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ORIGINAL ARTICLE

Contamination levels assessment of potential toxic metals in road dust deposited in different types of urban environment

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Abstract A total of 42 samples of road dust were collected along ring road, city centre, city side, and freeway in Urumqi, China. Total concentrations of Cd, Cr, Cu, Ni, Pb, Mn, Be, Co, Zn, and U were determined by using the inductively coupled plasma-mass spectrometry in order to assess and to compare road dust contamination levels of metals among the four roads. The results show that, among the four categories of roads, mean concentrations of Co and U vary little. City centre locations show strong enrichments of Cd, Cu, Pb, and Be. Along the ring road, the highest mean concentrations were found for Cr, Ni, Mn, and Co. However, the highest concentrations of Zn and U were found along the freeway. The cluster analysis shows that three main groups can be distinguished. Every group may be associated with different main sources and concentrations of the metals. The results of contamination assessment reveal that, among all of the potential toxic metals, Cd, Cu, and Zn pollution were obviously heavier with moderate or high contamination indices for most road dust samples, while Cr, Ni, and Pb contamination were lower along the four categories of roads. Compared with the city side, Cd, Cu, Pb, Ni, and Zn contamination were heavier along the ring road, the city centre, and the freeway with high traffic density. Low Pb contamination or no contamination in all the road dust samples may be related to the increasing usage of lead-free petrol.

Keywords Contamination assessment · Potential toxic metal · Cluster analysis · Road dust · Urumqi

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Introduction

Road dust, particularly the fine particle, can be absorbed by human through ingestion, inhalation, and dermal absorption. In today's urban area, road dust has been disturbed severely by human activities. As a result, the components of road dust in cities are significantly affected by anthropogenic pollutants. Particularly, potential toxic metals from anthropogenic sources in road dust may significantly affect the human health and well-being. Pb, Cr, Zn, Cd, and other toxic metals will continue to accumulate in urban environment due to their non-biodegradability and long residence time, thus they are known as "chemical time bombs" (Shi et al. 2008; Stigliani et al. 1991). In urban areas, these "bombs" have become a potential threat to human health and safety and severely disturbed the natural geochemical cycling of the ecosystem. Furthermore, metals have a direct influence on public health, particularly on children health as they can easily enter the human body (Abrahams 2002; Rasmussen et al. 2001; Shi et al. 2008). Therefore, in recent decades, more and more attentions have been focused on the investigation of metals in urban road dust (Akhter and Madany 1993; Charlesworth et al. 2003).

According to numerous studies, the anthropogenic sources of potential toxic metals in road dust mainly include traffic emission (vehicle exhaust particles, tire wear particles, weathered street surface particles, brake lining wear particles), industrial sources (power plants, coal combustion, metallurgical industry, auto repair shop, etc.), weathered building and pavement surface particles, domestic pollution sources and so on (Ahmed and Ishiga 2006; Amato et al. 2009; Banerjee 2003; De Miguel et al. 1997; Duzgoren-Aydin et al. 2006; Ferreira-Baptista and De Miguel 2005; Han et al. 2006; Kartal et al. 2006; Lu et al. 2008; Morton-Bermea et al. 2008; Ordóñez et al. 2003; Sindern et al. 2007; Wei et al. 2008; Zhou et al. 2008). Many studies regarding the spatial variability of potential toxic metals in contaminated road dusts deposited in different urban environment indicated that the spatial distribution characteristics of potential toxic metals were diverse (Ferreira-Baptista and De Miguel 2005; Han et al. 2006; Kartal et al. 2006; Lu et al. 2008; Morton-Bermea et al. 2008). They have been shown that the traffic density, spatial distribution pattern, and category of industry, soil properties, and other factors could affect the spatial distribution of metals. Therefore, elevated concentrations of metals in the road dusts from different types of roads in urban area may vary significantly.

Urumqi, as an important city in Northwest China, has experienced a rapid urbanization and industrialization in the last decades. The rapid growth of industry, population, and vehicle exerts a heavy pressure on its urban environment. In different categories of roads in Urumqi, the traffic densities, traffic components, and land use were diverse. The features may affect metals deposited in different urban environment in Urumqi city. Therefore, road dust series were classified into four categories mainly based on the characteristics of the roads in Urumqi. The main objectives of this study were to determine the concentrations of potential toxic metals (i.e., Cd, Cr, Cu, Ni, Pb, Mn, Be, Co, Zn, and U) in road dust samples from the four categories of roads in Urumqi and assess the levels of road dust contamination by potential toxic metals. Comparison of the metals contamination levels among the four categories of road dusts was also discussed. Moreover, the aim in performing cluster analysis (CA) was to identify the road dust samples which represented different areas where metal concentrations followed a similar pattern. The results obtained in this study can be used by authorities to identify sources of pollution, locate contaminated areas for remediation, and to find the appropriate remediation action. The results can also provide information of potential toxic metal contamination in road dust deposited in different types of urban environment for researchers and public.

