

Determining heavy metal contamination of road dust in Delhi, India

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RESUMEN

La contaminación del aire es considerada como uno de los mayores desafíos ambientales debido a sus efectos sobre los ecosistemas y la salud humana. En este estudio se investigan los niveles de concentración y las fuentes de la contaminación por metales pesados en muestras de polvo de caminos recolectadas en varios sitios que incluyen áreas con cuatro actividades diferentes en Delhi, India: industriales, carreteras, residenciales y de uso mixto. El contenido de metales en polvo de caminos se analizó mediante espectroscopia de emisión atómica por plasma de acoplamiento inductivo. Los resultados muestran altos niveles de concentración de Ni, Cr y Pb en áreas industriales. Los coeficientes de correlación de Pearson acoplados con análisis de componentes principales revelaron que el Cd, el Cr, el Ni y el Pb están vinculados con fuentes industriales en tanto que el Zn y el Cu proceden principalmente del tráfico vehicular. La contaminación en polvo de caminos se valoró a través de varios métodos: grado de contaminación, índice ecológico e índice de contaminación. El análisis de los factores de contaminación reveló que las muestras de polvo de caminos estaban contaminadas de manera considerable con Zn y Pb. Los índices de potencial ecológico indicaron la presencia de contaminación significativa por Cd y moderada por Pb en el polvo de camino, en tanto que la contaminación por Cr, Cu, Ni y Zn fue baja. El índice de contaminación de la mayoría de los metales fue mayor a 1, lo cual revela un deterioro en la calidad del polvo de caminos en Delhi a causa de las emisiones antrópicas. El grado de contaminación, el índice de potencia ecológico y el índice integrado de contaminación indican que el polvo de caminos en áreas industriales, de carreteras y de uso mixto exhiben alta contaminación por metales pesados. El polvo del camino también está contaminado de manera significativa. Evaluaciones realizadas por diversos métodos indicaron que todas las técnicas son importantes para valorar la calidad ambiental.

ABSTRACT

Air pollution has been considered one of the major environmental challenges because of its effect on ecosystems and human health. The concentration levels and sources of heavy metals contamination were studied in road dust samples collected from various locations including four different activity areas: industrial, highways, residential and mixed use in Delhi, India. Metal content in road dust was analyzed by inductively coupled plasma atomic emission spectroscopy. The results showed high concentration levels of Ni, Cr and Pb in industrial areas. Pearson's correlations coupled with principal component analysis revealed that Cd, Cr, Ni and Pb are associated with industrial sources whereas Zn and Cu are mainly contributed by vehicular traffic. Road dust contamination was assessed by various methods: degree of contamination, potential ecological index and pollution index. Contamination factor analysis showed that road dust samples are significantly contaminated by Zn and Pb. The potential ecological indices indicated high contamination of Cd and moderate contamination of Pb in road dust, but low contamination of Cr, Cu, Ni and Zn. The pollution index of most of the metals was higher than 1, indicating deterioration of road dust quality of Delhi city due to anthropogenic emissions. The degree of contamination, the potential ecological index and the integrated pollution index reveal that road dust from industrial, mixed use and highway areas are highly contaminated by heavy metals. The road dust from the residential area is also contaminated considerably. Evaluations by various methods indicated that all assessment methods are important for environmental quality evaluation.

Keywords: Correlation analysis, ecological risk index, pollution index, principal component analysis, toxic elements.

1. Introduction

Due to accelerated industrialization and urbanization, nearly half of the population in the world now lives in urban agglomerations. These intensive activities resulted in increasing quantities of contaminants into the urban environment. Consequently, a variety of environmental problems have cropped up and toxic metal pollution has become a major issue, especially in urban air, soils and road dust (Bilos *et al.*, 2001; Madrid *et al.*, 2002; Han *et al.*, 2006). Road dust is a complex mixture of particles and may contain various components like organics, heavy metals, other inorganics, mould spores, animal dander, pollen, pollen fragments etc., which can possibly get resuspended due to movement of vehicles and wind, resulting in an important source of atmospheric air pollution. It was observed that the particles and associated metals, particularly with fine dust, remain suspended in air longer under certain meteorological conditions. Road dust, an important environmental indicator of metal contamination from atmospheric deposition, receives varying inputs of anthropogenic metals from various stationary and mobile sources such as vehicular traffic, industrial activities, power plants, residential fossil fuel burning, waste incineration, construction and demolition activities, and resuspension of contaminated soil (Bilos *et al.*, 2001; Charlesworth *et al.*, 2003; Bhanarkar *et al.*, 2005, 2008; Gupta *et al.*, 2012). Road dust, therefore, is a significant contributor of pollution in the urban environment. The adverse effects of poor environmental conditions on human health are most evident in urban environments, particularly in developing countries where urbanization, industrialization and rapid population growth are taking place on an unprecedented scale (Duzgoren-Aydin, 2007).

Toxic metals in urban areas are a subject of great concern, due to their non-biodegradable nature and long residence time. The prolonged presence of the contaminants in the urban environment, particularly in road dust, and their close proximity to the human population significantly increase the exposure of the urban population to metals via inhalation, ingestion, and dermal contact (Mielke *et al.*, 1998; Abrahams, 2002). Metals can accumulate in fatty tissues,

affecting the functions of organs and disrupting the nervous system or the endocrinal system (Waisberg *et al.*, 2003; Duzgoren-Aydin, 2007) and some metals could cause mutagenic, teratogenic and carcinogenic effects in living beings (Lienesch *et al.*, 2000; Cook *et al.*, 2005).

