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Assessment of differences in elemental concentrations in particulate matter from road surfaces near and outside noise barriers in Poland

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Abstract: Road infrastructure has negative environmental effects, such as noise, vibration, disruption of ecosystem services, and pollution. Noise barriers are used to reduce air pollution and absorb sound waves, but studies have shown that they can impact pollutant concentrations. A study conducted in Poland analyzed the composition of dust collected from roads with and without noise barriers and road exits. The dust was tested using an energy-dispersive X-ray fluorescence spectrometer, and the results were analyzed statistically. The study found that road dust collected in areas without barriers had significantly higher levels of certain elements, such as calcium, chromium, copper, nickel, lead, sulfur, and zirconium. In contrast, dust collected from areas with noise barriers had lower pollutant levels. These findings highlight the effectiveness of noise barriers in reducing pollution levels in areas adjacent to roads.

Introduction

The growth of road transport is a global environmental problem. Fast and safe automobile travel, especially on highways, results in increased noise emissions (Can and Aumond 2018, Freitas et al. 2012, Li et al. 2016) along with air and roadside soil pollution (Bernardino et al. 2019, De Silva et al. 2021, 2016, Hołtra and Zamorska-Wojdyła 2022, Wang and Zhang 2018, Werkenthin et al. 2014, Yan et al. 2013) To mitigate noise nuisance, noise barriers are installed near roads to reduce sound intensity to legal limits (Vanhooreweder et al. 2017). Noise barriers can also affect the emissions of particulate pollutants from vehicles into the atmosphere (Amini et al. 2016, Baldauf et al. 2008, Ghasemian et al. 2017, Hagler et al. 2012, 2011, Jeong, 2015, Venkatram et al. 2016).

Air pollution levels along roads depend on traffic volume, flow, and the proportion of heavy vehicles. For example, above-average air pollution from vehicle exhaust is most common in large urban areas, where traffic volumes and congestion are highest. When roads pass through environmentally sensitive areas, safeguards are implemented to minimize the impact of exhaust emissions (Bęben 2011). However, these barriers also affect air pollutant dispersion, leading to increased vertical mixing as a result of the upward airflow deflection caused by the structure. Research suggests that this airflow deflection creates a recirculation cavity behind the barrier, where pollutants mix and concentrations may be lower. Noise barriers near carriageway can also restrict airflow, leading to higher pollutant concentrations on roads (Baldauf et al. 2008, Baldauf et al. 20089 Bowker et al. 2007).

Aluminum cassette screens are a popular solution in Poland. However, this type of acoustic barrier can cause permanent and irreversible changes in soil quality due to pollutants being washed off the screen's surface, particularly during rainfall (Karbowska et al. 2017, Różański et al. 2017, Świetlik et al. 2013). These dust particles, which contain trace elements, become airborne at low altitudes, affecting humans, animals, and plants. Unlike particulate matter (PM), road dust (RD) settles directly on roads and adjacent ground. Studies show that road dust and PM10 (particles with a diameter of less than 10 µm) are correlated and interdependent (Hołtra and Zamorska-Wojdyła 2022, Walczak 2010).

Particulate pollutants, due to their small size, can remain in the atmosphere for a very long time and spread over considerable distances. Their dispersion depends on the speed and direction of airflow (Charlesworth et al. 2011, Hołtra and Zamorska-Wojdyła 2022). For example, Hajok et al. (2017) demonstrated that heavy metal concentrations in soil samples varied depending on the presence of a noise barrier. On the side of the expressway without a noise barrier, the highest concentrations were found at a distance of 8 m from the traffic route. In contrast, on the side of the road with a noise barrier, peak concentrations were observed just 1 m from the noise barrier. In both cases, the distance from the motorway had a statistically significant effect on lead and zinc concentrations. On roads without noise barriers, the mean lead concentration in soil varied significantly between 8 and 30 m distance, while on roads with noise barrier, significant differences were observed at 1 and 10 m distance, as well as at 1 and 30 m distance. In general, heavy metal concentrations were significantly higher in soil samples collected near noise barriers than those from the opposite side of the road without barriers. This raises concerns about the effectiveness of noise barriers in reducing linear emissions (Hagler et al. 2012).

