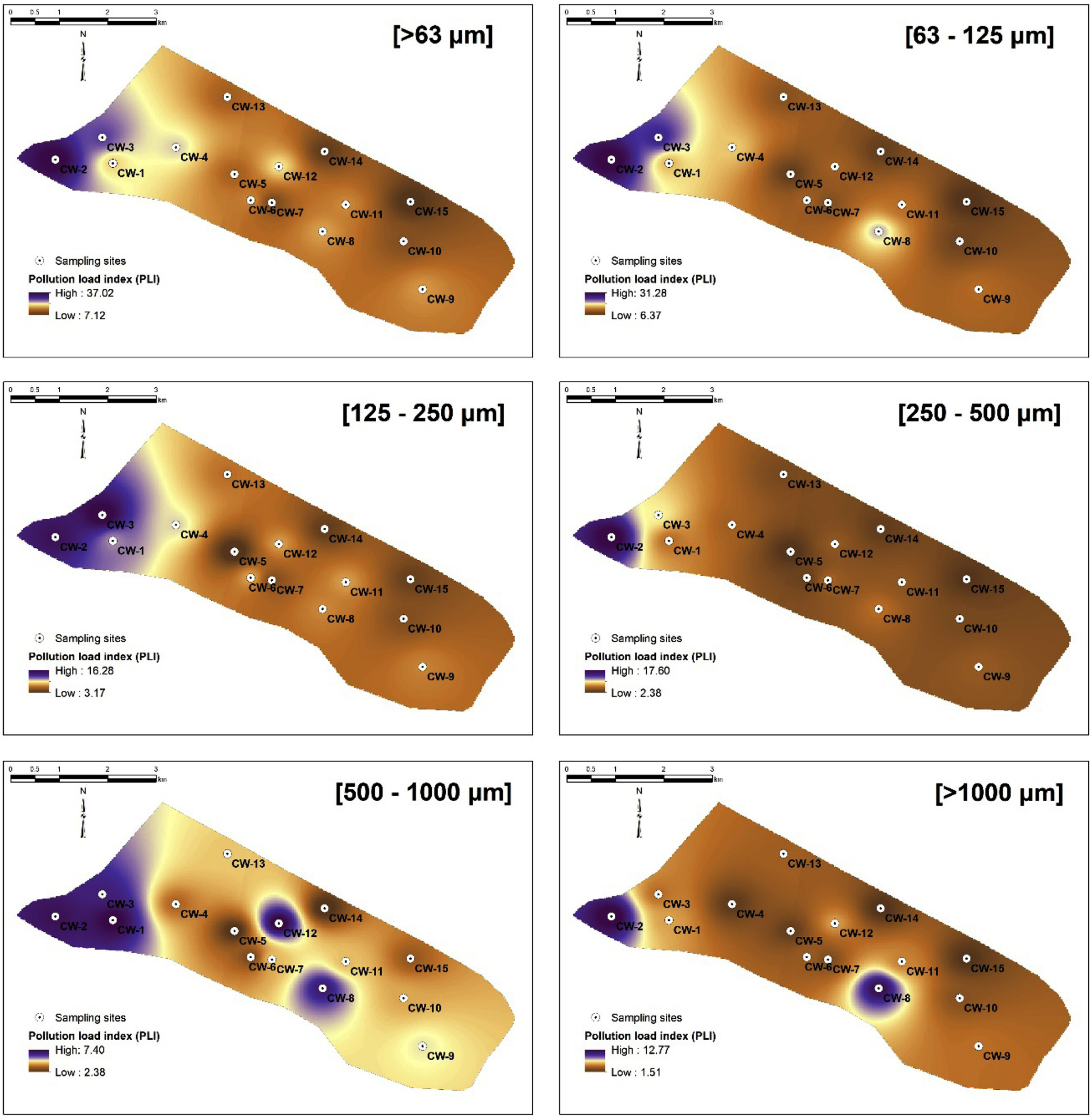

Fig. 3. Spatial distributions of pollution load index (PLI) in the different particle sizes of road dust.

evaluation of PTEs pollution in road dust can help establish an efficient road cleaning strategy.