Although several studies on metal pollution in road dust have been carried out in developed countries (de Miguel *et al.*, 1997; Arslan, 2001; Rasmussen *et al.*, 2001; Charlesworth *et al.*, 2003; Sezgin *et al.*, 2003; Tokalioglu and Karta, 2006; Shi *et al.*, 2008; Amato *et al.*, 2009), very little information is available on this topic in developing countries. Only few studies on quantification and distribution of metals in road dust have been conducted recently in Indian cities (Chatterjee and Banerjee, 1999; Banerjee, 2003; Rawat *et al.*, 2009; Rajaram *et al.*, 2014).

Considering the above, the main objectives of this study include: (1) determination of heavy metals concentration in road dust in various urban environments of Delhi, (2) identification of the possible sources of metals in road dust through statistical analysis and (3) assessment of the metal contamination in urban road dust by various methods.

2. Materials and methods

2.1 Study area

Delhi, the capital of India, is a major center of international and domestic activities in the Asian subcontinent. It is spread over a 1483 km² area with a population of about 16.7 millions (GOI, 2011). Rapid urbanization and industrialization of the city resulted in growth of vehicular population in the city. There has been an exponential growth in vehicular fleet, which increased from 3.05 million in 1998-1999 to 6.3 million in 2008-2009, thereby registering an overall annual compound growth rate of 7.52%. Delhi has about 85 private cars per 1000 inhabitants (Government of NCT Delhi, 2010). The total distance traveled by all categories of vehicles in the city is estimated to be about 79.2 million km. Out of the above, two-wheelers and four-wheelers (car/van) account for a major share of 42.7% and 38% respectively. Three-wheelers and local buses account for about 11.8% and 3.6% of vehicular fleet in Delhi respectively, whereas the share of light commercial

vehicles (LCV) and heavy commercial vehicles (HCV) together account for about 3.2% (GOI, 2002). Besides the vehicular fleet, the city has five power plants and 33 industrial estates in which many medium-scale and small-scale industries that include chemical, pharmaceutical, automobile part manufacturing, and rubber and plastic manufacturing are present.

2.2 Sample collection and analysis

Road dust samples were collected in winter 2009 from nine locations with due consideration to different representative aspects of urban environment in the metropolis including industrial (IND), national highway (HW), residential (RES) and mixed use (MIX) areas (Fig. 1). Samples of road dust were collected by using a vacuum cleaner. A representative composite bulk sample for every sampling location was obtained by taking subsamples from three points of the road at each location and then mixing thoroughly. Description of sampling locations is presented in Rajaram *et al.* (2014).

All samples were dried in the oven at 110°C for 48 h and sieved through 200 mesh sieve. The sieved dust samples were analyzed for metal content according to standard methods (US-EPA, 1999). Measurement of metal concentrations, i.e. Cd, Cr, Cu, Ni, Pb, and Zn was carried out using inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Jobin Yvon, model JY24). Calibration standards were prepared through serial dilution of standard stock solution of multi-elements having concentrations of 1000 mg L⁻¹ (Merck, Cat. No. 111355). Standard

solutions were used to validate the analytical method. All extractions and analysis were made with replicate samples ($n = 3$) and the mean values were reported. The details of sampling and analysis methodology are presented in a previous study (Rajaram *et al.*, 2014).

2.3 Statistical analysis

In this study, for the identification of the relationship between metals and their possible sources, Pearson's correlation coefficient analysis and principal components analysis (PCA) were performed using commercial statistics software package SPSS (version 17.0 for windows). The correlation coefficient measures the strength of the interrelationship between two metals.

PCA is the most common multivariate statistical method used in environmental studies to reduce the data while retaining important information and to extract a smaller number of independent factors (principal components, PCs) that can be easily interpreted for analyzing relationships among the observed variables (Massart *et al.*, 1997; Malinowski, 2002; Loska and Wiechuya, 2003; Tokalioglu and Kartal, 2006). PCA starts with the correlation matrix describing the dispersion of the original variables and extracting the eigenvalues and eigenvectors (Lu *et al.*, 2010). An eigenvector is a list of coefficients multiplying the original correlated variables to obtain new uncorrelated PCs, which are weighted linear combinations of the original variables. A matrix property, eigenvalue, is used to standardize the number of PCs that can be extracted. Usually, all the PCs with eigenvalues greater than 1 are considered as extracted PCs (Loska and Wiechuya, 2003; Lu *et al.*, 2010).

PCA extracts the PCs from an i, j matrix, where i corresponds to the number of samples and j to the number of pollutants measured (correlated variables, in this case all the heavy metal species measured) (Franco *et al.*, 2015). The PC extracted corresponds to pollutant (i.e., heavy metal) sources. The number of PCs that can be extracted from the measurements depends on the variability of the available data and on the number of monitored substances. The first PC extracted includes the highest possible variability, and each succeeding compound accounts for as much as possible of the remaining variability (Han *et al.*, 2006). The number of PCs that can be extracted depends on the retained variance of each PC (Franco *et al.*, 2015).

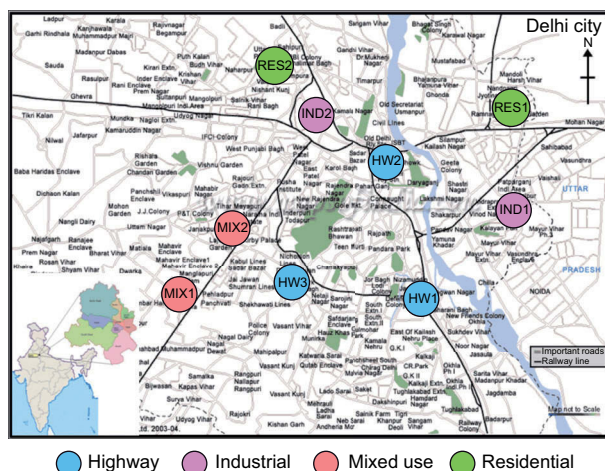


Fig. 1. Map of the study area showing sampling locations.

