Geochemistry of street dust in Tyumen, Russia: influence of traffic load

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Abstract
This study investigates the elemental composition, organic carbon content, pH values, and particle size characteristics in 50 road dust samples collected from Tyumen, a large city in Western Siberia (Russia). The content of 62 major and trace elements was studied using atomic emission spectrometry (ICP-AES) and inductively coupled plasma spectrometry (ICP-MS). It was revealed that the dust has an alkaline reaction pH = 7.4–10.2 and low organic carbon content (0.07–2.9%). The grain size distribution of the road dust samples revealed that the predominant grain size fraction was of 100–250 μm. The content of small particles (PM2 and PM10) representing the greatest environmental hazard is minimal on roads with an average traffic intensity. Studies have shown that the main road dust pollutants in Tyumen are Ni, Sb, Cr, Zn, and Co. The average geoaccumulation index (Igeo) values are ranked as Ni (2.2) > Sb (1.5) > Cr (1.3) > Zn (0.4) > Co (0.4) > Cu (0.2). The contamination evaluation through enrichment factor (EF) calculation showed that road dust is highly enriched in Ni and significantly in Cr and Sb. More than 80% of Zn, Co, and Cu and more than 90% of Ni, Sb, and Cr come from anthropogenic sources. The average concentration of Ni and Cr in the road dust of Tyumen is one order of magnitude higher than in other cities of the Earth where similar studies were carried out. The high Ni content is associated with the composition of local soils and roadways, increased content in vehicle exhaust gasses, and abrasion of metal parts. Calculations of the total enrichment index Ze showed that the level of road dust pollution in most of Tyumen’s territory is hazardous.

Keywords Road dust · Trace metals · Major elements · Contamination factor · Enrichment factor and Igeo · Principal component analysis · Traffic load · Tyumen City · Total enrichment index

Introduction
Road dust (RD) is currently one of the main objects in the study of the ecological state of urbanized areas. Studies on the RD composition, sources, and hazards to human health have been conducted in dozens of cities around the world. Here we can only mention the largest megacities, where the RD composition has been studied: Hong Kong (Li et al. 2001), Istanbul (Sezgin et al. 2003), Shanghai (Shi et al. 2008), Lanzhou (Wang et al. 2012), Guangzhou (Bi et al. 2013), Nanjing (Li et al. 2013), Beijing (Li et al. 2014), Delhi (Rajaram et al. 2014; Siddiqui et al. 2020), Moscow (Vlasov et al. 2015; Kasimov et al. 2019a, b, 2020; Ladonin and Mikhaylova 2020), Buenos Aires (Cappelletti et al. 2019), and Kolkata (Chenery et al. 2020). Globally, road dust is a major source of inhalable particulate matter in any urban environment (Jose and Srimuruganandam 2020). There are several reviews, where RD properties and hazards to human health are discussed (Loganathan et al. 2013; Gulia et al. 2019; Haynes et al. 2020; Gondwal and Mandal 2021).

As an object of environmental studies, RD has certain advantages. Many pollutants including trace metals and metalloids (TMMs), polycyclic aromatic hydrocarbons, and polychlorinated biphenyls accumulate within RD (Chow et al. 1996; Varrica et al. 2003; Denier van der Gon et al. 2013; Amato et al. 2014; Zhang et al. 2015; Kosheleva et al. 2018; Cappelletti et al. 2019). A wide range of pollutants accumulated within RD can be used for assessments of ecological conditions of urbanized areas. The advantages of using RD for evaluating the environmental pollution in urban and

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industrial areas also include its ease of sampling, its ubiquity and non-point source nature, and its strong relationship with car emissions (Sutherland 2003).

RD is formed through sedimentary process of particulate matter which mainly originates from atmospheric precipitation, urban traffic, construction, and industrial activities under the action of wind, water, and gravity in road surface and the use of deicing agents (Irvine et al. 2009; Cao et al. 2018). The RD composition is significantly influenced by the wind erosion of soils (Kasimov et al. 2019b; Vlasov et al. 2021). Variations in the degree of RD contamination are predetermined by many factors such as the type of industrial specialization of each particular city, the population size, and the number of motorized vehicles (Amato et al. 2009; Rajaram et al. 2014; Wang et al. 2020). The RD accumulation rates increase within areas where municipal street cleaning services are poorly performed. RD is a source of pollution of urban soils and water bodies. Soil horizons formed of dust aerosol deposits are found along large roads (Vlasov et al. 2015).

The high concentration of toxic substances in the dust makes it hazardous to human health. Road dust of urban can be a particular risk to humans due to small particle size and inherent mobility in windy weather conditions leading to the possibility of direct and indirect exposure; direct exposure from dust can occur by inhalation and ingestion (Shi et al. 2008; Lu et al. 2009; Wei et al. 2010; Benhaddya et al. 2016). Compared with the soil, trace metals adsorbed on the dust are easier to enter the human body through ingestion, inhalation, and dermal contact, and thus endanger human health (Tang et al. 2017). Dust microparticles increase the risk of respiratory, cardiovascular, and oncological diseases (Tager 2005). Small particles with a diameter < 10 μm are most dangerous because they are in the air for a long time, enter the lungs, and settle in them (Kjelgaard et al. 2004).

Urban areas are well-recognized hotspots for environmental health hazards due to rising population density, industrialization, and heavy transportation load (Siddiqui et al. 2020; Mondal and Singh 2021). Numerous studies reported that the road transport-related air pollution is one of the dominant sources of urban air pollution and continuously contributing emission (Li et al. 2016; Gulia et al. 2019; Othman and Latif 2020). In many cities of Russia, a hazardous environmental situation caused by atmospheric air pollution has been repeatedly noted (Kasimov et al. 2014; Krupnova et al. 2020). There is an increasing interest to RD composition studies in Russia recently due to the fact that RD objectively reflects the atmospheric pollution level. The greatest number of such studies has been conducted in Moscow (Vlasov et al. 2015, 2021; Kasimov et al. 2019b; Ladonin and Mikhaylova 2020). Regardless other Russian cities, similar studies have been carried out in the Perm region (Kaygorodov et al. 2009), Chelyabinsk (Krupnova et al. 2020), and Alushta (Kasimov et al. 2019a). The composition of urban surface deposited sediments was also studied in Rostov-on-Don, Ufa, Perm, Murmansk, Ekaterinburg, Tyumen, and Nizhny Tagil (Seleznev et al. 2020; 2021). In Tyumen, Konstantinova et al. (2020) have analyzed 20 samples of RD, where they found high concentrations of Cr, Ni, Sb, Mo, and Co and concluded that motorized vehicles were the main source of those elements in RD.

The present study had the following aims: to conduct an assessment of TMMs concentrations in the RD of Tyumen, to identify the sources of those TMMs, to determine the pollution levels, and to estimate the influence of road traffic intensity on the RD composition. Our research complements and expands the work of Konstantinova et al. (2020) by the following: (a) collecting a larger number of samples from a wider area within the city of Tyumen (50 sampling sites) and verifying the results obtained; (b) measuring concentrations of other major and trace elements that have not been analyzed in the considered study including Hg and rare earth elements; (c) identifying relationships between the RD composition and the road traffic intensity, and (d) estimating the ratio of natural to anthropogenic sources of TMMs in RD.

## Materials and methods

### Study area

The study was carried out in Tyumen, the largest city in the Tyumen oblast (province), known primarily as a region of the oil production. Tyumen is located in the southwestern part of the West Siberian Plain, in the south of the taiga zone. The climate of Tyumen is cold continental, the average annual air temperature is +0.9 °C, and the amount of precipitation for the year is 480 mm (Reference Book 1998). Southerly and westerly winds prevail. The Tyumen area is underlain by two principal geological formations: lower diorites and gabbros of the Pre-Jurassic formations and upper loams, clays, silts, and lake-alluvium of the Upper Pliocene and Holocene (Seleznev et al. 2021).