In addition, steel or galvanized noise barriers pose an environmental risk, particularly when exposed to winter road maintenance agents like NaCl, which accelerate corrosion. Contamination levels depend on the corrosion rate, estimated at 28-50 g/m2 per year. This results in Zn emission of 63-82 kg per kilometer of motorway annually (Van Bohemen and Janssen Van De Laak 2003). Damaged barrier fragments are deposited in the soil, increasing Zn concentration. This is particularly concerning due to Zn high mobility (Wawer et al. 2017). Additionally, Zn from tire tread abrasion and galvanized vehicle parts contributes significantly to roadside contamination (De Silva et al. 2016, Hołtra and Zamorska-Wojdyła 2022).

Trace elements identified in road dust, such as Mn, Cd, Cr, Cu, and Ni, pose significant environmental and health risks. Mn originates from worn car tires, while Cu, Cd, Cr, Fe, Ni, Pb, and Zn come from brake and clutch friction, radiator and chassis corrosion, and engine and exhaust system emissions, leading to increased concentrations in roadside soils. Chrome car parts contribute to Cr in road dust. Additionally, Ni, Cu, and Cd may come from fuel and lubricant spills, while road surface abrasion releases Cr and Ni (Hołtra and Zamorska-Wojdyła 2022, Penkała et al. 2018). Vehicle traffic wears down up to 0.04 mm of asphalt annually. Furthermore, leaching of road materials may occur, especially when recycled materials are used in construction (Van Bohemen and Janssen Van De Laak 2003).

Metals used in automotive technology, including antimony (brake pads), manganese (fuel), and platinum, palladium, and rhodium (catalyst layers), have been detected in roadside dust and soils near new roads (De Silva et al. 2016). Soil contamination near traffic can also occur due to transporting inadequately protected bulk materials and using sand mixed with road salt for winter de-icing (Aljazzar and Kocher 2016, Werkenthin et al. 2014). Industrial emissions and low emissions of solid fuel combustion products from individual sources can also contribute to soil contamination (Amato et al. 2011, Duong and Lee 2011, Hołtra and Zamorska-Wojdyła 2022, Wei and Yang 2010, Zechmeister et al. 2005).

Heavy metals persist in the environment for long periods, and their removal from soil is challenging. Soil acidification, caused by natural and human factors, facilitates the migration of metals from the soil to groundwater and plants. Fuel combustion is considered a major source of heavy metal contamination in soil. Unlike many pollutants, heavy metals are non-biodegradable. Instead, they undergo biotransformation through complex physico-chemical and biological soil processes. These processes determine their mobility, bioavailability, and uptake by crops, increasing environmental exposure to these xenobiotics. Factors such as pH, hydroxides of iron, aluminum and manganese, organic matter, clay fraction (<0.002 mm), sorption capacity, and moisture content significantly influence metal binding processes in soil (Czech et al. 2014, Hajok et al. 2017). Unlike air and surface water, heavy metals can persist in soil for several hundred years, while they self-purify much faster (Dziubanek et al. 2012, Pachana et al. 2010).

Road dust serves as an indicator of road pollution, as it contains heavy metal particles emitted by motor transport. Analyzing road dust for elemental concentrations, particularly heavy metals, is crucial. The mobility, bioavailability, and toxicity of chemical elements depend not only on their total concentrations but also on their physical and chemical forms (Świetlik et al. 2015). Research on heavy metal contributions in road dust emitted near traffic routes, particularly those with heavy traffic, remains limited and does not fully address the issue (Kiebała et al. 2015, Penkała et al. 2019, 2018, Rogula-Kozłowska et al. 2023, Rybak et al. 2020, Thorpe and Harrison 2008, Wang et al. 2024, Starzomska and Strużewska 2024). A major challenge in distinguishing PM from combustion and non-fuel sources, as well as from other emitters, is the lack of sufficient data and rationale (Rogula-Kozłowska et al. 2015). Additionally, data on categorizing non-fuel PM emissions, such as those from tire wear, brakes, and road surfaces, remains particularly scarce (Penkała et al. 2018).

Materials and methods

To conduct road dust surveys, we selected motorways in central and southern Poland with two surface types: asphalt and concrete. Table 1 presents the list of roads, and Figure 1 shows the location of measurement points on the map, along with the name of the road, and the surface type.