Methodologies

Study area

The urban area of Urumqi (NW of China) covers 144 km^2 (Fig. 1) with 2.3 million inhabitants. Such a high population concentration results in a high car density. Urumqi, as a classic oasis city far away from Pacific Ocean, the city experiences an arid climate, with an annual rainfall of 240 mm and an annual average temperature of 6.4°C. The soil type of Urumqi is mainly gray-brown desert soil. The whole studied area is highly urbanized with high traffic density and with most land area devoted to building, road surfaces, and paving. The central part of the studied area comprises the historic centre district with high urban activities and high traffic density.

Sampling sites

In order to characterizing the different urban environments in the city, comparing the contamination levels of the metals, finding the polluted sources and the spatial distributions of the metals, the 42 locations were selected across the city area, along a ring road surrounding the city core, along a freeway across the city, along the city centre and along the city side. The sampling sites were chosen to cover the four types of roads exposed to different traffic density, different congestions and braking frequency of traffic, different component of vehicles, and also with different influences of industrial sources and natural sources and different pollution sources (Fig. 1). Sampling areas were selected on asphalted pavement on the side of the road excluding the gutter where mass is not directly resuspended. In a sampling point, approximately 200 g of the dust particles was collected on impervious surfaces at the roadsides (the sampling resolution is 1 × 1 m square) with a clean plastic dustpan and a brush and were transferred to self-sealing polyethylene bags for transport to laboratory for further analysis (How was the dust collected?). The sampling campaign was carried out in August 2007. The main characteristics of all sampling sites (group into 4 main categories, namely, city center, city side, ring roads, and freeways) are described as followed:

City centre (C1–C10). This covers an area of approximately 20 km^2. The area was located in the old and commercial area of the city. Traffic is heavy with frequent congestions and high braking frequency. Ten sampling sites (C1–C10) were selected inside this area.

City side (S1–S11). Less busy areas, located at side areas of the city with low traffic flow. However, these sites may be influenced by industrial emission from nearby manufactories which are mainly located at side areas of the city.

Ring road (R1–R14). More than 100,000 vehicles per day move along the ring road, with 80 km h^{-1} speed limit and less congestion. Owning to freight cars forbidden to enter the city centre, the ring road has a higher volume of heavy diesel traffic than the city centre and the city side.

Freeways (F1–F7). The freeway crosses the city from NE to SW with more than 120,000 vehicles per day. Traffic