The rapid development of Tyumen began in the second half of the twentieth century after the discovery of numerous oil and gas fields in the north of Western Siberia. In the 1960s, the population of Tyumen was about 150 thousand people, at the end of the 1990s it was about 500 thousand, and now it has exceeded 800 thousand people. In Tyumen, there are enterprises of mechanical engineering, instrument making and metalworking, oil refining, production of building materials, and energy (combined heat and power plants). Transport streams pass through Tyumen to the northern regions, where oil and gas fields are located. The city operates 385 thousand vehicles; the total length of the road network is 1241 km (Konstantinova et al. 2019).
Emissions from vehicles account for more than 80% of the gross emissions of pollutants entering the city’s atmosphere (Krest’yannikova et al. 2015). The traffic load on the roads with the most intensive traffic reaches 8.1 thousand vehicles per hour (Germanova and Kernozhitskaya 2014). Regular road cleaning is undertaken by the Tyumen municipal services around 8–12 times a month depending on the traffic intensity.

**Sampling and laboratory analysis**

RD sampling was carried out in 10–12 June 2020. Considering the finding that the RD composition depends on the precipitation rate and the duration of dry periods (Pachon et al., 2021), sampling was performed 5 days after the last precipitation event. Roads with different traffic intensities were examined: high (>4 thousand vehicles per hour), moderate (1–4 thousand), and low (<1 thousand). The traffic intensity was determined according to the data (Guseinov 2001; Germanova and Kernozhitskaya 2014). Roads with low traffic volume are common mainly on the outskirts of Tyumen in low-rise residential area, while traffic intensity is highest in the city center. Samples weighing 200–300 g were taken with a plastic brush and a scoop from the surface of the roadway on test plots 1 × 1 m in size, placed in plastic bags, and delivered to the laboratory. A total of 50 samples were taken. The location of sampling points is shown in Fig. 1. A detailed description of the sampling sites is presented in Supplementary Materials (Table SM1).

In the laboratory, the samples were sieved through a sieve with a mesh size of 1 mm to remove impurities (vegetation residues, debris). Then, the samples were dried slowly using an oven at 60 °C over 24 h. The pH values were measured potentiometrically in continuously mixed 1:2.5 soil:water suspensions using a Starter3100 conductivity meter (OHAUS, Germany). The organic carbon (OC) content was determined by calcining to constant weight (GOST 23740-2016). The particle size distribution was determined by laser diffraction using a Mastersizer 3000 laser particle size analyze (Malvern Panalytical, UK). The content of 54 trace elements (Li, Be, Sc, V, Cr, Co, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Y, Zr, Nb, Mo, Rh, Pd, Ag, Cd, Sn, Sb, Te, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Ir, Pt, Au, Hg, Tl, Pb, Bi, Th, U) and 8 major elements (Na, Mg, Al, P, S, K, Ca, and Fe (in weight percent oxide for the particulate fraction)) were measured in

![Fig. 1 Sampling sites and land-use areas within the city of Tyumen, Russia: 1—sampling sites; 2—main federal roads; 3—Trans-Siberian railway; 4—main city roads; 5—power plants; 6—mechanical engineering and metalworking facilities; 7—oil refining and plastic production facilities; 8—high-rise residential area; 9—low-rise residential area; 10—modern business zones; 11—historical center; 12—industrial zones; 13—recreational and unbuilt zones](image)
RD samples by using inductively coupled plasma ICP-MS (X-7 Thermo Elemental, USA) and atomic emission method AES-MS (iCAP-6500, Thermo Scientific, USA).

For analysis, portions of samples weighing 100 mg were used. Sample digestion was carried out in an open beaker system. The samples were placed in Teflon beakers (volume 50 ml), 0.1 ml of a solution containing 8 µg dm$^{-3}$ 145Nd, 61Dy, and 174Yb was added (control of the chemical yield during the sample decomposition procedure), and moistened with several drops of deionized water. Then 0.5 ml of a solution was again evaporated to wet salts. Then 2 ml of HCl (hydrochloric acid fuming 37% OR, ISO, Merck) and 0.2 ml of 0.1 M H$_2$BO$_3$ solution (analytical grade) was added and evaporated to a volume of 0.5–0.7 ml. The resulting solutions were transferred into polylethylene bottles, 0.1 ml of a solution containing 10 mg l$^{-1}$ In (internal standard) was added, diluted with deionized water to 20 ml, and analysis was performed. As control samples in Teflon beakers, the above procedures were performed without samples, and the resulting solutions were used as controls. Along with the analyzed samples, the decomposition of standard samples was carried out. To check the correctness of the analysis of dust samples, we used multi-element standard samples Trapp ST-2a (Russian State Standard GSO 8671–2005) and Basalt BHVO-2 (US Geological Survey). The comparison with the standard samples showed a sufficient repeatability (85–115%) for the majority of the analyzed elements, except for Sn (59%), Ba (70%), Ag (153%), and W (63%), the measurements of which were excluded from the calculations of indices that characterize the intensity of pollution. There was no standard reference material to certify the analysis of Hg, As, Se, Rh, Pd, and Te.

The methods, recoveries, and analytical results of certified reference materials are given in Supplementary Materials (Table SM2). The detection limit (DL) for measured elements is listed in Table 2.

Data analysis

Statistical processing of the results was carried out using the Excel and Statistica 9.0 packages. Statistical indicators of the composition of R (mean, median, standard deviation) were determined for Tyumen as a whole and separately for roads with different traffic intensities. The significance of differences in mean values for roads with different traffic intensities was assessed using the Mann–Whitney test.

Contamination factor $Cf$ and geoaccumulation index $I_{geo}$ are commonly used for the comprehensive assessment of road dust contamination with TMMs (Khairi et al. 2011; Li et al. 2015; Wang et al. 2020), as well as enrichment factor $EF$ (Chenery et al. 2020; Jadoon et al. 2021). The enrichment index $Ze$ is widely used in Russian geochemistry research practice (Vlasov et al. 2015; Kasimov et al. 2016; 2020). The assessment accomplished by two or more methods could improve the accuracy of the assessment result (Trujillo-Gonzalez et al. 2016). Therefore, to improve the accuracy of the result and make the assessment more comprehensive and systematic, more methods should be applied (Zhang et al. 2020). We calculated all above-mentioned indices to compare our results of road dust pollution in Tyumen with the data obtained by other researchers in different cities of the world.

The contamination factor is calculated based on the following equation:

$$Cf = \frac{Ci}{Cb}$$

where $Ci$ is the concentration of the particular element in the dust and $Cb$ is the content of background values. For road dust, due to the absence of a background analog, the content of elements was compared with the average content in the continental crust according to Rudnick and Gao (2003). The same method of calculation was applied in other Russian cities (Vlasov et al. 2015, 2021; Kasimov et al. 2019a, 2020). The use of continental crust values is acceptable only in areas where there are no geochemical anomalies associated with the features of the geological structure. In this case, the elements content in soils, which are the source of particles in the atmosphere, is close to continental crust values. According to scientific research on some of the heavy metals and metalloids content in Western Siberia soils (Moskovchenko, 1998; Syso 2007), soil composition in the region is not that different from continental crust values. Thus, in the soils of Western Siberia, the average content of the elements is (in mg kg$^{-1}$): Co—13, Cr—84, Cu—31, Ni—42, Pb—18, Zn—73, and Zr—295 (Syso 2007). These values are quite close to continental crust values according to Rudnick and Gao (2003), as set out in Table 1. Consequently, comparison with the distribution of elements in the Earth’s crust is reasonable.

Hakanson (1980) divided the contamination factor into four categories: $Cf<1$ = low contamination factor indicating low contamination, $1 \leq Cf<3$ = moderate contamination, $3 \leq Cf < 6$ = considerable contamination, and $Cf \geq 6$ = very high contamination.