In this study, for the purpose of this exercise, a data matrix consisting of nine sites and six metals was considered (Rajaram *et al.*, 2014). PCA was performed by applying varimax rotation with Kaiser's normalization with eigenvalues > 1 to identify the sources of heavy metals in road dust. By extracting the eigenvalues and eigenvectors from the correlation matrix, the number of significant factors and the percent of variance explained by each of them were calculated. Data were checked for normality prior to PCA using Kolmogorov-Smirnov test and Shapiro-Wilk test, which indicated that the normalized data were suitable for PCA.

2.4 Metal contamination assessment methods

In this study, contamination factor index (C_f^i), degree of contamination (C_{deg}), potential ecological risk index (RI), pollution index (PI) and integrated pollution index (IPI) were calculated to assess the metal contamination levels in the road dust. The road dust metal concentrations described in Rajaram *et al.* (2014) were also utilized to estimate metal contamination assessment.

Hakanson (1980) suggested four classes of C_f^i and C_{deg} to evaluate the metal contamination levels. The degree of contamination (C_{deg}) is the sum of contamination factors for all of the elements. The contamination factor C_f^i was defined as (Hakanson, 1980):

$$C_f^i = C^i / C_n^i \quad (1)$$

where C^i is the mean content of metal and C_n^i is the concentration of a reference value for individual metal. In this study, the C_n^i values represent the concentrations of the metals in the soil from a remote background area in India (Kuhad *et al.*, 1989; Gowd *et al.*, 2010).

The degree of contamination by the six heavy metals in road dust from the study areas was determined as follows (Hakanson, 1980):

$$C_{deg} = \sum C_f^i \quad (2)$$

The classification for degrees of contamination suggested by Hakanson (1980) was based on eight pollutants, while there were only six heavy metals analyzed in this study. Thus, the original degree of contamination classification was adjusted according to Zhang *et al.* (2013). The modified classification is presented in Table I.

The assessment of degree of heavy metal pollution was carried out using the RI, based on the toxicity of metals and the response of the environment, as proposed by Hakanson (1980) according to the following equations:

$$RI = \sum E_r^i \quad (3)$$

$$E_r^i = T_r^i f^i \quad (4)$$

$$f^i = C^i / C_n^i \quad (5)$$

where E_r^i is the monomial potential ecological risk factor, T_r^i is the metal toxic factor, f^i is the metal pollution factor, C^i is the concentration of metals in samples, and C_n^i is a reference value for metals. The RI classification suggested by Hakanson (1980) was based on eight pollutants. In this study, a modified RI classification suggested by Zhang *et al.* (2013), was applied in order to evaluate the RI by the analyzed six heavy metals (Table II).

To assess the degree of metal contamination, a revised PI for each metal and an IPI of the six metals were estimated for each sampling site using the following equations as suggested by Huang (1987). PI was defined as follows and classified as presented in Table III:

$$PI = C/Xa \quad C \leq Xa \quad (6)$$

$$PI = 1 + (C - Xa)/(Xb - Xa) \quad Xa < C \leq Xb \quad (7)$$

Table I. Categories of contamination factors and contamination degree.

Class	C_f^i value	Category	C_{deg} value	Category
Class 1	$C_f^i < 1$	Low contamination	$C_{deg} < 6$	Low degree of contamination
Class 2	$1 \leq C_f^i < 3$	Moderate contamination	$6 \leq C_{deg} < 12$	Moderate degree of contamination
Class 3	$3 \leq C_f^i < 6$	Considerable contamination	$12 \leq C_{deg} < 24$	Considerable degree of contamination
Class 4	$6 \leq C_f^i$	Very high contamination	$24 \leq C_{deg}$	Very high degree of contamination

Table II. Indices and grades of potential ecological risk of heavy metals contamination.

Class	E_r^i value	Grades of ecological risk of single metal category	RI value	Grades of potential ecological risk of the environment
Class 1	$E_r^i < 40$	Low risk	$RI < 50$	Low risk
Class 2	$40 \leq E_r^i < 80$	Moderate risk	$50 \leq RI < 100$	Moderate risk
Class 3	$80 \leq E_r^i < 160$	Considerable risk	$100 \leq RI < 200$	Considerable risk
Class 4	$160 \leq E_r^i < 320$	High risk	$RI \geq 200$	High risk
Class 5	$E_r^i \geq 320$	High risk		

Table III. Categories of pollution index and integrated pollution index of metals.

Class	PI value	Category of contamination of single metal	IPI value	Category of integrated contamination index of the environment
Class 1	$PI \leq 1$	No contamination	$IPI \leq 0$	No contamination
Class 2	$1 < PI \leq 2$	Low contamination	$0 < IPI \leq 6$	Low contamination
Class 3	$2 < PI \leq 3$	Moderate contamination	$6 < IPI \leq 18$	Moderate contamination
Class 4	$PI > 3$	High contamination	$IPI > 18$	High contamination

$$PI = 2 + (C - Xb)/(Xc - Xb) \quad Xb < C \leq Xc \quad (8)$$

$$PI = 3 + (C - Xc)/(Xc - Xb) \quad C > Xc \quad (9)$$

where C is the measured concentration of specific metal, Xa is the threshold concentration of the metal enrichment, Xb is the threshold concentration of the low level of pollution and Xc is the threshold concentration of the high level of pollution. The values of Xa , Xb and Xc , were taken from Huang (1987) and Bai *et al.* (2009).