The test material was collected from the road surface using a brush and a dustpan, and then transferred into a 100 ml sterile container. Each collection area was at least 2 m^2. The brush and dustpan were cleaned with isopropyl alcohol between each sample collection. Test material was collected on both sides of the specified highway/expressway sections at three control points: in the space between sound-absorbing screens (S), in areas without screens (F), and at road exits (E), resulting in 6 samples per road section.

The control points (S, F, and E) were spaced approximately 5 km apart. To ensure a representative sample unaffected by wind or vehicle traffic direction, samples were taken at a similar height on both the left and right sides of the selected road. For the space between the screens, sections were selected approximately 2 km from the screen's edge and were shielded by barriers on both sides. A total of 48 samples were collected (2 road sides 3 control points 8 road sections 48). In order to eliminate sample asymmetry, the samples were aggregated for both directions, resulting in 24 analyzed samples. The material was mainly collected during the summer months to minimize the impact of de-icing agents on road dust (Rogula-Kozłowska et al. 2023).

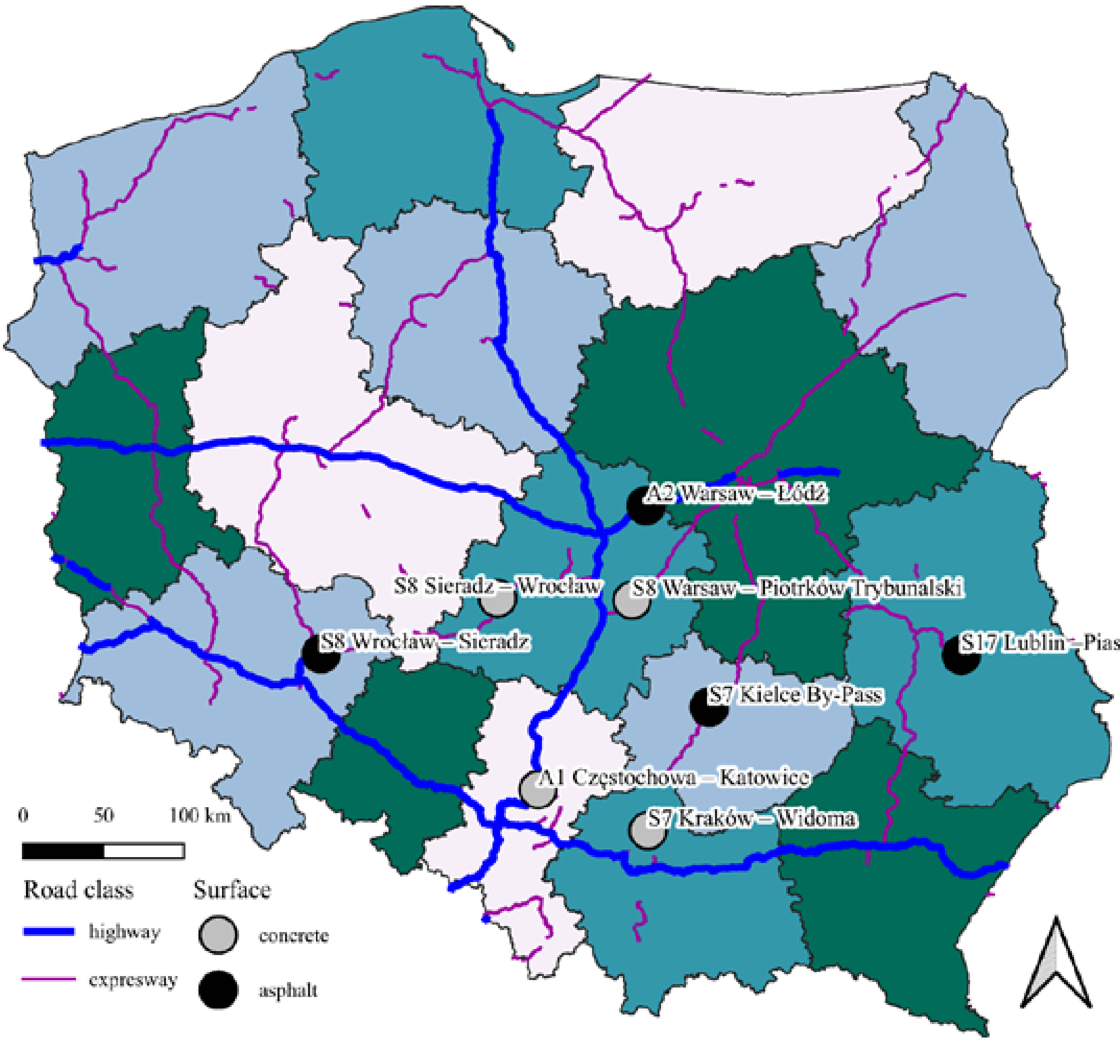

Figure 1. Map of Poland showing roads selected for the survey, road network based on (GDDKiA, 2015; OpenStreetMap Contributors, 2023; Rogula-Kozłowska et al., 2023).