$I_{geo}$ index was calculated according to Müller (1969) using the following equation:

$$I_{geo} = \log_2\left(\frac{Ci}{1.5Cb}\right)$$

(2)
where $C_i$ is the measured concentration of the particular element and $C_b$ is the geochemical background (crustal average). The $I_{geo}$ defines the impact of human activities on heavy elements pollution and makes it possible to identify and classify the level of pollution in studied dust samples (Wang et al. 2020). According to Müller (1969), the contamination level can be classified based on a scale, where $I_{geo} \leq 0$ classified as uncontaminated, $0 < I_{geo} \leq 1$ slightly contaminated, $1 < I_{geo} \leq 2$ moderately contaminated, $2 < I_{geo} \leq 3$ moderately to heavily contaminated, $3 < I_{geo} \leq 4$ heavily contaminated, $4 < I_{geo} \leq 5$ extremely contaminated, and $I_{geo} > 5$ extremely contaminated (Müller 1969; Sutherland 2000).

The enrichment factor ($EF$) of an element, an important parameter for evaluating the impact degree of human activities on its enrichment, is the normalization of a measured element against a reference element in a studied sample (Al-Awadhi and AlShuaibi 2013). The $EF$ was calculated according to equation:

$$ EF = \frac{C_x (sample)}{C_{Al}} / \frac{C_x (crust)}{C_{Al}} $$

(3)

where $C_x (sample)$ is the measured concentration of the element of interest, $C_x (crust)$ is the concentration of the same element in the Earth’s crust, and $C_{Al}$ is the concentration of the reference element (aluminum) in the same sample and the Earth’s crust. Composition of the upper continental crust was used as a reference for normalization due to the absence of background analog for road dust, which is a specific anthropogenic object (Vlasov et al. 2021). $EF \leq 2$ means deficiency to minimal enrichment, $2 < EF \leq 5$ corresponds to moderate enrichment, $5 < EF \leq 20$ signifies significant enrichment and significant pollution signal, $20 < EF \leq 40$ indicates very high enrichment and very strong pollution signal, and $40 \geq EF$ means extremely high enrichment (Sutherland 2000; Yongming et al. 2006; Lu et al. 2009). Unfortunately, available data on soil composition within the Tyumen area include only very few trace elements, which makes it impossible for us to compare the enrichment of RD with that of local soils. Determination of regional baseline concentrations of TMMs in soils still remains an unresolved problem due to the vastness of the territory of Western Siberia, highly variable TMMs concentrations in soils, and only small datasets analyzed to date (Il’in et al. 2003).

Further, based on the $EF$ values, an assessment was made of the ratio between natural and anthropogenic sources that affect the composition of dust. A simple formula (Han et al. 2007; Chen et al. 2012) is used as below: assuming the concentration of element $X$ in resuspended road dust is the sum of the two sources: crustal and pollution, i.e.:

$$ X_{roaddust} = X_{crust} + X_{pollution} $$

(4)

$$ X_{crust} = Al_{roaddust} (X/Al)_{crust} $$

(5)

$$ X_{pollution}\% = (1 - (Al/X)_{roaddust} (X/Al)_{crust}) \times 100\% $$

(6)

The generalized level of RD pollution by TMMs was estimated using the total enrichment index (Kasimov et al. 2012):

$$ Ze = \sum EF(n - 1) $$

(7)

for $EF > 1.5$, where $n$ is the number of elements with $EF > 1.5$. The latter (coefficient 1.5) is used in this equation in order to exclude random variations in background values. This index characterizes the levels of accumulation of chemical elements in the road dust solely under the impact of technogenic sources and excludes the effects related to blown off soils or surface materials (Kasimov et al. 2020). $Ze$ index has been very widely applied in ecological studies in Russia, in particular, for analyses of road dust contamination (Vlasov et al. 2015, 2021; Kasimov et al. 2016, 2020). The calculation of this index made it possible to compare the level of road dust pollution in Tyumen with pollution levels in other Russian cities. The following values are taken as gradations of the pollution level: $Ze < 32$—non-hazardous pollution level, $32–64$—moderately hazardous, $64–128$—hazardous, and $128–256$—very hazardous (Vlasov et al. 2015; Kasimov et al. 2016).
To make the results more easily interpretable and to determine sources of pollution, the principal component analysis (PCA) with varimax normalized rotation was also applied. When PCA with varimax normalized rotation was performed, each PC score contains information on all of the metal elements combined into a single number, while the loadings indicate the relative contribution each element makes to that score (Yongming et al. 2006).

Results and discussion

Physical and chemical properties of road dust

Table 1 shows the physicochemical indicators and particle size distribution of RD on roads with different traffic intensities.

The dust has an alkaline reaction; the pH value varies from 7.4 to 10.2. The alkaline reaction is caused by the entry of microparticles of carbonate construction dust, as well as the redistribution of pollutants emitted by vehicles. Acidifying gaseous compounds, mainly nitrogen oxides, migrate off the roadway, while alkalinizing dust particles (construction carbonate dust, deicing mixtures) remain on the road. The differences in the average pH values on roads with different traffic intensities are small (7.82–8.10) and, according to the Mann–Whitney test, are statistically insignificant. The content of organic matter varies from 0.07 to 2.9% (average 1.1%). The minimum content of organic matter on roads with moderate traffic intensity, the maximum on roads with low traffic (Table 1). The increased content of organic carbon in the dust from small roads is explained by a lack of roadside borders, which allows for spreading of soil from roadside loans onto the road surface.

RD from different cities of the world has a predominantly alkaline reaction of pH 7–10; the content of C_{org} varies significantly—from 1 to 17% (Al-Khashman 2007; Ladonin and Plyaskina 2009; Acosta et al. 2011; Yisa et al. 2011; Hu et al. 2011; Sutherland et al. 2012; Vlasov et al. 2015; Gabarron et al. 2017). Thus, in terms of physical and chemical properties, RD of Tyumen does not differ from other cities on Earth.

The technical salt, halite (NaCl), is the most usual road deicing agent used in Tyumen, which causes an increase in the salinity of snow meltwater due to the presence of Cl\(^-\) anions (Moskovchenko et al. 2021). Halite can contain 3–7% of admixtures such as Mg and K salts and iron oxides. Granite grit and sand-gravel mixtures are only used in cases of severe icing. Research in Moscow (Vlasov et al. 2021) has shown that precipitation during the warm season does not lead to the complete leaching of salts out of urban ecosystems and from road surfaces. It is very probable that components of deicing agents are not completely removed from RD in Tyumen, which has a similar annual precipitation as Moscow, but a shorter warm season.

The particle size distribution is dominated by the fine sand fraction (grain size 100–250 μm, PM_{100–250}), the content of which is 52% on average (varying from 3.8 to 67.4%). The content of very fine sand (50–100 μm, PM_{50–100}) is much less and averages 11.2%. The content of the silt fraction is 18.1% (4.6–31.2%). The amount of clay particles (PM_{2}) is very low (0.7–3.2%).

It is believed that the predominance of particles with a size of 180 … 240 μm in road dust is evidence of the influx of soil particles and particles associated with traffic—abrasion of the roadway, tires, and metal parts of cars (Christoforidis and Stamatis 2009). Particles with a size of 60 … 90 μm come with emissions from industrial sources and thermal power plants (Krupnova et al. 2020). According to Zaytseva et al. (2013), the dust particles less than 10 μm are formed in all technological processes at metallurgical enterprises. A significant predominance of particles with a diameter of 100–250 μm and a very small amount of PM_{10} particles (Fig. 2) in the Tyumen RD indicates a weak influence of industrial enterprises on its composition and the predominant effect of transport and soil erosion processes. Measurements of the number of particles PM_{2.5} and PM_{10} in the air confirm the low dustiness of the surface layer of the atmosphere in Tyumen. During the sampling period of road dust (June 2020), the average concentration of PM_{10} particles in the air was 0.020 mg/m\(^3\), which is significantly less than in most cities on Earth (Pozhitkov 2020).