Table 2 shows the mean I_{geo} value and pollution grade based on I_{geo} calculation for each size of road dust. Like the concentration, the I_{geo} value also showed a tendency to increase the pollution grade as the particle size of road dust became smaller. The mean of I_{geo} values in the [<63 μm] particle size fraction of road dust was in descending order of Cd≈Zn>Pb>Cu>Cr>Ni>Hg>As. In road dust less than 63 μm, both Cd and Zn were found to have a mean of 5.22, which corresponds to a pollution grade of extremely heavy pollution. Of the total 15 sampling sites, 11 sites of Cd and 8 sites of Zn had I_{geo} values exceeding 5. For the [63-125 μm] particle size, Cd and Zn were the pollution grade of heavy to extremely heavy pollution ranging from 4 to 5 of I_{geo} value. At 5 sampling sites including CW-1~4 and -14, the [63-125 μm] particle size of road dust also exceeded I_{geo} 5,

Table 2. Mean values of geo-accumulation index (I_{geo}) and classification for PTEs pollution in the different size of road dust in this study

Size (μm)	Cr	Ni	Cu	Zn	As	Cd	Pb	Hg
>1000	1.96	-0.85	1.52	3.27	0.92	3.18	3.24	-2.36
500-1000	1.70	-0.07	2.13	3.09	1.56	3.20	3.30	-2.23
250-500	1.89	0.03	2.61	3.42	1.43	3.25	3.12	-1.51
125-250	2.52	1.37	3.28	3.98	1.07	3.83	3.36	-0.68
63-125	3.23	1.95	3.65	4.83	1.18	4.79	3.96	1.09
<63	3.52	2.36	3.85	5.22	1.24	5.22	4.38	1.61
<63[a]	2.48	2.15	5.43	5.16	1.74	4.70	5.82	1.68
<63[b]	-0.14	-0.78	2.55	4.48	0.13	3.03	2.20	-0.91
<63[c]	1.76	-0.49	1.93	3.17	1.12	3.37	3.02	-0.91
<63[d]	1.94	0.98	3.73	4.64	1.26	4.92	3.92	2.34

Igeo<0, practically unpolluted
0<Igeo<1, unpolluted to medium polluted
1<Igeo<2, medium pollution
2<Igeo<3, medium to heavy pollution
3<Igeo<4, heavy pollution
4<Igeo<5, heavy to extremely heavy pollution
Igeo>5, extremely heavy pollution

[a]Lee et al., 2020b, [b]Jeong et al., 2020a, [c]Jeong et al., 2020b, [d]Jeong and Ra, 2022.

showing an extremely heavy pollution status. For road dust with a size of 125-250 μm, the I_{geo} of Cd and Zn at St. CW-3 exceeded 5, and the mean values were between 3 and 4, indicating the pollution status of heavy pollution. The mean I_{geo} values of road dust greater than 250 μm were between 3 and 4 for both Cd and Zn, and there were no sampling sites with I_{geo} exceeding 5. The high I_{geo} values of Zn and Cd evidence significant accumulation of these PTEs in the study area that could be attributed to the industrial activities taking place in the surrounding areas. Zn and Cd have been reported in heavy traffic emissions (Tian *et al.*[2018]). Additionally, Zn and Cd are included in the manufacturing process of automobile tires, with Zn being present in both inorganic and organic forms in tires (Vlasov *et al.*[2021]). Corrosion of cars and mechanical abrasion can also originate Zn pollution on road surfaces (Alves *et al.*[2020a]). In the Changwon industrial complex, there are numerous automobile manufacturing companies that could potentially emit these PTEs that ultimately accumulate in road dust.

For Pb, the mean of I_{geo} value for less than 63 μm of particle size was 4.38, corresponding to heavy to extremely heavy pollution level. Road dust larger than 63 μm had a mean of I_{geo} between 3 and 4, indicating heavy pollution. For Cu, road dust less than 250 μm corresponded heavy pollution status. Road dust sizes between 250 and 1000 μm and greater than 1000 μm corresponded to medium to heavy pollution and medium pollution, respectively. The I_{geo} values of Cu did not exceed 5 at any sampling site and particle sizes. For Cr, road dust with a size smaller than 125 μm had a heavy pollution grade, but road dust larger than 125 μm presented a medium to heavy pollution. For Ni, the mean Igeo of road dust with a size smaller than 63 μm was 2.36, which was found to correspond to the medium pollution grade. As and Hg showed significantly lower levels of pollution compared to other PTEs. Road dust of less than 1000 μm for As, and of less than 125 μm for Hg showed a pollution grade corresponding to medium pollution.