The IPI of all measured elements for each sample is defined below in Eq. (10) (Bai *et al.*, 2009) as the sum of the difference between the individual element's PI and 1, and then classified (Bai *et al.*, 2009) in Table III:

$$IPI = \sum(PI - 1) \quad (10)$$

3. Results and discussion

3.1 Heavy metal concentrations

Results on the concentrations of heavy metals in road dust samples collected from the study area and reported in Rajaram *et al.* (2014), were summarized and are presented in Fig. 2. The concentrations varied as follows: Cd, from 1.9 to 3.8; Cr, from 56.4 to 500.3; Cu, from 87.3 to 499.0; Ni, from 27.2 to 61.7; Pb, from 69.0 to 316.0, and Zn from 187.7 to 524.3 mg kg⁻¹. The mean concentrations \pm 95% confidence intervals of Cd, Cr, Cu, Ni, Pb and Zn in Delhi road dust were

found to be 2.65 ± 0.5 , 148.8 ± 83.3 , 191.7 ± 104.4 , 36.4 ± 6.6 , 120.7 ± 47.9 and 284.5 ± 67.6 mg kg⁻¹, respectively. Metal concentrations found in this study were comparable to those observed by Rajaram *et al.* (2014).

Except Zn, mean metal concentrations in the industrial areas (Cd, Cr, Cu, Ni and Pb: 3.61, 299.5, 383.6, 49.9 and 236.5 mg kg⁻¹, respectively) were relatively higher than those of other activity zones in Delhi (Rajaram *et al.*, 2014). Industrial processes such as metallurgical, electroplating, chemical, and fuel combustion may be the main reasons for metal emissions in those industrial areas and high metal concentrations (Madrid *et al.*, 2002; Wang and Qin, 2006; Li *et al.*, 2008). The lowest concentrations of Cd, Cu and Ni were found to be 1.9, 58.3 and 27.2 mg kg⁻¹ near the highway, respectively, whereas the lowest Cr and Pb levels were found to be 56.4 and 69.0 mg kg⁻¹ in residential areas, respectively. The average highest Zn concentration of 407.3 mg kg⁻¹ was found to be in mixed areas and lowest concentration of 187.7 mg kg⁻¹ near highways. The highest Zn concentration found in mixed areas was comparable to that observed by Rajaram *et al.* (2014). In general, lower metal concentrations were obtained in the samples near the highways as compared to those obtained near the roads in other areas (Rajaram *et al.*, 2014). This may be due to the fact that the roads are always jammed with the high vehicular traffic in other areas resulting in heavy metal emission and metal pollution

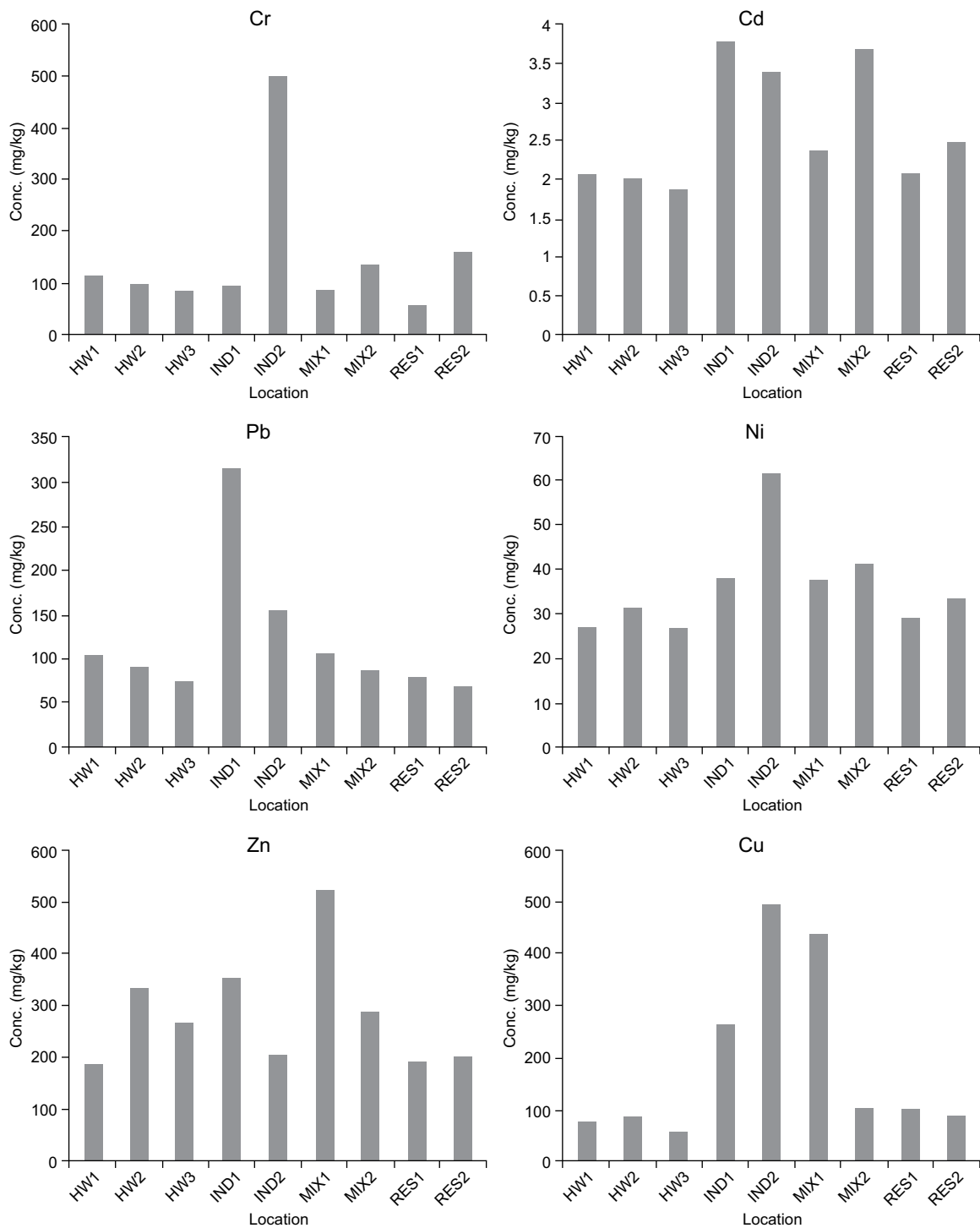


Fig. 2. Metal concentrations in road dust samples in Delhi. Concentration values of Cr, Pb, Ni, Zn and Cu for HW1, HW2, HW3, IND1, IND2, MIX2 and RES2 are taken from Rajaram *et al.* (2014).