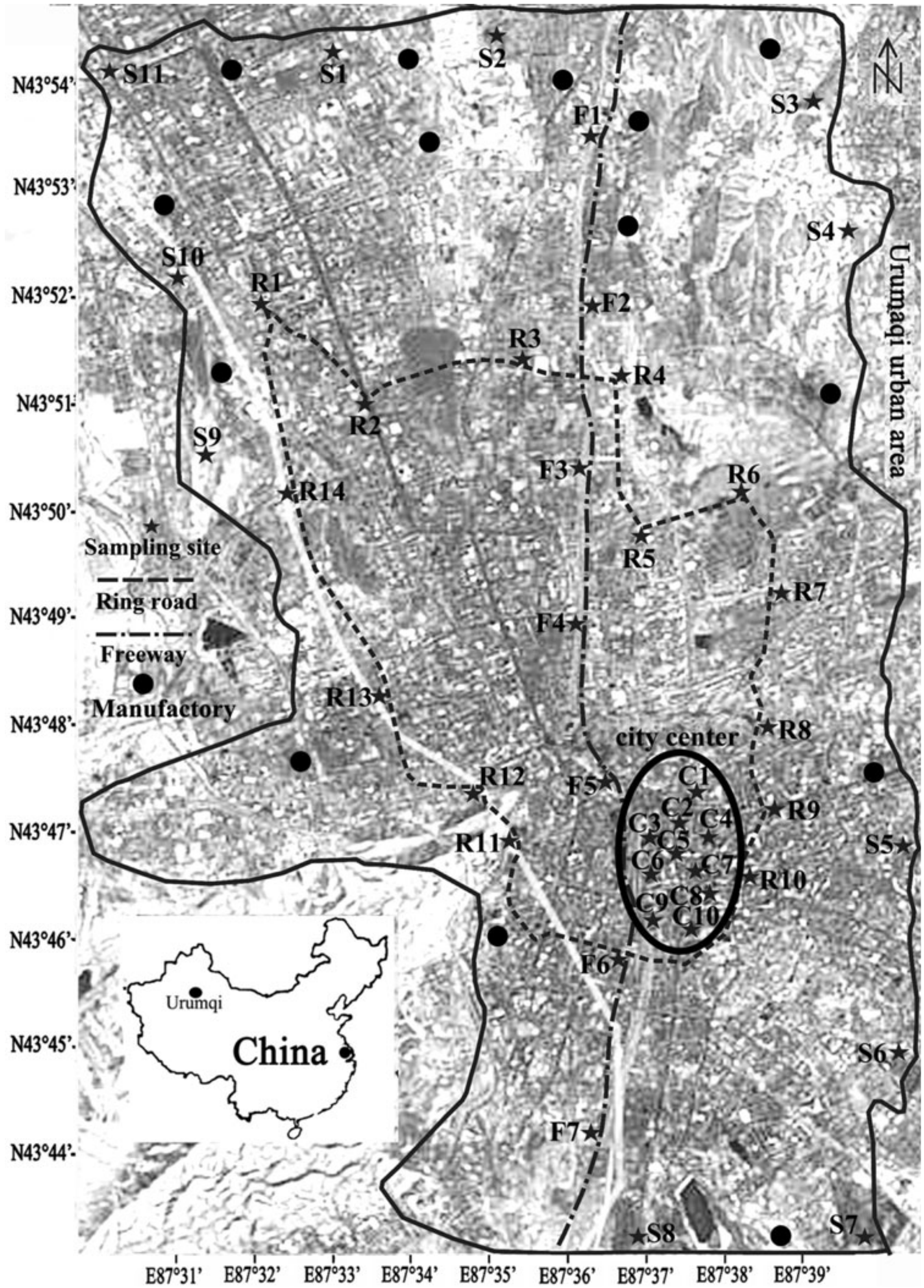

Fig. 1 The left image is the sketch map of locations of the 42 sampling sites, the right image is the satellite map of Urumqi (*F* freeway, *S* city side, *C* city centre, *R* ring road)

is heavy with less braking frequency and high speed limit. Most of traffics which pass by Urumqi city are move along the road. Therefore, the freeway has the highest volume of heavy diesel traffic than the others. Moreover, in the area of freeway, hand wind speed is higher than the other areas.

Sampling procedure and analysis

All the samples were air-dried in the laboratory with standard method (Ferreira-Baptista and De Miguel 2005; Tokalioğlu and Kartal 2006), and then these dried samples were sieved via a nylon sieve with a diameter of $\leq$0.149 mm. Then 0.1 g of the sieved dust samples was digested with 5:2:1 HNO_3–H_2SO_4–HF mixture. The well-prepared solution was heated at 120° for 30 min, at 150° for 30 min, at 200° for 30 min, and at 260–270° for 60 min in turn (Charlesworth et al. 2003; Lv et al. 2006). Finally, the molten samples were diluted in a 50 ml flask with deionized water. Ten types of heavy metals (i.e. Cd, Cr, Cu, Ni, Pb, Mn, Be, Co, Zn, and U) were analyzed with Inductively Coupled Plasma–Mass Spectrometry (ICP–MS, ELANDRC II, PerkinElmer). Quality controls were realized with: (1) analysis of 12 random samples and 4 national standard samples; and (2) random selection of samples to ensure that the mean deviation be less than 3%.

Assessment method of metal contamination

Assessment of the road dust contamination was performed by the contamination index (P_i) and integrated contamination index (P_c). According to Huang (1987) and Bai et al. (2008), a contamination index (P_i) to describe the contamination of a given toxic substance in one region was expressed by the fuzzy functions:

$$P_i = C_i/X_a \quad (C_i \leq X_a) \tag{1}$$

$$P_i = 1 + (C_i - X_a)/(X_b - X_a) \quad (X_a < C_i \leq X_b) \tag{2}$$

$$P_i = 2 + (C_i - X_b)/(X_c - X_b) \quad (X_b < C_i \leq X_c) \tag{3}$$

$$P_i = 3 + (C_i - X_c)/(X_c - X_b) \quad (C_i > X_c) \tag{4}$$

where C_i is observed concentration of the metal; X_a is the non-polluted threshold value; X_b is the low-polluted threshold value and X_c is the highly polluted threshold value.

Based on Chinese Environmental Quality Standard for Soil (GB 15618-1995) (SEPAC 1995), Class I criteria was suitable to keep natural background values, and Class II could be used to the threshold values for protecting human health, while Class III could be used to the threshold values for plant growth. Therefore, X_a, X_b, and X_c in above functions could be defined according to Class I, Class II, and Class III, respectively (Table 1).

The following terminologies are used to describe the contamination index: $P_i \leq 1$ no contamination; $1 < P_i \leq 2$ low contamination; $2 < P_i \leq 3$ moderate contamination; $P_i > 3$ high contamination.

Integrated contamination index (P_c) defined as the sum of all the minus between contamination index and one for a given region (Bai et al. 2008; Huang 1987). It could be calculated by the form as follows:

$$Pc = \sum_{i=1}^{6} (Pi - 1) \tag{5}$$

For the description of integrated contamination index, the following terminologies have been used: $P_c \leq 0$ no contamination; $0 < P_c \leq 6$ low contamination; $6 < P_c \leq 18$ moderate contamination; $P_c > 18$ high contamination.

Table 1 The threshold values (X_a, X_b, and X_c) for potential toxic metals by Chinese Environmental Quality Standard for Soil (GB 15618-1995) (mg/kg)

	Cd	Cr	Cu	Ni	Pb	Zn
X_a	0.20	90	35	40	35	100
X_b	0.30	150	50	60	250	200
X_c	1.0	300	400	200	500	500

Results and discussion

Levels of potential toxic metal concentration per area

Table 2 shows the potential toxic metals in road dust obtained by averaging the samples from different roads in Urumqi. In order to comparison, the background values of the metals in Urumqi were also listed. Tables 3, 4, 5 and 6 show the concentrations of the metals from the four categories of sampling sites. Mean concentrations and standard deviations of the metals in different types of roads were also represented. The results indicate that, in general, the mean concentrations of potential toxic metals show wide ranges of concentration. Except for the mean concentrations of Co and U in all the 4 categories of roads and mean concentration of Cr in freeway, all the other mean concentrations of the metals in road dusts were higher than their background values. Moreover, except for Co, Be, and U, the concentrations of Cd, Cr, Cu, Ni, Pb, Mn, and Zn were higher than their background values in nearly all the road dust samples, implying that the road dust was significantly polluted by the metals from anthropogenic sources.