Using a mechanical sieve shaker, road dust samples were subjected to granulometric analysis. Seven material fractions were obtained using a standard sieve: 10-2 mm, 2-1 mm, 1-0.5 mm, 0.5-0.25 mm, 0.25-0.1 mm, 0.1-0.063 mm and <0.063 mm. The particle fraction <0.1 mm was analyzed for elemental composition using a Shimadzu EDX 7000 energy-dispersive X-ray fluorescence spectrometer. Approximately 15g of pre-dried material was placed into the sample container. The dust material did not require grinding prior to testing. The camera was set to a 10 mm collimator, an air atmosphere, and a total radiation exposure time of 60 seconds was used for the sample. The results were normalized to 100% for qualitative analysis (Rogula-Kozłowska et al. 2023). Table 1 summarizes the data obtained from the elemental composition analysis of road dust with a fraction <0.1 mm.

To assess the statistical significance of differences in elemental concentrations found in road dust studies, a Welch's t-test was conducted. This test compares the expected values of two populations, and the t statistic was calculated using the formula below. After calculating the t-value, the Student's t-distribution with the corresponding degrees of freedom was used to determine the probability of the null hypothesis. To evaluate whether two populations have equal expected values, a two-sided confidence interval can be used. Alternatively, a one-sided interval can determine if the mean of one population is greater than or equal to the other. The appropriate confidence interval should be chosen based on the study's context and specific research question (Welch 1947):

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}. \tag{1}$$

where: $\overline{x_i}$ – average of the i-th sample, s_i^2 – variance in the -th sample, N_i – size of the *i*-th sample

Enrichment factors (EF) were calculated to investigate the impact of human activity on element concentrations (Zoller et al. 1974). EF values indicate the relative increase or decrease in element content compared to the geochemical background and reference elements, according to following equation:

$$EF = \frac{\frac{C_n}{C_{ref}}}{\frac{B_n}{B_{ref}}} \tag{2}$$

where: C_n – concentration of the tested element in the sample medium, C_{ref} – concentration of the reference element in the