Comparison of data on the granulometric composition of Tyumen’s RD with data for other cities showed that the predominance of the sand fraction with a particle size > 50 μm
is typical for RD and weakly depends on the composition of urban soils, population size, and industrial specialization. So, in Moscow, road dust has a predominantly sandy loam composition; the share of \( PM_{>50} \) averages 69.1%, \( PM_{10-50} \)—16.3%, \( PM_{1-10} \)—12.8%, \( PM_1 \) 1.8% (Vlasov et al. 2015). In Chelyabinsk (Russia), RD was dominated by particles ranging in size from 30 ... 40 to 250 ... 300 µm (Krupnova et al. 2020). In Turin (Italy), RD was significantly dominated by fractions of 50–200 µm and 200–2000 µm, the content of which was 27 and 62%, respectively (Padoan et al. 2017). In Shanghai, China, RD is dominated by particles ranging in size from 100 to 400 µm (Shi et al. 2011). The predominance of the sandy fraction in road dust is associated with the removal of \( PM_{10-50} \) particles, which rise during the movement of vehicles as a result of the action of turbulent eddies and can be carried even by weak winds (Vlasov et al. 2015).

The distribution of RD fractions on roads with different traffic intensities in Tyumen is given in Fig. 2. The largest number of small particles (\( PM_2 \) and \( PM_{10} \)), which are most easily carried by the wind and pose the greatest danger to public health, was noted on roads with medium and high traffic. The lowest contents of all particles were found on roads with a low traffic intensity. Verification using the Mann–Whitney test showed that the difference in the average values of the content of particles of the same aerodynamic diameter, depending on the traffic intensity, was not significant. At the same time, the content of silt and clay particles in RD on roads with low traffic is reduced in relation to moderate and high traffic.

The distribution of grain size fractions in RD of Tyumen differs from the distribution of grain size in the Moscow. Studies performed in Moscow showed that with an increase in traffic intensity, the proportion of sand in road dust increases, while the amount of other particles decreases due to the wind erosion (Kasimov et al. 2016). Probably, on Tyumen’s small roads located mainly on the outskirts of the city, natural winds intensity have a decisive influence, under the influence of which \( PM_2 \) and \( PM_{10} \) particles are carried away. The average wind speed in Tyumen is 3 m/s, during the sampling period (May)—3.3 m/s (Reference Book 1998). Even at low wind speeds (2–3 m/s), particles 1–2 µm in size do not settle due to gravity (Charron and Harrison 2005; Viana et al. 2006).

**Major elements**

The compositions of major elements in RD of Tyumen are shown in Fig. 3. For comparison, the composition of Quaternary deposits (eolian sand) in the vicinity of Tyumen is presented in accordance with Sizov et al. (2020). The composition of RD is dominated by MgO (on average 12.9%), CaO (7.7%), \( Al_2O_3 \), and \( Fe_2O_3 \) (5.2%). Then \( K_2O \), \( Na_2O \), and \( P_2O_5 \) follow in descending order. RD contains more CaO, MgO, \( P_2O_5 \), and \( Fe_2O_3 \) than sandy eolian deposits (see Fig. 3). Thus, road dust is enriched with calcium and magnesium, which is caused by the intake of carbonate cement dust during abrasion of curbs and the use of anti-ice reagents. The intake of phosphorus is associated with soil organic matter. \( Fe_2O_3 \) comes from the corrosion of metal parts of vehicles; magnesium is part of deicing agents.

**Trace elements content in road dust**

Table 2 shows statistics related to the contents of trace elements. A number of elements (Se, Rh, Pd, Te, Re, Ir, Pt, Au) were excluded from the calculations, since their content in more than 50% of the samples was below the detection limit. For other elements, in the event that the content was < DL, half the value of the DL was indicated.

The values of the pollution index \( Cf \) are maximal for Ni, Sb, Cr, Zn, and Co (Table 2). The concentrations of Mo, As, Sn, and Bi are close to the average content in the Earth’s crust; the rest of the elements are in deficit. According to the classification of Hakanson (1980), in terms of \( Cf \), the content of Co, Cu, Zn, As, Mo, Ag, Cd, Sn, W, Pb, and Bi corresponds to the level of “moderate contamination” (1 \( \leq Cf < 3 \)), Cr—“considerable contamination” (3 \( \leq Cf < 6 \)), and Ni and Sb—“very high contamination” (\( Cf \geq 6 \)).
Table 2  Summary statistics of trace elements content (mg kg\(^{-1}\)) in Tyumen road dust, \(n=50\)

| Element | Detection limit | Mean | SD  | Median | Min | Max | Earth crust (Rudnick and Gao 2003) | Cf   |
|---------|-----------------|------|-----|--------|-----|-----|----------------------------------|------|
| Li      | 0.03            | 6.8  | 1.4 | 6.7    | 4.1 | 10.2| 21.0                             | 0.32 |
| Be      | 0.03            | 0.6  | 0.14| 0.6    | 0.4 | 1.0 | 2.1                              | 0.29 |
| Sc      | 0.09            | 10.1 | 1.2 | 9.9    | 5.5 | 13.3| 14.0                             | 0.72 |
| V       | 0.8             | 66.4 | 10.5| 66.5   | 27.5| 104.9| 97.0                            | 0.68 |
| Cr      | 0.7             | 508  | 113 | 495.3  | 282.6| 740.6| 92.0                           | 5.5  |
| Co      | 0.08            | 39.6 | 8.3 | 38.8   | 24.8| 59.3| 17.3                            | 2.3  |
| Ni      | 0.7             | 632  | 165 | 617.2  | 322 | 1042| 47.0                           | 13.4 |
| Cu      | 0.8             | 57.4 | 21.5| 52.2   | 18.0| 130.4| 28.0                          | 2.1  |
| Zn      | 0.5             | 161  | 45  | 157.8  | 59.6| 271 | 67.0                           | 2.4  |
| Ga      | 0.1             | 5.2  | 0.8 | 5.3    | 3.1 | 6.6 | 17.5                           | 0.29 |
| As      | 0.1             | 5.7  | 3.0 | 5.3    | 1.7 | 20.9| 4.8                            | 1.19 |
| Rb      | 0.1             | 27.1 | 6.4 | 28.0   | 15.6| 40.3| 84.0                          | 0.32 |
| Sr      | 0.07            | 147  | 29  | 145.8  | 100 | 244 | 320                           | 0.46 |
| Y       | 0.02            | 7.3  | 1.6 | 7.5    | 3.1 | 10.7| 21.0                          | 0.35 |
| Zr      | 0.04            | 60.7 | 21.2| 60.4   | 17.4| 133.5| 193.0                       | 0.31 |
| Nb      | 0.02            | 6.6  | 2.4 | 6.3    | 1.7 | 12.4| 12.0                         | 0.55 |
| Mo      | 0.04            | 1.4  | 0.7 | 1.2    | 0.53| 4.6 | 1.1                           | 1.30 |
| Cd      | 0.04            | 0.2  | 0.08| 0.15   | 0.02| 0.44| 0.09                         | 1.8  |
| Sb      | 0.06            | 3.1  | 1.9 | 2.6    | 1.1 | 13.2| 0.4                           | 7.8  |
| Cs      | 0.01            | 0.9  | 0.20| 0.84   | 0.4 | 1.4 | 4.90                          | 0.17 |
| Ba      | 0.05            | 317  | 70  | 328.4  | 177.6| 435.8| 624                        | 0.51 |
| La      | 0.009           | 8.9  | 2.7 | 8.9    | 3.7 | 15.2| 31.0                         | 0.29 |
| Ce      | 0.008           | 20.1 | 5.6 | 20.3   | 8.4 | 31.2| 63.0                         | 0.32 |
| Pr      | 0.005           | 2.0  | 0.6 | 2.1    | 0.9 | 3.3 | 7.1                         | 0.29 |
| Nd      | 0.009           | 8.7  | 2.5 | 9.0    | 4.2 | 14.8| 27.0                         | 0.32 |
| Sm      | 0.004           | 1.6  | 0.4 | 1.6    | 0.8 | 2.8 | 4.7                         | 0.35 |
| Eu      | 0.006           | 0.4  | 0.09| 0.42   | 0.22| 0.62| 1.0                         | 0.43 |
| Gd      | 0.007           | 1.4  | 0.34| 1.5    | 0.63| 2.2 | 4.0                        | 0.36 |
| Tb      | 0.004           | 0.2  | 0.05| 0.22   | 0.10| 0.33| 0.7                        | 0.31 |
| Dy      | 0.007           | 1.3  | 0.30| 1.32   | 0.55| 2.0 | 3.9                        | 0.34 |
| Ho      | 0.005           | 0.3  | 0.06| 0.27   | 0.11| 0.41| 0.8                       | 0.33 |
| Er      | 0.003           | 0.8  | 0.17| 0.82   | 0.36| 1.19| 2.3                   | 0.35 |
| Tm      | 0.004           | 0.1  | 0.03| 0.12   | 0.04| 0.17| 0.3                   | 0.39 |
| Yb      | 0.003           | 0.8  | 0.2 | 0.8    | 0.29| 1.3 | 2.0                     | 0.41 |
| Lu      | 0.005           | 0.1  | 0.03| 0.1    | 0.04| 0.20| 0.3                     | 0.40 |
| Hf      | 0.02            | 1.9  | 0.7 | 1.8    | 0.5 | 4.8 | 5.3                     | 0.35 |
| Ta      | 0.01            | 0.5  | 0.24| 0.5    | 0.15| 1.8 | 0.9                     | 0.61 |
| Hg      | 0.01            | 0.024| 0.021| 0.019 | 0.005| 0.146| 0.1                 | 0.48 |
| Tl      | 0.005           | 0.143| 0.026| 0.146 | 0.1 | 0.2 | 0.9                   | 0.16 |
| Pb      | 0.06            | 33.9 | 20.7| 28.7   | 8.5 | 120.2| 17.0                     | 2.0  |
| Bi      | 0.01            | 0.17 | 0.28| 0.12   | 0.03| 2.08| 0.2                    | 1.07 |
| Th      | 0.01            | 1.9  | 0.6 | 1.9    | 0.7 | 3.5 | 10.5                    | 0.18 |
| U       | 0.01            | 1.1  | 0.5 | 1.0    | 0.50| 4.4 | 2.7                    | 0.41 |