Among the four categories of roads, mean concentrations of Co and U vary little. It seems that the levels of Co, Be, and U contamination were not obviously related to traffic sources. The city centre locations show strong enrichments of Cd, Cu, Pb, and Be with mean concentrations of 1.19, 112.49, 61.05 and 2.83 mg/kg, respectively. Along the ring road, the highest mean concentrations were Cr, Ni, Mn, and Co (63.69, 46.48, 968.08, and 11.65 mg/kg). However, the highest concentrations of Zn and U (441.20 and 2.38 mg/kg) were found along the freeway. The freeway profiles were also characterized by lowest concentrations of Cr, Cu, Ni, Pb, Mn, Be, and Co. The city side profiles were characterized by low concentrations of Cd, Cr, Cu, Zn, Ni, and Pb and high concentrations of Be, Co, and U.

The concentrations of Cd, Cu, Pb, and Zn were higher along the city centre, the ring road and the freeway, and vary little among the three roads, suggesting that the enrichment of Cd, Cu, Pb, and Zn in the road dust may be mainly attributed to traffic sources. Concentrations of Cr, Ni, and Mn were higher along the ring road and the city centre may be influenced by traffic sources, while the higher concentrations of the metals along the city side may be related to industrial sources. Along the city side and the freeway with significant influence of natural sources (the areas along the two sides of the freeway, about 50 m away

Table 2 Mean concentrations and back ground values of metals along the four roads (mg/kg)

Element	Freeway	City side	City centre	Ring road	Mean	Background value[a]
Cd	0.77	0.41	1.19	0.90	0.82	0.12
Cr	48.25	50.07	56.27	63.69	55.86	49.3
Cu	80.77	90.50	112.49	108.19	100.81	26.7
Ni	38.77	40.10	43.23	46.48	43.54	26.6
Pb	49.41	50.40	61.05	60.83	57.03	19.4
Mn	830.88	940.80	914.11	968.08	925.22	688
Be	2.20	2.71	2.83	2.70	2.67	1.65
Co	9.82	11.58	10.17	11.65	10.97	15.9
Zn	441.20	217.04	407.76	364.81	349.07	68.8
U	2.38	2.27	1.83	1.92	2.07	2.8

[a] CEPA and CGSEM (1990)

Table 3 Concentrations and standard deviations of metals in the analyzed road dust samples along freeway (mg/kg)

	Cd	Cr	Cu	Ni	Pb	Mn	Be	Co	Zn	U
F1	1.53	38.83	55.55	37.08	76.69	778.17	2.50	10.97	526.28	2.40
F2	0.52	36.79	57.88	32.15	51.66	746.90	1.82	9.08	367.69	2.27
F3	0.32	44.59	76.92	28.81	24.48	752.08	2.14	8.44	555.06	2.06
F4	0.66	78.80	109.52	44.35	57.57	833.99	2.06	10.77	745.34	2.31
F5	0.42	65.73	89.37	37.46	31.99	880.98	2.99	9.94	230.99	2.27
F6	1.12	40.48	81.77	39.41	50.77	768.00	1.88	9.70	462.60	2.10
F7	0.83	32.52	94.38	52.14	52.71	1,056.05	1.99	9.86	200.47	3.28
Mean	0.77	48.25	80.77	38.77	49.41	830.88	2.20	9.82	441.20	2.38
Std.	0.43	17.22	19.41	7.72	17.10	110.47	0.41	0.89	191.79	0.41

Table 4 Concentrations and standard deviations of metals in the analyzed road dust samples along city side (mg/kg)

	Cd	Cr	Cu	Ni	Pb	Mn	Be	Co	Zn	U
S1	0.69	44.72	74.40	44.16	66.52	971.73	2.58	10.79	263.54	1.97
S2	0.67	55.92	108.54	34.44	64.54	1,044.05	2.87	10.86	250.75	2.11
S3	0.42	35.51	128.23	43.97	99.45	934.51	1.89	8.61	248.57	1.59
S4	0.16	44.57	58.29	35.84	43.76	840.03	2.81	11.17	123.74	2.32
S5	0.15	37.41	43.32	32.27	29.45	728.52	2.19	9.10	134.58	1.96
S6	0.19	37.63	46.31	35.74	25.86	866.49	3.16	12.36	117.46	2.34
S7	0.21	33.68	49.73	36.89	18.40	806.48	2.76	13.76	76.62	3.78
S8	0.37	39.61	81.38	34.76	82.99	971.04	2.55	9.08	224.94	1.66
S9	0.37	72.87	252.17	62.93	56.36	1,062.21	2.87	12.66	242.08	2.69
S10	0.79	57.61	84.20	53.71	57.96	984.77	3.66	15.27	347.87	2.24
S11	0.46	94.58	102.26	59.75	42.16	1,138.96	3.31	13.71	357.38	2.35
Mean	0.41	50.07	90.50	40.10	50.40	940.80	2.71	11.58	217.04	2.27
Std.	0.23	18.85	59.32	10.92	24.69	121.36	0.49	2.17	93.24	0.59

from the freeway, were natural soil), the concentrations of Co and U were higher than that along the city centre, implying that Co and U may be mainly derived from natural sources. However, the concentration of Be vary little among all of the road dust samples.