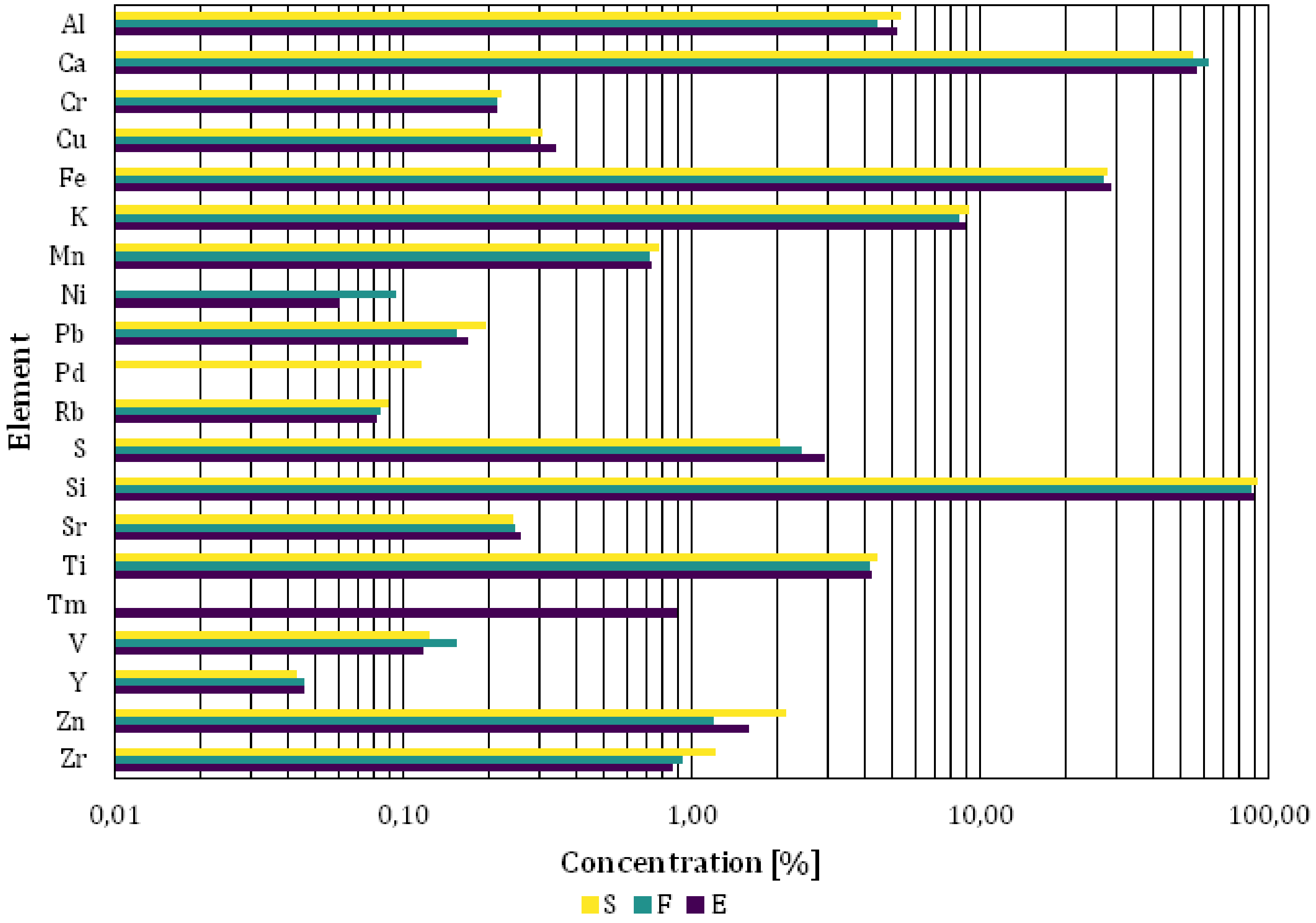

Figure 2 Average mass fraction (%) in road dust with a fraction <0.1 mm for control points (S, F, E)

sample medium, B_n – concentration of the tested component in the reference medium (background), B_{ref} – concentration of the reference element in the reference medium.

Aluminum was used as the reference element ($_{ref}$) as it is a typical marker of mineral dust (Lazo et al. 2018, Pastuszka et al. 2010, Sardans and Peñuelas 2005). The values for B_n, B_{ref} were referenced to concentrations in the upper crust (Wedepohl 1995).

Results and discussion

The tests determined the mass proportion of elements in each of the 24 samples. The results for dust with a fraction <0.1 mm, collected at measurement points 1-8 on both sides of the road, were averaged. The mean values for each element and measurement point (S, F, E) are presented in Table 2.

The identified elements in road dust with a fraction <0.1 mm, ranked in descending order of average weight percentage, are: Si, Ca, Fe, K, Al, Ti, S, Tm, Zn, Zr, Mn, Cu, Sr, Pd, Cr, Pb, V, Ni, Rb, and Y. The elements with the highest mass contribution in each sample ranged from 58.958% to 0.46%. The highest mass proportions in road dust for the noise screened space (S) were observed for potassium (K), silicon (Si), and titanium (Ti), while for point F, it was calcium (Ca), and for the exits (E), it was aluminum (Al), iron (Fe), and sulfur (S). Additionally, the mass proportions of Ca and Si in road dust varied significantly depending on the control point type. Elements such S Tm, Zn, Zr, Mn, Cu, Sr, Pd, Cr, Pb, V, Ni, Rb, and Y contributed less than 1% (with a few cases slightly exceeding 1%) or were absent altogether. Figure 3 indicates that the average mass contribution of Cr, Rb, Sr, and Y in road dust with a fraction <0.1 mm, collected at the three control points (S, F, E), is comparable. For elements detected across all locations, the highest mass fractions in road dust were observed for Mn, Pb, Rb, Zn, and Zr in areas shielded by sound-absorbing screens (S), for Cr, V, and Y at point F, and for Cu, Sr, and Y at exits (E). Notably, the mass fractions of Cu, Mn, Pb, V, Zn, and Zr in road dust varied significantly depending on the control point type. Pd was found only in road dust collected in areas protected by a barrier (S), Tm was found near the motorway / expressway exits (E), and Ni was present at points F and E. To determine whether the differences in concentrations presented in Figure 2 were statistically significant, a Welch's t-test was performed.