(Chen *et al.*, 2010; Sun *et al.*, 2010). The distribution of metals in different functional areas was comparable to the one observed by Wong *et al.* (1996), who reported that within the urban areas, industrial areas

have the highest metal concentration, followed by commercial and residential districts. Wang and Qin (2006) also found that Pb concentration varied in different functional areas in Shenyang in the order of

Table IV. Heavy metal concentrations (mg kg⁻¹) in road dust in Delhi and various cities of the world.

City	Cd	Cr	Cu	Ni	Pb	Zn	Size (μm)	Reference
Delhi	2.65	148.8	191.7	36.4	120.7	284.5	< 75	This study
Birmingham	1.62		466.9	41.1	48	534	< 63	Charlesworth <i>et al.</i> (2003)
Ottawa	0.37	43.3	65.84	15.2	39.05	112.5	100-250	Rasmussen <i>et al.</i> (2001)
Calcutta	3.12	54	44	42	536	159	< 600	Chatterjee and Banerjee (1999)
Hong Kong	3.77		173		181	1450	< 2000	Li <i>et al.</i> (2001)
Shanghai	1.23	159.3	196.8	83.9	294.9	733.8	< 125	Shi <i>et al.</i> (2008)
Luanda		26	42	10	351	317	< 100	Ferreira Baptista and de Miguel (2005)
Oslo			123	41	180	412	< 100	De Miguel <i>et al.</i> (1997)
Madrid		61	188	44	1927	467	< 100	De Miguel <i>et al.</i> (1997)
Dhaka		104	46	26	74	154	< 1000	Ahmed and Ishiga (2006)
Kuala Lumpur	2.9		35.5		2466	344	< 63	Ramlan and Badri (1989)
Seoul	3		101		245	296	< 2000	Chon <i>et al.</i> (1995)
Indian natural soil background	0.9	114	56.5	27.7	13.1	22.1		Kuhad <i>et al.</i> (1989); Gowd <i>et al.</i> (2010)
China soil guidelines ^a	0.3	200	100	50	300	250		NEPA (1995)
Canada soil guidelines ^b	10	64	63	50	140	200		CCME (2007)
Canada soil guidelines ^c	22	87	91	50	600	360		CCME (2007)

^aClass II. Metal levels in class II are threshold values established to protect agricultural production and maintain human health.

^bResidential/parkland land use.

^cIndustrial land use.

industrial area > commercial area > residential area > suburb. Since the ban of Pb in gasoline, the content of this element in the troposphere has decreased (Wang *et al.*, 2003). The Pb concentration in road dust could still be attributed to emissions from fossil fuels, historical Pb contamination and the long half-life of Pb in soils (Wang *et al.*, 2003; Saint' Pierre *et al.*, 2004). The above results indicate that industrial and traffic activities were the main sources of metal pollution in road dust of Delhi.

Since no guidelines on metals in road dust or soil have been prescribed by regulatory authorities in India, results of this study were compared with the maximum permissible limits prescribed by China (NEPA, 1995) and Canada (CCME, 2007) for metals in soil. As shown in Table IV, the mean concentrations of Pb and Ni were lower than the guideline values of China and Canada, whereas the mean concentrations of Cu and Zn were higher than the permissible limits prescribed by those countries (Rajaram *et al.*, 2014). The mean concentration of Cd was lower than values recommended by Canadian guidelines, but higher than Chinese guidelines, whereas the mean concen-

tration of Cr was higher than the permissible limit prescribed by Canada but lower than the guideline value of China.

In comparison to documented studies, it was observed that the levels of heavy metals in the road dust of Delhi are comparable with those determined in other cities (Table IV) (Rajaram *et al.*, 2014). In general, the concentration of Pb in Madrid and Kuala Lumpur, and Zn in Hong Kong were higher than the concentration recorded in Delhi road dust.

3.2 Correlation coefficient analysis

Pearson's correlation coefficient was estimated to evaluate the inter-element relationship of metals in road dust (Table V). The significant positive correlations (> 0.624) observed between Ni-Cr-Cd-Cu indicate that the general contamination sources of these metals were primarily industrial and traffic activities (de Miguel *et al.*, 1997; Lu *et al.*, 2010; Rajaram *et al.*, 2014). While Pb showed very weak positive correlations with Cu, Cr, Ni and Zn varying from 0.146 to 0.433, a moderate correlation (0.660) was found between Pb and Cd thereby indicating

Table V. Pearson's correlation coefficients between different metals.

	Cd	Cr	Cu	Ni	Pb	Zn
Cd	1.000					
Cr	0.432	1.000				
Cu	0.446	0.624	1.000			
Ni	0.682	0.901	0.796	1.000		
Pb	0.660	0.146	0.433	0.330	1.00	
Zn	0.096	-0.304	0.438	0.026	0.244	1.000

that the source for Pb may be industrial activities apart from the vehicular emissions (Rajaram *et al.*, 2014). Zn showed poor correlation with all other metals except Cu (0.438), which may be due to the influence of traffic activities in these areas (Arslan, 2001; Gray *et al.*, 2003).