Since the ban of Pb in gasoline, Pb emissions from traffic have decreased by two orders of magnitude in Europe. However, the Pb concentration in urban environment can still be attributed to emission from fossil fuels (Amato et al. 2009). Pb concentrations in this study

Table 5 Concentrations and standard deviations of metals in the analyzed road dust samples along city centre (mg/kg)

	Cd	Cr	Cu	Ni	Pb	Mn	Be	Co	Zn	U
C1	1.38	47.42	101.34	34.36	61.99	961.16	3.01	9.82	384.54	1.69
C2	0.79	73.78	138.57	42.14	60.33	984.00	2.86	11.01	335.84	1.92
C3	0.46	46.69	60.97	37.54	52.54	767.15	2.22	9.74	298.89	1.83
C4	1.10	76.77	113.10	63.54	75.64	992.74	2.52	10.90	465.45	1.84
C5	0.76	67.46	103.94	47.64	86.41	1,071.31	2.85	10.71	443.98	1.79
C6	1.25	52.66	226.89	44.45	49.89	870.55	2.50	10.09	643.65	1.56
C7	1.29	59.98	119.72	46.06	65.20	830.77	3.29	9.50	542.57	2.12
C8	0.92	50.88	73.53	37.81	41.60	908.35	2.73	9.59	352.88	1.74
C9	3.38	49.32	82.72	35.51	71.38	945.18	3.79	9.90	292.12	1.89
C10	0.55	37.69	104.14	43.25	45.53	809.86	2.49	10.39	317.71	1.95
Mean	1.19	56.27	112.49	43.23	61.05	914.11	2.83	10.17	407.76	1.83
Std.	0.83	12.79	46.12	8.45	14.13	94.46	0.46	0.55	115.72	0.15

Table 6 Concentrations and standard deviations of metals in the analyzed road dust samples along ring road (mg/kg)

	Cd	Cr	Cu	Ni	Pb	Mn	Be	Co	Zn	U
R1	0.39	129.45	112.59	56.16	58.40	1,051.42	2.43	12.10	282.71	1.98
R2	1.25	55.32	137.44	50.78	58.85	841.09	2.42	12.05	463.40	2.13
R3	0.57	37.22	59.62	36.89	41.71	788.68	2.43	9.37	295.15	1.94
R4	0.40	48.11	61.34	35.97	64.26	801.31	2.77	10.19	249.14	1.76
R5	0.33	102.96	123.15	57.37	62.54	1,140.51	2.16	12.47	448.50	1.86
R6	0.43	39.97	59.72	30.24	30.28	862.96	2.29	9.83	187.14	1.91
R7	1.43	52.55	78.23	48.81	76.58	906.76	3.28	11.74	324.49	2.06
R8	1.13	63.97	142.89	52.24	91.11	924.14	2.93	11.06	252.62	1.87
R9	2.27	57.82	116.57	46.03	77.35	914.73	2.68	12.23	846.15	1.98
R10	0.76	86.13	113.44	62.50	54.54	1,284.67	3.96	13.89	335.39	1.83
R11	0.61	62.11	149.70	49.81	57.85	988.82	2.09	11.81	282.80	1.80
R12	1.22	53.70	139.27	38.73	47.07	950.77	3.00	10.79	292.93	1.85
R13	0.41	52.44	72.13	49.98	53.21	1,000.62	2.82	12.34	242.62	2.31
R14	1.45	49.84	148.58	35.20	77.85	1,096.66	2.54	13.24	604.34	1.60
Mean	0.90	63.69	108.19	46.48	60.83	968.08	2.70	11.65	364.81	1.92
Std.	0.57	25.61	34.89	9.62	16.05	138.94	0.49	1.28	176.34	0.17

(18.40–99.45 mg/kg) were considerable with a slight dependence with traffic volume but in general lower than other studies (Accornero et al. 2008; Al-Khashman 2004, 2007; Banerjee 2003; Chatterjee and Banerjee 1999; Li et al. 2001; Sezgin et al. 2003; Yeung et al. 2003). The highest concentrations of Pb appeared at sites F1 and S3 with high industrial activities, revealing their may be strong link with the industrial sources.