The results are shown in Table 2. None of the obtained p-values indicate statistically significant differences between

Table 1. The mass fraction of elements in road dust with a fraction less than 0.1 mm at eight points and divided into three control points (S, F, E).

Road dust with a particle size of <0.1 mm												
Measurement points	1	2	3	4	5	6	7	8	Average	Non-biased standard deviation estimator ŝ	Minimum	Maximum
Road No.	A2	S7	S8	S17	A1	S8	S7	S8				
Selected sections	Warsaw – Łódź	Kielce By – Pass	Wrocław – Sieradz	Lublin – Piaski	Częstochowa – Katowice	Warsaw – Piotrków Trybunalski	Cracow – Widoma	Sieradz – Wrocław				
Elements [%]	**Soundproof screens (S)**											
Al	2.159	2.231	3.108	2.719	3.461	1.825	2.126	3.256	2.611	0.609	1.825	3.461
Ca	24.548	40.855	24.793	23.478	17.404	26.351	41.873	22.590	27.736	8.816	17.404	41.873
Cr	0.157	<dl	0.121	0.079	0.052	0.152	0.049	0.107	0.102	0.044	<dl	0.157
Cu	0.231	0.082	0.195	0.120	0.086	0.190	0.083	0.160	0.143	0.059	0.082	0.231
Fe	19.919	8.560	16.184	9.477	9.725	18.970	8.579	15.021	13.304	4.772	8.560	19.919
K	3.896	3.696	4.565	5.246	6.620	3.760	3.801	5.654	4.655	1.085	3.696	6.620
Mn	0.450	0.314	0.376	0.389	0.278	0.469	0.321	0.411	0.376	0.068	0.278	0.469
Ni	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	*	<dl	0.000
Pb	0.065	<dl	0.095	<dl	<dl	0.119	<dl	<dl	0.093	0.027	<dl	0.119
Pd	<dl	0.116	<dl	<dl	<dl	<dl	<dl	<dl	0.116	*	<dl	0.116
Rb	0.037	0.036	0.046	0.042	0.054	0.040	0.040	0.062	0.044	0.009	0.036	0.062
S	1.656	0.507	1.354	0.772	0.820	0.965	0.464	1.212	0.969	0.416	0.464	1.656
Si	42.811	41.725	45.362	54.448	59.051	41.282	40.860	46.466	46.500	6.734	40.860	59.051
Sr	0.142	0.097	0.148	0.112	0.099	0.129	0.096	0.116	0.117	0.020	0.096	0.148
Ti	3.269	1.355	2.343	2.019	1.847	2.539	1.279	2.414	2.133	0.656	1.279	3.269
Tm	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	*	<dl	0.000
V	<dl	<dl	0.072	0.071	<dl	<dl	<dl	0.053	0.065	0.011	<dl	0.072
Y	0.027	0.013	0.029	0.018	0.016	0.021	0.012	0.027	0.020	0.007	0.012	0.029
Zn	0.723	0.126	0.760	0.660	0.126	3.324	0.140	1.722	0.947	1.097	0.126	3.324
Zr	0.992	0.287	0.535	0.540	0.360	0.790	0.310	0.759	0.572	0.255	0.287	0.992