Cf, contamination factor

Element concentrations were above their detection limits in all samples, except for the Hg concentration that was below DL in 6% of the analyzed samples.
Konstantinova et al. (2020) previously noted the pollution of RD in Tyumen with chromium and nickel and revealed that the concentration of these elements is four and 7 times higher, respectively, compared to urban soils. An increased content of Cr, Ni, Pb, and V was also noted in the snow cover (Guseinov et al. 1997), which confirms the atmospheric input of these metals. The concentrations of As (1.7–20.9 mg kg⁻¹), Cu (18–130.4 mg kg⁻¹), Ni (322.4–1042 mg kg⁻¹), Mo (0.53–4.6 mg kg⁻¹), Hg (0.01–0.15 mg kg⁻¹), Sb (1.1–13.2 mg kg⁻¹), Pb (8.5–120.2 mg kg⁻¹), Bi (0.03–2.08 mg kg⁻¹), and Cd (0.02–0.44 mg kg⁻¹) in street dust of Tyumen varied greatly. This indirectly indicates the influence of pollution sources that cause an increase in the TMMs content in RD. Elements dominated by natural source are expected to have relatively lower variation, while those affected by anthropogenic sources should display higher variation (Yuan et al. 2014; Cao et al. 2018). Significant variations in TMMs concentrations indicate a significant contribution from anthropogenic sources and a spatial heterogeneity of anthropogenic impacts on the roads (Vlasov et al. 2021) and reflect differences in the rates of pollution depending on road traffic, industrial emissions as well as street cleaning. It has been noted that Tyumen’s road dust is a dynamic medium in the urban environment and reflects pollution related to current activities (Konstantinova et al. 2020).

**Geoaccumulation index and enrichment factor**

The calculated results of Igeo of TMMs in RD from Tyumen are presented in Fig. 4. In terms of Igeo values, the elements form the following row: Ni 2.2, Sb 1.5, Cr 1.3, Zn 0.4, Co 0.4, Cu 0.2, Cd 0.1, Pb 0.1, W 0.04 (the index denotes the average of the Igeo). For the rest of the elements, Igeo < 0. Thus, according to the classification (Müller 1969), Ni belongs to the category “moderately to heavily contaminated,” Sb and Cr—“moderately contaminated,” and Zn, Co, Cu, Cd, and Pb—“slightly contaminated.” As Cd, Mo, Hg, Sb, and Pb are characterized by a wide variation in Igeo values (Fig. 4), depending on local sources of pollution. For example, for Pb, the values of Igeo > 1, corresponding to the “moderately contaminated” level, were noted near the car battery production plant. Earlier it was revealed that the concentration of Pb in the soils on the territory of the battery plant is extremely high (> 1000 mg kg⁻¹) (Skipin and Berseneva 2014).

High values of the Igeo index of such elements as Ni, Sb, and Cr distinguish Tyumen from other cities in the world. Usually maximum Igeo values in RD are observed in chalcophile elements (Cu, Pb, Cd, Zn), but Ni and Cr are classified as “slightly contaminated” or “not contaminated.” For example, based on Igeo values, RD in Chelyabinsk (Russia) were unpolluted or slightly polluted by Co, Cr, Mn, Ni, As, Cd, Pb, Sb, and Sr; moderately polluted by Cu; and extremely polluted by Zn (Krupnova et al. 2020). In Thessaloniki, Greece, the mean values of Igeo decreased in the order of Cu > Cd > Pb > Zn > Ni > Cr > Mn (Bourliva et al. 2017). In RD of Baogi (China), the Igeo of Ni is low and the assessment results indicate an absence of distinct Ni pollution (Lu et al. 2009). All Igeo values of Ni and Cr in Zhengzhou City (China) were at zero, which indicates that nickel and chromium pollution were not present in the road sediment (Wang et al. 2020). The RD from Alexandria (Egypt) was not contaminated by Co, Cr, Mn, and Ni (Igeo class < 0); moderately contaminated by Pb (Igeo class = 1–2); and slightly by Zn (Igeo class = 0–1) (Jadoon et al. 2021).

EF calculations showed that Tyumen’s RD is very high enriched in Ni and significantly enriched in Cr and Sb. Seventy percent of the samples are significantly enriched in Zn, 62% in Co, 42% in Cu, 34% in Pb, and 26% in Cd. Moderate enrichment was noted for Mo, As, W, Sn, Bi, and W. The remaining 30 elements are classified as “deficiency to minimal enrichment” (EF < 2). The value of EF values on roads with different traffic intensities is given in Table 3 (only metals with EF values > 1.5 are presented). On low-traffic roads, the EF value of Ni, Co, Cr, and Sb is lower than on roads with high and medium traffic volumes. Verification using the Mann–Whitney test showed that small roads significantly differ from medium and large ones in the enrichment of RD with chromium, nickel, antimony, mercury, and...
Identification of sources of pollution

Our results indicate that Ni, Sb, Cr, Zn, and Co are the main road dust pollutants in Tyumen. The content of these elements is increased throughout the city. Ni, Cr, and Co belong to the geochemical group of siderophilic elements (Kabata-Pendias 2011), i.e., elements related to iron. The main source of nickel and chromium pollution is metallurgical plants (Saet al. 1990). Elements related to ironworking activities are Fe, Co, Cr, Mn, and Ni (Žibret and Rokavec 2010). In Tyumen, the few and low-power metallurgical and metal-working enterprises (Tyumen electrometallurgical plant, JSC Sibneftemash, Zavod Tyumenremdormash CJSC) do not cause road dust pollution throughout the city, since no increase in Ni and Cr was found in their locations. Only the influence of the Tyumen battery plant, in the area of which a high lead content was found, has been reliably confirmed (Konstantinova et al. 2020; Moskovchenko et al. 2021).