At crossroad with traffic light and high traffic density sites C4, C6, C9, S9, R9, and several others, the concentrations of Cd, Ni, Cu, and Zn were much higher than that of other sites. The sources of the metals may be originated from engine exhausts, tire wear, degree brake pads, mechanical abrasion of vehicles and oil spills (Amato et al. 2009; Charlesworth et al. 2003). At these sites, higher frequency of stop and startup of vehicles may emit more Cd, Ni, Cu, and Zn into the road dust.

However, Co and U reached relative higher concentrations at sites S7, S10, R2, R13, and other city side sites with high natural influences, suggesting that Co and U in road dust may be significantly attributed to natural sources.

The metal concentration results highlight the importance of distinguishing four categories of roads in order to shed light on how local factors influence enrichment properties of potential toxic metals. The low standard deviation for concentration of every element inside each group supported the classification of sites according to the type of environment (Table 3, 4, 5, 6).

Cluster analysis (CA)

Although performing CA on variables rather than on cases is preferred in most research studies (Franco-Uría et al. 2008; Jondreville et al. 2003), CA was developed in this study on road dust samples in order to identify similarities in metals concentrations between the analyzed road dust samples. This approach was selected instead of trying to discriminate between the different sources of metals. Thus, the aim in performing CA was to identify the samples which represented different areas in where metal concentration followed as similar pattern (anthropogenic metal influence, background lithogenic metal levels, etc.) (Franco-Uría et al. 2008).

Three main groups can be distinguished in the dendrogram shown in Fig. 2, performed with the Ward method, which uses the square Euclidean distance as a similarity measure. Group 1 (26.2%) includes road dusts with the lowest mean concentrations of Cd, Cr, Cu, Ni, Pb, Mn, Co, and Zn, while with the highest mean concentration of U. This indicates that road dusts associated in this group were slightly disturbed by traffic sources and industrial sources.

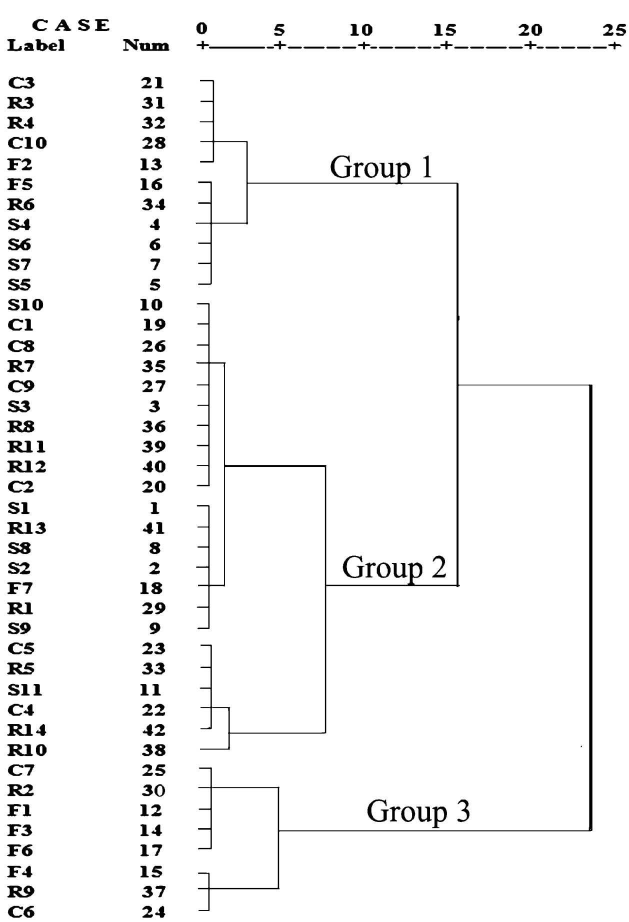

Fig. 2 Hierarchical cluster results or dendrogram obtained by CA of the road dust samples (Ward's method)

However, the highest level of U suggested that road dusts in the group may be significantly influenced by natural sources.

Group 2 (54.8%) includes road dusts with the highest mean concentrations of Cr, Ni, Pb, Mn, Be and Co, and moderate values of Cd, Cu, and Zn, which were much higher than their background values. Except for Co and U, the enrichment of the remaining metals was detected in the samples. Road dusts associated in this group may be significantly influenced by industrial sources. However, the moderate levels of Cd, Cu, and Zn may also suggest that the road dusts were moderately influenced by traffic sources. Therefore, this group can be classified as "potential toxic metals of strong anthropogenic sources".

Finally, the last cluster (Group 3) includes 19% of the road dust samples, which presented the highest mean concentrations of Cd, Cu, and Zn, which have an obvious traffic sources. In these road dusts, the sampling sites were associated with high traffic density and high frequency of stop and startup of vehicles.

Contamination assessment of potential toxic metal

Figure 3 shows that the proportions of contamination levels of Cd, Cr, Cu, Ni, Pb, and Zn in total road dust samples along the freeway, the city side, the city centre and the ring road. Be, Mn, Co, and U contamination were not observed in all road dust samples.