3.3 Principal component analysis

The results of PCA indicated that all the elements are well represented by two components (Rajaram *et al.*, 2014), which account for nearly 78% of the total variance for the data (Table VI). The initial component matrix indicated that Ni, Cu and Cd are correlated, displaying high loading values in the first component (PC1) whereas Zn showed greater loading values in the second component (PC2) (Rajaram *et al.*, 2014). Cr and Pb are partially represented in both PC1 and PC2. The rotation of the matrix eliminated ambiguities. As shown in Table VI, PC1 included Ni and Cr; PC2 included Zn, whereas Cd, Cu and Pb are distributed in both PC1 and PC2. This implies that Cu, Ni, Cd, Cr, Pb and Zn can be defined as anthropogenic components and may originate from similar pollution sources such as particles released by industrial and traffic activities (Rawat *et al.*, 2009; Lu *et al.*, 2010). Cr and Ni are important constituents of many metal alloys (Siegel, 2002; Manno *et al.*, 2006); therefore, the emission sources of these elements could be attributed to the metal processing industries (non-ferrous metal, electroplating, galvanizing, etc.) in the area. Although Pb has been banned as additive in petrol since a number of years, the concentration of Pb in urban road dust still reflects the significant degree of historical Pb contamination and the long half-life of Pb in soils. Some of the Pb in the road dust might have originate from particles emitted by industrial activities, whereas Zn and Cu may have been contributed by vehicular sources i.e. use of

Table VI. Total variance explained and component matrices for the metal.

Component	Initial eigenvalues loading			Extraction sums of square loading			Rotation sums of square loading		
	Total	% variance	Cumulative %	Total	% variance	Cumulative %	Total	% variance	Cumulative %
	3.2	54.2	54.2	3.2	54.2	54.2	3.0	50.5	50.5
1	1.4	23.9	78.1	1.4	23.9	78.1	1.6	27.6	78.1
2	0.9	15.2	93.4						
3	0.3	5.4	98.8						
4	0.06	1.0	99.85						
5	0.008	0.014	100.0						
6									
Element	Component matrix			Rotated component					
	PC1	PC2		PC1	PC2				
Cd	0.790	0.128		0.696	0.395				
Cr	0.782	-0.581		0.936	-0.272				
Cu	0.856	0.183		0.738	0.470				
Ni	0.945	-0.253		0.97	0.091				
Pb	0.603	0.477		0.399	0.657				
Zn	0.170	0.870		-0.143	0.875				

brake pads and wear and tear of tires (Saint' Pierre *et al.*, 2004; Amato *et al.*, 2009).

3.4 Metal contamination assessment

3.4.1 Contamination factor and degree of contamination

Contamination factor and the degree of contamination were estimated as suggested by Hakanson (1980) (Fig. 3). The contamination factors (C_f^i) indicated very high contamination levels ($6 \leq C_f^i$) of Pb, Zn and Cu, and considerable contamination levels ($3 \leq C_f^i < 6$) of Cd and Cr in the road dust from the industrial areas. The road dust from the mixed areas had concentrations of Cd and Cu of considerable contamination and concentrations of Zn and Pb of very high contamination. In the road dust near the highways, the contamination factors indicated very high contamination by Zn and Pb. The road dust from the residential areas had considerable contamination of Pb and very high contamination of Zn. These results indicate that road dust is most significantly contaminated by Zn and Pb, followed by considerable contamination by Cu and Cd. The concentrations of Cr and Ni indicated moderate contamination of the road dust.

The proportions of the contamination of each metal to the total degree of contamination by the six heavy metals determined in the road dust samples are 6.0–14.4% for Cd, 1.7–10.8% for Cr, 4.5–21.7% for Cu, 2.6–5.7% for Ni, 18.3–36.1% for Pb, and 23.1–54.7% for Zn (Fig. 4). The degree of contamination in road dust from highways, and industrial, mixed and residential areas are 24.2, 46.0, 36.5 and 20.8, respectively (Fig. 3). These results indicate that the

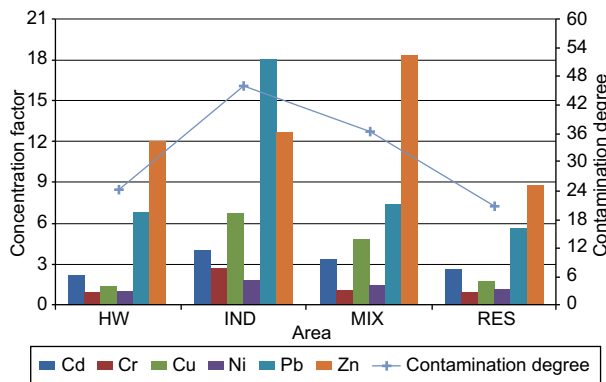


Fig. 3. Contamination factor and degree of contamination of road dust by heavy metals in different areas.

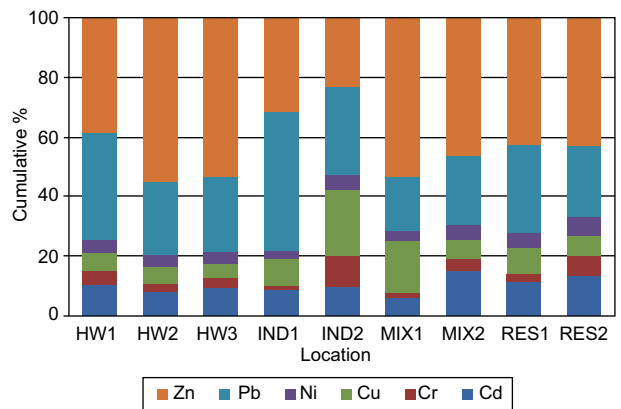


Fig. 4. Contribution of heavy metals to the degree of contamination.

road dust from the highways, the mixed areas and the industrial areas has a very high degree of contamination ($24 \leq C_{deg}$). Road dust from residential areas has a considerable degree of contamination ($12 \leq C_{deg} < 24$). In particular, the degree of contamination for the mixed area 1 was much higher than the value at the other mixed area, which had lesser industrial units. These results indicate that industrial units might have contributed to the increased concentrations of heavy metals in road dust.