Soils are a natural source of Ni input. In the soils of Tyumen, the Ni content is increased; its average concentration in urban areas with low traffic is 1.6 mg kg\(^{-1}\) (Konstantinova et al. 2019) to 95 mg kg\(^{-1}\) (Moskovchenko 1998).

Table 3 EF values on roads with different traffic volumes (mean ± SD)

| Elements | Traffic intensity |
|----------|-------------------|
|          | Low (n = 7)        | Moderate (n = 19) | High (n = 24) |
| Ni       | 23.7 ± 4.1        | 33.6 ± 7.4        | 33.7 ± 8.7    |
| Sb       | 16.7 ± 6.4        | 21.9 ± 16.5       | 19.8 ± 6.0    |
| Cr       | 10.3 ± 1.5        | 13.9 ± 2.6        | 13.6 ± 3.1    |
| Pb       | 5.6 ± 2.6         | 5.6 ± 4.0         | 3.9 ± 1.6     |
| Cd       | 5.5 ± 2.8         | 5.0 ± 2.4         | 3.6 ± 1.4     |
| Zn       | 4.9 ± 0.7         | 6.1 ± 1.6         | 5.7 ± 1.7     |
| Cu       | 4.7 ± 1.3         | 5.2 ± 1.6         | 4.7 ± 2.1     |
| Co       | 4.4 ± 0.6         | 5.7 ± 1.0         | 5.7 ± 1.2     |
| Mo       | 3.3 ± 2.1         | 3.3 ± 1.8         | 2.9 ± 1.0     |
| As       | 3.1 ± 0.8         | 2.8 ± 1.3         | 2.9 ± 1.8     |
| Bi       | 1.6 ± 0.4         | 2.2 ± 1.1         | 3.2 ± 6.2     |
| Hg       | 1.9 ± 2.2         | 1.2 ± 0.6         | 1.0 ± 0.57    |
| Sc       | 1.69 ± 0.1        | 1.75 ± 0.2        | 1.73 ± 0.25   |
| V        | 1.74 ± 0.1        | 1.66 ± 0.3        | 1.60 ± 0.3    |

n, number of samples used to calculate the EF

bismuth (ρ = 0.01). Differences between the EF of cadmium for small and large roads are also significant. Differences in the content of other elements are statistically insignificant. Thus, the EF calculations confirm the effect of transport on the release of Ni, Cr, and Sb into the environment. An assessment of the ratio between natural and anthropogenic sources affecting the composition of dust, carried out in accordance with Eqs. 4–6, showed that the elements form the following series (the index means the share of anthropogenic input (%)): Ni \(_{97}\), Sb \(_{95}\), Cr \(_{93}\), Zn \(_{85}\), Co \(_{84}\), Cu \(_{82}\), Pb \(_{79}\), Cd \(_{76}\), Mo \(_{71}\), Sc \(_{53}\), Bi \(_{52}\), V \(_{50}\). The rest of the elements come primarily from natural sources.

According to the obtained EF values, on low-traffic roads the dust is enriched with some chalcophile elements (As, Mo, Pb, Cd). This is probably due to the influence of burning coal for heating private residential buildings, which prevail in urban areas with low traffic. Combustion of hard coal is the major source of airborne Mo and a very significant source for As, Cr, Mn, and Sb (Nriagu and Pacyna 1988).

To assess the features of pollution in Tyumen, we compared the calculated EF values with the EF values in other cities (Table 4). In Tyumen, the composition of elements enriched in road dust differs sharply from other cities. As a rule, in most cities on Earth, the maximum degree of enrichment is characteristic of chalcophile elements, which are highly mobile. In Changsha City, the mean EFs revealed the following order: Cd > Zn > Pb > Cu > Cr (Li et al. 2016). Similarly, in Kabul (Afghanistan), the EF values decrease in the sequence Cd > Pb > Zn > Cu > Ni > Cr (Jadoon et al. 2018). In Beijing, bulk atmospheric deposition Cd is the most anthropogenic enrichment metal with an EF of 32.4 proceeding As (11.5), Zn (9.3), Pb (7.7), and Cu (5.4) (Guo et al. 2017). In Tyumen, a different distribution of EF values is observed, which decrease in the sequence Ni > Cr > Zn > Co > Pb > Cd. To understand the reasons for the identified differences, it is necessary to determine the sources of the main road dust pollutants in Tyumen.

Table 4 The average EFs values of heavy metals in road dust collected in different areas

| City, country         | Cr    | Co    | Ni    | Cu    | Zn    | As    | Cd    | Pb    | Mn    | Reference                  |
|-----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----------------------------|
| Tyumen, this study    | 13.3  | 5.5   | 32.3  | 4.9   | 5.8   | 2.9   | 4.4   | 4.8   | 2.8   | This study                  |
| Kabul, Afghanistan    | 1.10  | 0.82  | 1.76  | 2.46  | 3.92  | –     | 8.75  | 5.97  | 0.88  | Jadoon et al. (2018)        |
| Changsha City, China  | 1.71  | –     | –     | 2.6   | 4.0   | –     | 128.0 | 3.41  | –     | Li et al. (2016)            |
| Tongchin, China       | 1.74  | 3.32  | 0.88  | 1.55  | 2.04  | 0.61  | –     | 3.58  | 0.67  | Zhang et al. (2015)         |
| Delhi, India          | 3.5–16.1 | –     | 2–3   | 3.3–22.4 | 3.3–7.3 | –     | –     | 5.1–21.9 | – | Rajaram et al. (2014) |

EF ≤ 2 means a deficit to a minimum enrichment; 2 < EF ≤ 5 means moderate enrichment; 5 < EF ≤ 20 means significant enrichment; 20 < EF ≤ 40 - very high enrichment; 40 ≥ EF - extremely high enrichment
which is significantly higher than the average world content in the surface horizon of background chernozem soils constituting, according to Kabata-Pendias (2011) 25 mg kg\(^{-1}\). However, the Ni content in road dust is one mathematical order of magnitude higher than in soil (on average 632 mg kg\(^{-1}\), see Table 2). Similarly, the average Cr content in the soils of Tyumen is estimated from 107 mg kg\(^{-1}\) (Konstantinova et al. 2019) to 176 mg kg\(^{-1}\) (Moskovchenko 1998), with an average world value for chernozems of 77 mg kg\(^{-1}\) (Kabata-Pendias 2011). But in Tyumen road dust, the concentration of Cr exceeds 500 mg kg\(^{-1}\). Co content in soils is 16–20.9 mg kg\(^{-1}\) (Moskovchenko 1998; Konstantinova et al. 2019) and in road dust 39.6 mg kg\(^{-1}\). A significant excess of the content of Ni, Cr, and Co in road dust compared to soils, as well as an increased content in snow of Tyumen (Guseinov et al. 1997), gives grounds for the conclusion that there are anthropogenic sources of these elements.

According to Yang et al. (2010), Ni, Fe, and Cr enter city dust mainly from transport. At the same time, the sources of Ni input are diverse. The most important source of Ni is the combustion of petroleum and petroleum products (Nriagu and Pacyna 1988). Global emission of Ni from oil products combustion is estimated to range from 10 to > 40 kt year\(^{-1}\) (Kabata-Pendias 2011). Diesel engines use fuels with Ni additives (Al-Khashman 2007). Nickel in road dust is also found in asphalt bitumen and gabbro rock material (Lindgren 1996). Crushed stone used in road construction in Tyumen consists of rocks, including diorite and gabbro. Corrosion of metal parts of motor vehicles is a significant source of Ni (Ferguson and Kim 1991; Akhter and Al-Jowder 1997; Atiemo et al. 2011). Cr, Co, and W also come with metal abrasive dusts, including as a result of abrasion of metal parts of vehicles (Saet et al 1990).