3.3 Ecological risk assessment of PTEs

There has been an increasing significance in PTEs' contamination risks in environmental research over the last 40 years (Teh *et al.*[2016]). This is because PTEs pose a substantial risk to the environment when in large quantities. In the study area in Masan Bay, some PTEs showed significant environmental risk. Particularly, Cd presented an extremely high risk for all the particle size fractions of road dust (Table 3). The highest ecological risk degree (E^i_r) in the study was found for the [<63 μm] particle size fraction of Cd (1766), which is more than 5 times the threshold value for extremely high ecological risk. While there are some PTEs that are essential for the environment, Cadmium is a non-essential element that affects the biological functions of plants, animals, and human beings (Suhani

Table 3. Mean values of single factor ecological risk degree (E^i_r) of PTEs in road dust of this study

Size (μm)	Cr	Ni	Cu	Zn	As	Cd	Pb	Hg
>1000	20.5	6.8	35.7	19.0	41.2	535	156	13.7
500-1000	12.8	9.2	40.3	14.4	49.3	458	93.5	15.2
250-500	16.6	13.3	65.0	18.7	42.0	482	69.5	33.7
125-250	23.7	27.0	109	26.7	32.9	712	82.3	56.0
63-125	37.5	41.8	106	46.4	37.4	1320	123	188
<63	44.7	52.9	119	59.7	39.5	1766	164	221

E^i_r<40, low risk

40<E^i_r<80, moderate risk

80< E^i_r <160, considerable risk

160< E^i_r <320, high risk

E^i_r >320, extremely high risk

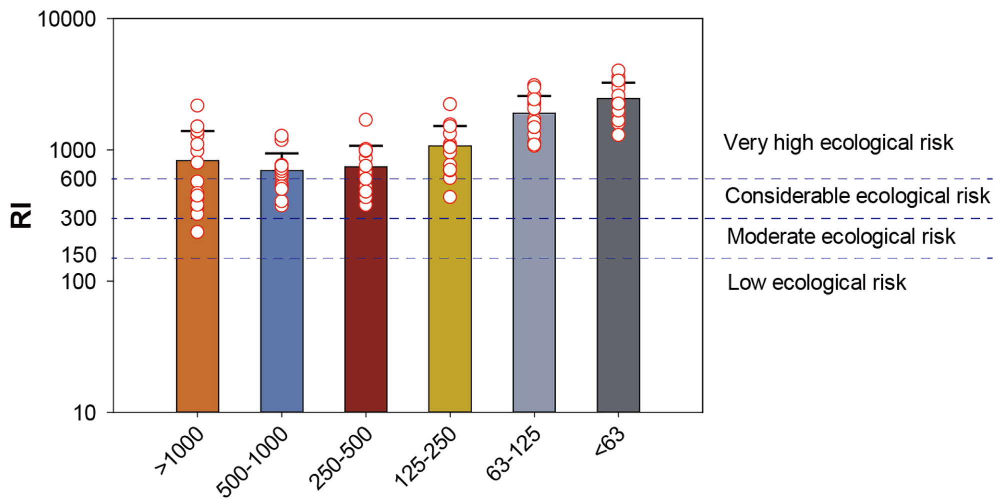

Fig. 4. Comparison of potential ecological risk index (RI) for PTEs in the size-fractionated road dust of this study.

et al.[2021]).

Pb and Hg showed high ecological risk in their finest particle sizes. Pb also showed considerable risk for all the particle sizes of road dust. Cu presented moderate risk for particle sizes less than 250 μm. Cr, Ni, and Zn pose moderate ecological risk to the environment in their finer particle size fractions. On the contrary, As showed moderate risk in coarser particles sizes and low risk in finer particle size fractions of road dust.

The potential ecological risk index (RI) for all the PTEs in every particle size fraction is displayed in Fig. 4. The average RI values for each fraction increased with decreasing particle size: [<63 μm] (2.466) > [63-125 μm] (1.901) > [125-250 μm] (1.069) > [250-500 μm] (828) > [500-1000 μm] (741) > [>1000 μm] (630). Thus, the highest ecological risk was found in the smallest particle size fraction of the study. Yet, there was a very high ecological risk for all the particle size fractions of road dust, revealing that the ecological risk posed by PTEs in the study area was, overall, prevalent in every particle size fraction and it increased with decreasing particle size.

Given the high E^i_r and RI values calculated for road dust in the study area in the Changwon industrial complex, the PTEs contamination, especially from Cd, should be addressed immediately as it poses a high risk to the environment and the biota within.