3.4.2 Potential ecological risk index

Results of ecological risk assessment of heavy metals in road dust (Fig. 5) revealed that the monomial risk indices (E_r^i) of heavy metals were ranked in the following order: $Cd < Pb < Cu < Zn < Ni < Cr$. The average E_r^i of Cd in samples from industrial and mixed areas is above 80 whereas the same average

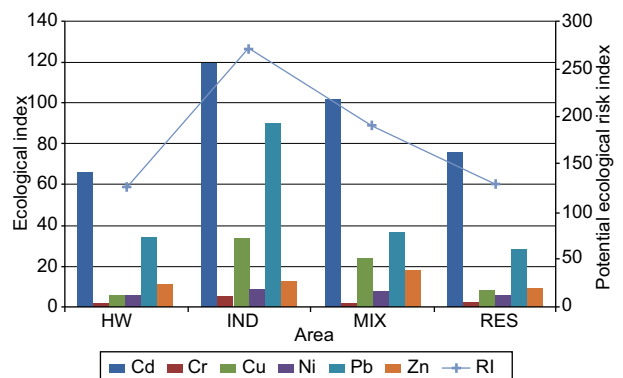


Fig. 5. Ecological risk index of heavy metals in road dust in different areas.

can be found in residential areas, indicating that Cd poses a potentially considerable risk to the local ecosystem. The E_r^i of Pb in road dust samples from the industrial area (90.3) poses considerable risk to the environments. E_r^i values for the other metals were below 80, indicating low to moderate risk.

The overall RI of observed metals in road dust was calculated as the sum of all six risk factors (Fig. 5). RI in road dust ranged from 115.6 to 295.7, with an average of 173.5. RI values were higher in the samples from industrial areas and vary between 246.8 and 295.7, indicating that there is a high potential ecological risk. Among different functional areas, the RIs pose high risk in industrial areas, and considerable risk in other areas.

The percent contribution of individual metal to overall RI is demonstrated in Fig. 6. It is shown that Cd accounted for most of the total risks, and the percentages ranged from 41.7% to 65.2% with a mean of 52.4%. Pb ranked the second among the six metals contributing to the total risk, and the average

was 25.5%, which was followed by 8.9% (Cu), 7.9% (Zn), 3.9% (Ni), and 1.5% (Cr). It could be concluded that the high ecological risk was primarily posed by two heavy metals, Cd and Pb, as their contribution is nearly 78% of the total potentially ecological risk.

3.4.3 Pollution index

The minimum, maximum and mean values of PI for each metal are shown in Table VII. The mean PI values are generally high, indicating that there was serious pollution of road dust. However, PI values varied among metals. PI values of metals in road dust ranged as follows: Cd, 4.3 to 7.0; Cr, 0.6 to 4.3; Cu, 2.0 to 3.3; Ni, 0.7 to 2.0; Pb, 1.2 to 2.3, and Zn, 1.0 to 3.1 with an average value of 5.3, 1.6, 2.4, 0.9, 1.4 and 1.9, respectively. Most of the samples recorded middle or high pollution level PI values for Cd, Cu and Zn, indicating that urban road dust in Delhi is moderately to highly contaminated.

The PI values of metals were generally higher in industrial areas, indicating the presence of relatively serious heavy metal pollution (Fig. 7). Cd recorded high PI values in all the road dust samples from industrial areas, mixed use areas, residential areas and highways. PI of road dust from industrial areas indicated moderate contamination by Cr, Zn and Cu, whereas road dust from mixed-use areas had moderate contamination by Zn and Cu. In highways and residential areas, the mean PI values of Zn and Cu were close to 2. These findings suggest that the major sources of these metals may be vehicular emissions, and the mechanical parts and tires of vehicles as they are subjected to abrasion (Sadiq *et al.*, 1989; Smolders and Degryse, 2002; Adachi and Tainosho, 2004).

The results showed the following proportions of heavy metal contamination levels (Table VII): 44.4, 11.1, and 88.9% of the road dust samples

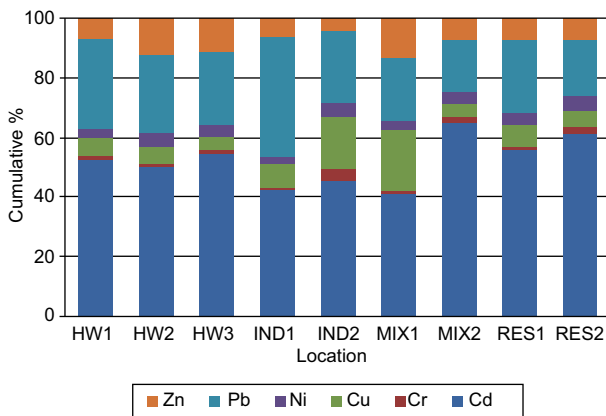


Fig. 6. Contribution of heavy metals to the potential ecological risk.

Table VII. Statistical results of pollution index and integrated pollution index of metals.

	PI			Number of samples				IPI			Number of samples			
	Min	Max	Mean	No.	Low	Moderate	High	Min	Max	Mean	No.	Low	Moderate	High
Cd	4.3	7.0	5.3	0	0	0	9							
Cr	0.6	4.3	1.6	3	4	1	1							
Cu	2.0	3.3	2.4	0	0	7	2							
Ni	0.7	2.0	0.9	7	1	1	0							
Pb	1.2	2.3	1.4	0	8	1	0							
Zn	1.0	3.1	1.9	2	0	6	1	4.2	13.6	7.8	0	3	6	0

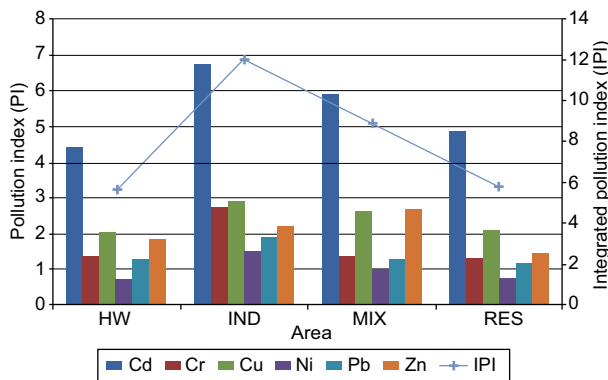


Fig. 7. Pollution index of road dust by heavy metals in different areas.