In addition road dust pollutants in Tyumen are Sb, Zn, Cu, Cd, Pb, and W. Antimony is used in the manufacture of car batteries. Abrasion of tires, metal parts of cars, and road markings is also a source of Sb (Vlasov et al. 2015; Ozaki et al. 2021). As noted by Hjortenkrans et al. (2006) on motorway sections where traffic is braked (traffic lights, intersections, etc.), the Sb concentration was more than 8 times the background level. Similarly, Amato et al. (2009), studying the variability of the chemical composition of road dust in Spain, found that Sb, Zn, and Mo are concentrated in the areas of vehicle braking, showing a strong relationship with brake pad and tire wear. It was also noted that Sb, As, and Sn are supplied by burning coal for heating residential buildings (Landing et al. 2010).

Zinc and copper are also classified as elements which largely come to the environment from transport. Zn may have its origin from automotive sources, such as wear and tear of vulcanized rubber tires, lubricating oils, and corrosion of galvanized vehicular parts (Banerjee 2003; Ellis and Revitt 1982). Zn is added to tire tread as zinc oxide and organozinc compounds to facilitate the vulcanization process (Dall’Osto et al. 2014). The concentration of Zn in car tires is about 1% (Adachi and Tainosho 2004). Principal source of Cu in the atmosphere is mainly fossil fuel burning, traffic emissions, fuel combustion, and industrial combustion (Nriagu 1996).

To clarify the sources of pollution, a PCA analysis of the obtained dataset was carried out, including the content of macro- and microelements, physical and chemical properties, and particle size distribution. PCA with varimax normalized rotation was applied to assist in the identification of sources of pollutants. The essence of PCA analysis is to “fold” a multicomponent dataset to a limited, user-selected number of factors that determine the sample variance. The results obtained made it possible to identify 3 main components (PC), which determine the regularities of the formation of the chemical composition of road dust (Table 5).

| Variables | PC1 | PC2 | PC3 |
|-----------|-----|-----|-----|
| V         | −0.04 | 0.13 | 0.69 |
| Cr        | 0.92 | 0.11 | −0.21 |
| Co        | 0.93 | 0.16 | −0.16 |
| Ni        | 0.92 | 0.10 | −0.26 |
| Cu        | −0.14 | 0.26 | 0.61 |
| Zn        | 0.15 | 0.77 | 0.08 |
| As        | 0.32 | 0.41 | −0.15 |
| Ag        | −0.25 | 0.32 | 0.03 |
| Cd        | 0.04 | 0.69 | 0.13 |
| Sb        | −0.04 | 0.54 | 0.14 |
| Hg        | −0.35 | 0.24 | −0.03 |
| Pb        | −0.24 | 0.51 | 0.10 |
| Bi        | 0.17 | 0.32 | −0.18 |
| MgO       | 0.88 | 0.21 | −0.37 |
| Al2O3     | −0.65 | 0.24 | 0.58 |
| P2O5      | −0.01 | 0.65 | −0.13 |
| S         | 0.42 | 0.54 | 0.02 |
| K2O       | −0.80 | −0.07 | 0.45 |
| CaO       | 0.34 | 0.41 | 0.02 |
| TiO2      | −0.48 | −0.09 | 0.68 |
| MnO       | 0.05 | 0.33 | 0.83 |
| Fe2O3     | 0.75 | 0.17 | 0.51 |
| Ctotal    | 0.12 | 0.53 | −0.70 |
| Clay      | 0.12 | 0.53 | −0.70 |
| pH        | −0.17 | 0.03 | 0.49 |
| Expl.Var  | 6.25 | 4.90 | 4.50 |
| Variance, % | 22 | 17 | 16 |

Bold entries in the table indicate the high contribution of the element to that component.
Factor loads are classified as “strong,” “medium,” and “weak” with values $>0.75$, $0.75–0.50$, and $0.5–0.3$, respectively (Liu et al. 2003). Heavy loads are shown in bold in Table 5. The three PCs together account for 55% of the variance. The first component explains 22% of the total variance and has strong loading of Cr, Co, Ni, MgO, and Fe$_2$O$_3$. This PC is to be associated with the traffic sources. The second factor has strong loading of Zn and moderate loading of Cd, Sb, Pb, P$_2$O$_5$, $C_{\text{total}}$, and clay content. The most important source of Cd and Zn is the combustion of solid fuels and household waste (Saet et al 1990; Nriagu and Pacyna 1988), which gives grounds to associate this PC with the influence of household activities of the population. The third factor account for 16% of the total variance. It is composed of MnO (strong correlated), V, TiO$_2$, Cu, Al$_2$O$_3$, $C_{\text{total}}$, and clay content (moderate correlated). This factor can be interpreted as a natural factor of soil erosion. A similar distribution of factor loads was established in the soils of Tyumen. According to Konstantinova et al. (2020), V–Cr–Co–Ni–Cu association had the most significant strong positive value (47.5% of total variance).

Environmental assessment

Calculations of the total enrichment index $Ze$ showed that in 82% of cases the pollution level was hazardous ($Ze=64–128$). $Ze$ values vary within 46–174, mean value of $Ze=98$. The level of road dust pollution in Tyumen is higher than in Moscow, where the mean value of $Ze=54$ (Vlasov et al. 2021).

The average $Ze$ values on the roads with different traffic intensities increased in the following order: low (82) $<$ moderate (106) $<$ high (107). The prevalence of the most polluted samples on the roads with a high traffic intensity confirmed that motorized vehicles represent the main source of the road dust contamination. The maximum level of enrichment ($Ze=174$) was detected at the sampling points located within the industrial zone of the city, near the thermal power plant. At this observation point, abnormal concentrations of antimony (13.2 mg kg$^{-1}$) and zinc (258 mg kg$^{-1}$) were detected. Hazardous level of enrichment ($Ze>128$) was also observed in the samples taken in the city center on streets with heavy traffic and near the Tyumen storage battery plant, where batteries for cars and machinery as well as electrolytes are produced. Therefore, in addition to motorized vehicles, industrial sources also contributed to the contamination of road dust.

To assess the ecological situation, we made a comparison with the data obtained in various cities of the Earth where the population size is comparable to Tyumen (Table 6). Our selection of cities for such a comparison was based also on the presence of comparable assemblages of analyzed elements.

The concentration of trace elements in the road dust of different cities is very different, which is caused by differences in the intensity of the traffic load, the use of fuel of different composition, the characteristics of the road surface, the soils prevailing in the city, etc. The comparison shows that Tyumen has significant pollution with nickel, cobalt, and chromium. The average concentration of Ni and Cr in the road dust of Tyumen is one order of magnitude higher than in other cities. Both our data and the data obtained earlier by Konstantinova et al. (2020) indicate that Tyumen is far superior to other cities in the concentration of these elements. In addition to the papers presented in Table 6, we analyzed several other studies (Stone and Marsalek 1996; Amato et al. 2011; Han et al. 2014; Li et al. 2014; Mirzaei Aminiyan et al. 2018; Najmeddin et al. 2018; Praveena 2018; Chenery et al. 2020; Wang et al. 2020; Jadoon et al. 2021). Only in Zurich, a higher concentration (about 504 mg kg$^{-1}$) of Ni has been found in the PM $<10$ µm fraction of road dust (Amato et al. 2011). It is known that the TMMs concentrations in RD increase with decreasing sizes of analyzed fractions (Vlasov et al. 2015). Therefore, the extremely high concentration of Ni in Zurich can partly be explained by the small size of the analyzed fraction. Pollution by other elements was notably less significant in Tyumen. As compared to other cities, Tyumen’s RD had moderate concentrations of Cu, Zn, As, and Sb and low concentrations of Pb and Cd.