3.4 Health risk assessment of PTEs

The Human health risk assessment (HHRA) model is used to evaluate the risk posed by PTEs on human health (Men *et al.* [2021]). Table 4 displays the hazard quotients (HQ, unitless) and hazard indexes (HI, unitless) of the PTEs analyzed in this study. HQ reflects the non-carcinogenic risk posed by PTEs to human health through direct ingestion (hand to mouth), inhalation (mouth and nose), and dermal absorption (Heidari *et al.* [2021]; Alves *et al.*[2020b]). In the study, HQ values were generally

Table 4. The results of hazard quotient (HQ) and hazard index (HI) of non-carcinogenic hazards for potentially toxic elements in the finest of road dust (<63 μm)

	Adult				Children			
	HQ_{ing}	HQ_{inh}	HQ_{derm}	HI	HQ_{ing}	HQ_{inh}	HQ_{derm}	HI
Cr	2.4×10^{-1}	1.5×10^{-2}	2.2×10^{-1}	5.4×10^{-1}	2.3	1.4×10^{-1}	5.0×10^{-1}	3.1
Ni	8.8×10^{-3}	5.3×10^{-6}	5.8×10^{-4}	9.5×10^{-3}	8.2×10^{-2}	4.9×10^{-5}	1.3×10^{-3}	8.4×10^{-2}
Cu	5.9×10^{-3}	3.5×10^{-6}	3.5×10^{-4}	6.3×10^{-3}	5.5×10^{-2}	3.3×10^{-5}	8.1×10^{-4}	5.6×10^{-2}
Zn	4.7×10^{-3}	2.8×10^{-6}	4.2×10^{-4}	5.2×10^{-3}	4.4×10^{-2}	2.6×10^{-5}	9.7×10^{-4}	4.5×10^{-2}
As	2.2×10^{-2}	1.3×10^{-5}	9.8×10^{-4}	2.3×10^{-2}	2.1×10^{-1}	1.2×10^{-4}	2.2×10^{-3}	2.1×10^{-1}
Cd	1.9×10^{-3}	1.1×10^{-6}	3.4×10^{-3}	6.1×10^{-3}	1.7×10^{-2}	1.0×10^{-5}	7.7×10^{-3}	2.7×10^{-2}
Pb	5.6×10^{-2}	3.4×10^{-5}	6.7×10^{-3}	6.5×10^{-2}	5.2×10^{-1}	3.1×10^{-4}	1.5×10^{-2}	5.4×10^{-1}
Hg	3.2×10^{-4}	1.9×10^{-7}	8.3×10^{-5}	4.3×10^{-4}	3.0×10^{-3}	1.8×10^{-6}	1.9×10^{-4}	3.3×10^{-3}

higher in children than in adults, suggesting that children are more susceptible to PTEs contamination in road dust. Moreover, for both children and adults, HQ values followed the order: ingestion > dermal absorption > inhalation. Hence, PTEs in road dust in the study area are more prone to pose a health risk to children, and through ingestion rather than dermal contact or inhalation.

The highest HQ values for all the PTEs were assigned to Cr for children, which followed the descending order: ingestion (2.3) > dermal contact (5.0×10^{-1}) > inhalation (1.4×10^{-1}). Since no health risk is found in values lower than 1, health risk was found on Cr via ingestion of road dust for children. Likewise, HI was higher than 1 in Cr for children (3.1), indicating that adverse non-carcinogenic health effects are possible for children through their exposure to Cr-contaminated road dusts in the study area. Thanks to its corrosion resistance and strength, Cr is used for aluminum and titanium alloys and stainless steel in automobile industries for the manufacturing of car parts (Lu *et al.*[2017]). As a result, the presence of automobile industries in the study area could explain the high HI values found for Cr. Potential non-carcinogenic health effects due to the exposure to Cr include irritation and eardrum damage (Wahan *et al.*[2020]). Thus, pollution control strategies are advised to prevent negative health effects on the population residing in the study area.

4. Conclusion

This study evaluated the pollution levels and ecological and health risks of PTEs in six particle size fractions of road dust in the Changwon industrial complex of South Korea. Overall, the study area was found to be highly contaminated, especially with Zn, Cd, and Cr. Ecological and health risk assessments showed that PTEs pollution should be immediately addressed in the land watershed of Masan Bay. Cd showed extremely high ecological risk, while Cr was found to pose a non-carcinogenic risk to children, especially via ingestion. Fine particle size fractions of road dust should be given particular attention as they had the highest PTEs concentrations and ecological and health risks in the study. Regulation of industrial activities and their PTEs emissions is suggested in order to improve the environmental quality of this industrial area. The highest PTEs pollution was located near a stream close to the ocean. Hence, investigation of PTEs in multi-environmental matrices, including road dust, soil, seawater and marine sediments is suggested to further the understanding of the environmental and health impacts posed by PTEs in the Changwon industrial complex.

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