exhibited low contamination by Cr, Ni and Pb, respectively; 11, 77.8, 11.1, 11.1 and 66.7% of the samples were moderately contaminated by Cr, Cu, Ni, Pb, and Zn, respectively, and 11.1, 22.2 and 11.1% of the samples were highly contaminated by Cr, Ni and Zn, respectively. All the samples were highly contaminated by Cd. These results indicate that Delhi has an important contamination by Cd and a moderate contamination by Cu and Zn. In addition, as shown in Fig. 7, all the roads in this study reported very high values of PI for Cd indicating that Cd contamination in road dust in Delhi is prominent. Furthermore, high (> 1) PI values were observed in only 22% of the samples for Ni. These data indicate that Ni pollution is relatively low in Delhi road dust when compared with other elements.

The IPI value of urban road dust varied from 4.2 to 13.6 with an average of 7.8 (Table VII). There was no sample with IPI < 1 , while low pollution levels with IPI lower than 6 accounted for about 33% of all samples. About 67% of all samples with IPI between 6 and 18 indicated moderate contamination. Thus, it is very likely that urban road dust in Delhi is moderately polluted with heavy metals.

Figure 8 shows the spatial distributions of C_{deg} , RI, and IPI of the road dust of Delhi. It can be seen from this figure that five out of nine locations in this study had very high values (> 24) of C_{deg} while the remaining four locations also had higher values of C_{deg} , close to 24 (very high contamination). RI levels at two locations, out of nine, showed high risk; whereas RI levels indicated considerable risk at all other locations, of which two locations are nearing high-risk category. Similarly, IPI at six locations showed moderate contamination and at remaining

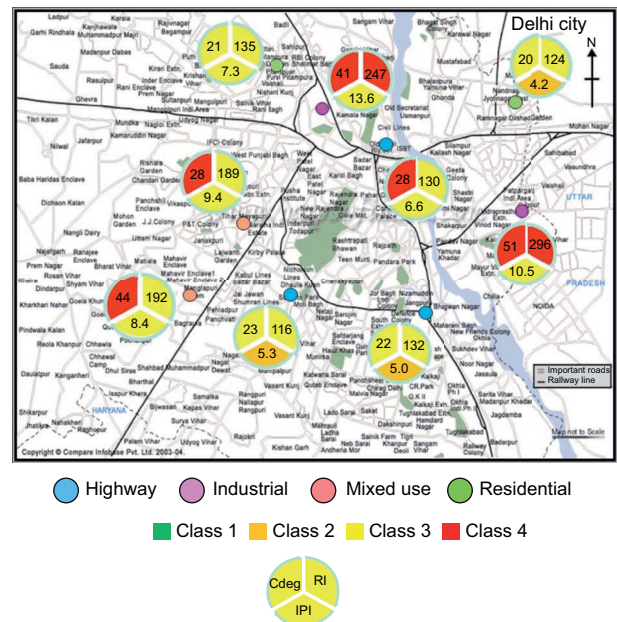


Fig. 8. Spatial distributions of degree of contamination, potential risk index and integrated pollution index in the road dust of Delhi.

three locations the IPI values are close to 6 (high contamination). It can be concluded that the road dust of Delhi has been highly polluted by anthropogenic emissions of heavy metals. These heavy metals can easily enter into human bodies through ingestion, inhalation and dermal contact and they can accumulate in the body and pose risks to human health, potentially causing serious problems at high levels. Therefore, strict heavy metal source control is essential to reduce heavy metal pollution in road dust in Delhi.

From the results of contamination factor evaluation, Cd is mainly in the moderately contaminated category. However, ecological risk caused by Cd was considerable due to its high toxicity. On the other hand, Zn accumulated significantly in the road dusts, but its ecological risk is relatively low. Pollution index results showed that road dust is highly contaminated with Cd and Cu, however, Cu has not accumulated significantly as can be seen from estimated contamination factors, and its ecological risks are also relatively low. Thus, it can be seen that C_i^f method mainly focused on the accumulation levels of individual metal without taking into account the toxic response factor. RI could describe both ecological risk caused by single pollutant and overall risk or contamination from different kinds of pollutants. PI estimation uses

threshold concentrations and can be useful for comparing metal accumulation with the regulatory standards. Therefore, for environmental quality evaluation, all studied assessment methods are important.

4. Conclusion

The analysis of nine road dust samples from different activity zones in Delhi city indicated that the concentration of heavy metals in the road dust collected from industrial area are higher, especially Ni, Cr and Pb. This supports the results of source identification through statistical analysis, which indicates Cd, Cr, Ni and Pb in road dust may be of industrial origin, whereas vehicular traffic may be the major source of Zn and Cu (Rajaram *et al.*, 2014). The metal contamination assessment results based on degree of contamination, potential ecological index and integrated pollution index, revealed that road dusts are mostly contaminated by Zn, Cd and Pb. The road dust from the industrial areas, mixed use areas and highways can be included under a very high degree of contamination with respect to the heavy metals, whereas the road dust from the residential area is having a considerable degree of metal contamination.

The results of the study indicated that the pollution level of road dust in Delhi city is in the category of “moderately to highly contaminated”, and for environmental quality evaluation all assessment methods should be combined so that more comprehensive and accurate assessment results can be achieved. The findings of the study are based on the limited number of samples; however, a further comprehensive study is needed in order to better understand the metal contamination of road dust in Delhi and to develop environmental policies and strategies to minimize the contamination.

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