The high level of Ni, Cr, and Co content in the Tyumen road dust is caused, in our opinion, by several reasons. Firstly, the increased content of these elements in soils, caused by natural lithological features, affects. The enrichment of soils and parent rocks of Cr and Ni in the vicinity of Tyumen was noted by Konstantinova et al. (2019). High contents of those elements in soils are associated with the composition of bedrocks, which are represented by diorites and gabbros of the Pre-Jurassic formations (Seleznev et al. 2021). Gravel of these rocks is used in road construction and, therefore, the road wear results in the formation of dust enriched in Cr and Ni. High concentrations of both elements are often mentioned in descriptions of Uralian ultramafic rocks such as gabbro (Lesovaya et al. 2012; Alexeeva-Popova and Drozdova 2013). High Ni contents have also been noted in clastic rocks of the Central Urals, i.e., the part of the Ural Mountains that is closest to Tyumen (Mizens 2009).

Secondly, there are a large number of cars in the city and a high traffic load, which leads to a significant intake of these microelements due to corrosion and abrasion of metal parts.

Conclusion

In the presented work, the composition of RD in Tyumen, an intensively developing industrial city in Siberia, has been studied. The physicochemical parameters, particle size
distribution, the content of heavy metals, and metalloids on roads with different traffic intensities have been determined. RD in Tyumen, like in most other cities on Earth, has an alkaline reaction, which is caused by the entry of carbonate microparticles. The total content of organic matter varies from 0.07 to 2.9%; the largest amount of organic matter is noted on roads with low traffic intensity, which indicates the influence of soils. The particle size distribution is dominated by the PM fraction of 100–250 μm. The content of finer particles (PM<50 μm), which largely come from industrial plants, is low. Thus, the composition of road dust is formed mainly under the influence of traffic-related and soil erosion sources. The largest number of small particles (PM2 and PM10) was observed on roads with medium traffic intensity. On roads with the most intensive traffic, blowing out small particles leads to a decrease in their proportion in the particle size distribution. The increased content of small particles on roads with medium traffic volumes leads to the fact that there is the highest concentration of pollutants.

Compared with the average content in the Earth’s crust, Tyumen’s RD is enriched in Ni, Sb, Cr, Zn, Co, Cu, Pb, Cd, and W. More than 90% of Ni, Sb, and Cr comes from anthropogenic sources. Dust collected on low-traffic roads contains less Cr, Ni, Sb, Bi, and Hg than on medium-to-high-traffic roads. The Mann–Whitney test showed a high degree of significance of differences (p = 0.01), which indicates a transport source of these elements. So more attention should be devoted to the pollution caused by traffic. Further in-depth assessment of pavement materials as sources of heavy metals is needed. The results obtained in this study can be used to develop an appropriate management strategy to minimize the contamination in Tyumen.

Comparison of the obtained results with the data on the trace elements content in the road dust of other cities of the Earth showed that in Tyumen the road dust contains a lot of Ni, Cr, and Co. The average concentration of Ni and Cr in the road dust of Tyumen is one order of magnitude higher than in other cities of the Earth. The high content of these metals is associated with the composition of local soils and roadways and abrasion of metal parts of machines. However, other trace elements that are considered indicators of anthropogenic impact (Cu, Cd, Pb) are contained in Tyumen’s RD in moderate amounts. The values of the total enrichment index (Ze) at most observation points (82%) correspond to the hazardous level of pollution.

Table 6 Literature data on published metal median concentrations (mg kg−1) in street dust from cities around the world

| City, country | Cr  | Co  | Ni  | Cu  | Zn  | As  | Cd  | Pb  | Sb  | Reference                   |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|----------------------------|
| Tyumen, this study | 508 | 39.6 | 632 | 57.4 | 161 | 5.7 | 0.2 | 33.9 | 3.1 | This study                  |
| Tyumen, Russia | 415 | 25.6 | 324 | 51.3 | 105 | 8.8 | 0.19 | 20.1 | 1.83 | Konstantinova et al. (2020) |
| Moscow, Russia | 50  | 8.0  | 26  | 93  | 252 | 2.8 | 0.61 | 53   | 4.6 | Vlasov et al. (2015)        |
| Chelyabinsk, Russia | 48.5 | 6.3  | 21.9| 55.9| 154 | 3.8 | 0.4  | 14.4 | 1.3 | Krupnova et al. (2020)      |
| Alushta, Crimea | 31  | 7.4  | 33  | 44  | 127 | 8.0 | 0.3  | 37   | 1.5 | Kasimov et al. (2019a)      |
| Kabul, Afghanistan | 38.4 | 8.52 | 66.4| 43.6| 122.5 | –  | 1.16 | 28.7 | –   | Jadoon et al. (2018)        |
| Hangzhou, China  | 51  | 20   | 26  | 116 | 321 | –   | 1.59 | 202  | –   | Zhang and Wang (2009)       |
| Urumqi, China    | 54.3| 10.9 | 43.3| 94.5| 294 | –   | 1.17 | 53.5 | –   | Wei et al. (2010)           |
| Tongchuan, China | 106.5| 31.7 | 25.3| 32.4| 142 | 6.7 | –   | 75.2 | –   | Zhang et al. (2015)         |
| Xi’an, China     | 145 | 30.9 | 30.8| 54.7| 268.6| –  | –   | 125  | –   | Pan et al. (2017)           |
| Shanghai, China  | 159 | –   | 84  | 197 | 734 | –   | 1.23 | 295  | –   | Shi et al. (2008)           |
| Seoul, Korea     | 151 | –   | –   | 396 | 795 | –   | –   | 144  | –   | Kim et al. (2007)           |
| Dhanbad and Bokaro region, India | 57  | 10  | 24  | 26  | 78  | –   | –   | 48   | –   | Singh (2011)                |
| Luanda, Angola   | 26  | 2.9  | 10  | 42  | 317 | 5.0 | 1.1  | 351  | 3.4 | Ferreira-Baptista and De Miguel (2005) |
| Kuala Lumpur, Malaysia | 74.1 | 3.36 | 11.3| 87.0| 314 | 68.8| 0.71 | 98.8 | –   | Othman and Latif (2020)     |
| Ahvaz, Iran      | 51.5| 9.2  | 59.7| 74.4| 309 | –   | 0.5  | 85.4 | 2.1 | Najmeddin et al. (2018)     |
| Katowice, Poland | 211 | –   | 43.7| 239 | 2030| –   | 0.35 | 430  | –   | Adamiiec et al. (2016)      |
| Oslo, Norway     | –   | 19   | 41  | 123 | 412 | –   | 1.4  | 180  | 6.0 | de Miguel et al. (1997)     |
| Thessaloniki, Greece | 105 | –   | 89  | 662 | 452 | –   | 1.76 | 209  | –   | Bourliva et al. (2017)      |
| Nicosia, North Cyprus | 321 | –   | 65  | 52  | 136 | 17.5| –   | 35.6 | –   | Musa et al. (2019)          |
| Ottawa, Canada   | 43.3| 8.3  | 15.2| 65.8| 112 | 1.3 | 0.6  | 39   | 0.89| Rasmussen et al. (2001)     |
| Toronto, Canada  | 198 | –   | 58.8| 162 | 233 | –   | 0.51 | 183  | –   | Nazzal et al. (2013)        |
| Houston, TX, USA | 67  | 4.8  | 119 | 183 | 557 | –   | –   | 40   | –   | Fiala and Hwang (2021)      |

The bold italic font indicates the highest concentration in the areas compared.
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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable (this paper does not contain studies involving human participants, human data, or human tissue).

Consent for publication Not applicable (this paper does not contain any individual person’s data in any form).

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