Nearly all of road dust samples were moderately or highly polluted by Cd along the four types of roads (Fig. 3). Cd pollution in road dusts followed the order of city centre > ring road > freeway > city side. In the city side, less than 30% of road dust samples were low or no contamination by Cd. It shows that the level of Cd contamination was significantly related to traffic. Similarly, more than 65% of road dust samples were moderately or highly polluted by Cu and Zn along the four types of roads, particular the levels of Cu and Zn contamination along the freeway, the city centre, and the ring road (Fig. 3). These roads are characterized by high traffic density. Several studies over the world have reported that, in urban road dust or urban soil, Cd, Cu, Zn, and Pb are mainly derived from traffic emission sources (Al-Khashman 2004, 2007; Bai et al. 2008; Chatterjee and Banerjee 1999; Huang 1987; Lv et al. 2006; Sezgin et al. 2003; Yeung et al. 2003).

Compared with Cd, Cu, and Zn, the level of Cr or Ni contamination was not heavier, because their low contamination or no contamination levels in more than 90% of road dust samples could be observed in the four types of sampling sites (Fig. 3). Low Ni contamination was observed in more than 60% of road dust samples along the ring road and the city centre, while more than 30% along

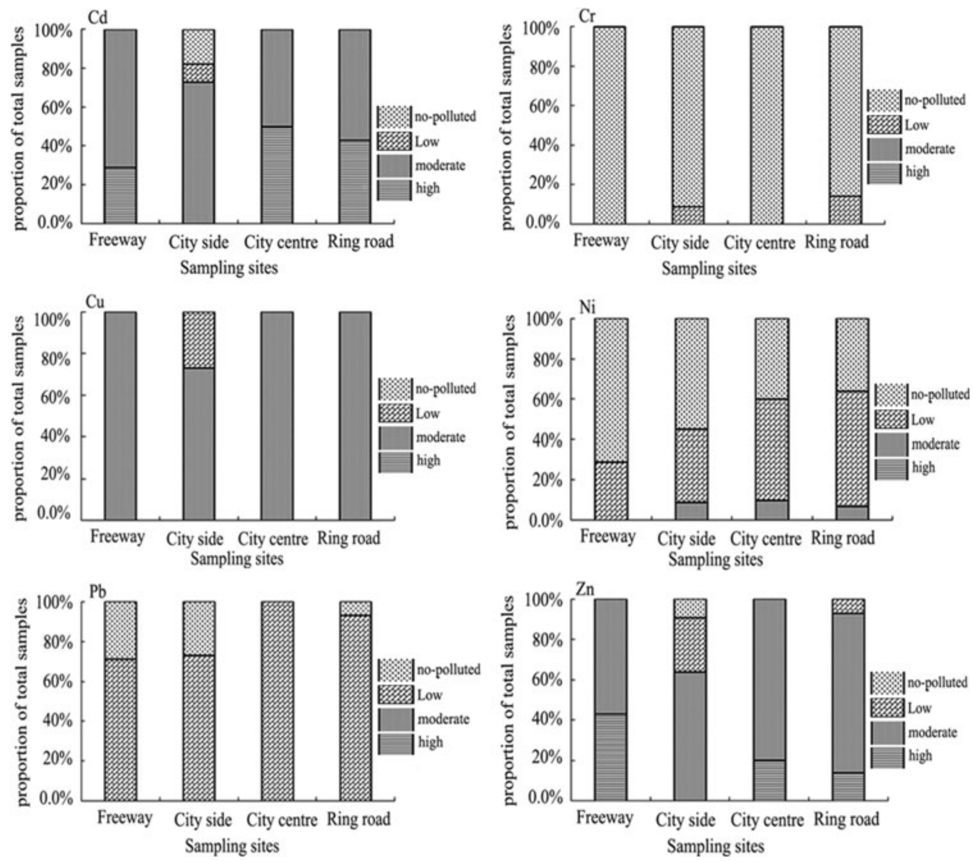

Fig. 3 Proportions of contamination levels of Cd, Cr, Cu, Ni, Pb, and Zn in total road dust samples

the freeway and the city side. All road dust samples along the freeway and the city centre, and more than 80% of road dust samples along the city side and the ring road showed that there was no contamination by Cr. These features show that there is no obvious relationship between levels of Cr and Ni contamination and traffic sources. Pb contamination was low in the region for all samples along the four types of roads, was lowly or no contaminated by Pb, followed by the order of city centre > ring road > city side > freeway (Fig. 3). Low Pb contamination or no contamination in all the road dust samples may be related to the increasing usage of lead-free petrol, the lead level will tend to decrease continuously (Bai et al. 2008).

The integrated contamination indexes (P_c) are shown in Fig. 4. P_c values generally showed that low contamination or no contamination level for all road dust samples along four roads in the study region, followed by the order of city centre > ring road > freeway > city side. The integrated contamination indexes exceeded zero for all road dust samples along the city centre, the ring road and the freeway, with moderate contamination for two sampling locations along the ring road and four sampling locations along the city centre, suggesting that the road dusts with higher traffic density contaminated by potential metals were heavier than the road dusts with lower traffic density. As for the city side, no contamination could be observed in about 30% of road dust samples, and these road dust-sampling locations were far away from the roads with high traffic density. However, these sampling locations may be influenced by industrial emission sources located in the city side (including machine factories, tire factories, rubber factories, cement factories, paper mills, firepower plants, textile mills, automobile factories, chemical plants, and other manufactories). Therefore, about 70% of road dust samples from the city side were lowly contaminated by potential toxic metals.

Conclusions

Contamination levels assessment of potential toxic metals in road dust deposited in different types of urban environment from Urumqi city were carried out. The results show that, in general, the concentrations of Cd, Cr, Cu, Ni, Pb, Mn, and Zn were higher than their background values in nearly all of the road dust samples, implying that the road dust was significantly polluted by the metals from anthropogenic sources. Among the four categories of roads, mean concentrations of Co, Be, and U vary little. The concentrations of Cd, Cu, Pb, and Zn were higher along the

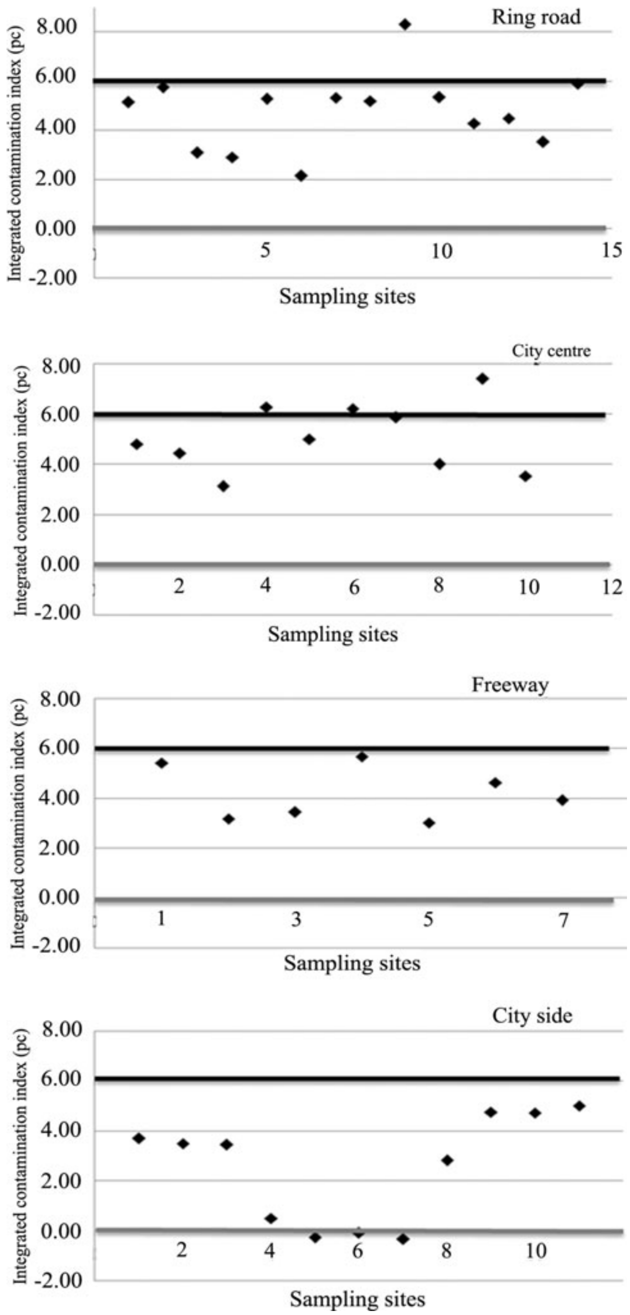

Fig. 4 Integrated contamination indexes of all road dust samples from four roads. *Black* and *gray* lines are the threshold value of low contamination and no contamination, respectively

city centre, the ring road and the freeway, and vary little among the three roads, suggesting that Cd, Cu, Pb, and Zn in road dust may be mainly attributed to traffic sources. Concentrations of Cr, Ni, and Mn were higher along the ring road and the city centre may be influenced by traffic sources, while along the city side the higher concentration of the metals may be related to industrial sources. Along the city side and the freeway with significant influence of natural sources, the concentrations of Co and U were higher than that along city centre, implying that Co and U were mainly derived from natural sources.

Three main groups can be distinguished according to CA. Group 1 (26.2%) include road dusts with the lowest mean concentrations of Cd, Cr, Cu, Ni, Pb, Mn, Co, and Zn, while with the highest mean concentration of U. Group 2 (54.8%) include road dusts with the highest mean concentrations of Cr, Ni, Pb, Mn, Be, and Co, and moderate values of Cd, Cu, and Zn, which were much higher than their background values. Group 3 includes 19% of the road dust samples, which presented the highest mean concentrations of Cd, Cu, and Zn, have an obvious traffic sources.

The integrated contamination indices show nearly all of the road dust samples along the four roads were low contamination. Among the potential toxic metals, Cd, Cu, and Zn pollution were obviously heavier with moderate or high contamination indices for most road dust samples, while Cr, Ni and Pb contamination levels were lower along the four types of roads. Compared with the city side, Cd, Cu, Pb, Ni, and Zn contamination in road dusts were heavier along the ring road, the city centre or the freeway with high traffic density. Low Pb contamination or no contamination in all the road dust samples may be related to the increasing usage of lead-free petrol.

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