Road dust with a particle size of <0.1 mm												
Measurement points	1	2	3	4	5	6	7	8	Average	Non-biased standard deviation estimator ŝ	Minimum	Maximum
Road No.	A2	S7	S8	S17	A1	S8	S7	S8				
Selected sections	Warsaw – Łódź	Kielce By – Pass	Wrocław – Sieradz	Lublin – Piaski	Częstochowa – Katowice	Warsaw – Piotrków Trybunalski	Cracow – Widoma	Sieradz – Wrocław				
Elements [%]	**Free space (F)**											
Al	2.215	1.701	3.073	2.014	2.363	1.606	<dl	2.414	2.198	0.495	<dl	3.073
Ca	24.6	46.015	25.744	26.077	21.433	31.349	44.162	26.915	30.787	9.254	21.433	46.015
Cr	0.116	0.083	0.141	0.087	<dl	0.121	0.052	0.123	0.103	0.031	<dl	0.141
Cu	0.203	0.095	0.159	0.104	0.082	0.192	0.087	0.163	0.136	0.049	0.082	0.203
Fe	16.768	10.213	16.544	10.340	9.781	16.869	9.42	16.493	13.303	3.610	9.420	16.869
K	4.375	3.112	4.382	5.184	6.355	3.588	3.887	4.351	4.404	1.002	3.112	6.355
Mn	0.375	0.370	0.399	0.267	0.293	0.409	0.336	0.409	0.357	0.054	0.267	0.409
Ni	0.035	<dl	0.044	<dl	<dl	<dl	<dl	0.055	0.045	0.010	<dl	0.055
Pb	<dl	0.046	0.091	<dl	<dl	0.086	<dl	0.086	0.077	0.021	<dl	0.091
Pd	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	*	<dl	0.000
Rb	0.043	0.040	0.045	0.039	0.051	0.036	0.038	0.047	0.042	0.005	0.036	0.051
S	1.462	0.686	1.055	1.232	1.216	1.925	0.488	1.523	1.198	0.462	0.488	1.925
Si	45.621	36.211	44.329	51.318	55.470	40.329	39.495	43.465	44.530	6.328	36.211	55.470
Sr	0.153	0.065	0.130	0.126	0.107	0.156	0.104	0.139	0.122	0.030	0.065	0.156
Ti	2.326	1.715	2.406	2.285	2.186	2.176	1.441	2.358	2.111	0.346	1.441	2.406
Tm	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	*	<dl	0.000
V	0.089	<dl	<dl	<dl	<dl	<dl	0.063	0.067	0.073	0.014	<dl	0.089
Y	0.024	<dl	0.027	0.019	0.019	0.019	<dl	0.026	0.022	0.004	<dl	0.027
Zn	1.012	0.360	0.970	0.315	0.129	0.662	0.172	0.991	0.576	0.378	0.129	1.012
Zr	0.659	0.185	0.510	0.599	0.514	0.491	0.314	0.482	0.469	0.152	0.185	0.659

Road dust with a particle size of <0.1 mm												
Measurement points	1	2	3	4	5	6	7	8	Average	Non-biased standard deviation estimator $\hat{s}$	Minimum	Maximum
Road No.	A2	S7	S8	S17	A1	S8	S7	S8				
Selected sections	Warsaw – Łódź	Kielce By – Pass	Wrocław – Sieradz	Lublin – Piaski	Częstochowa – Katowice	Warsaw – Piotrków Trybunalski	Cracow – Widoma	Sieradz – Wrocław				
Elements [%]	**Exit from the road (E)**											
Al	2.161	1.848	4.146	2.818	3.285	2.238	2.169	2.550	2.652	0.752	1.848	4.146
Ca	25.520	42.052	24.326	22.379	17.711	30.349	43.177	23.813	28.666	9.292	17.711	43.177
Cr	0.112	0.058	0.166	0.075	0.067	0.134	0.036	0.127	0.097	0.045	0.036	0.166
Cu	0.220	0.083	0.261	0.102	0.086	0.146	0.085	0.291	0.159	0.086	0.083	0.291
Fe	16.088	9.146	20.289	9.736	9.610	15.811	9.267	19.324	13.659	4.751	9.146	20.289
K	4.145	3.864	4.582	5.727	6.672	3.352	3.794	4.220	4.544	1.111	3.352	6.672
Mn	0.371	0.321	0.512	0.257	0.264	0.406	0.340	0.390	0.357	0.083	0.257	0.512
Ni	<dl	<dl	0.061	<dl	<dl	<dl	<dl	<dl	0.061	*	<dl	0.061
Pb	0.077	<dl	0.099	<dl	<dl	0.075	<dl	0.095	0.087	0.012	<dl	0.099
Pd	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	*	<dl	0.000
Rb	0.040	0.037	0.046	0.041	0.051	0.030	0.039	0.050	0.042	0.007	0.030	0.051
S	1.764	0.460	1.373	0.762	0.647	3.877	0.527	1.418	1.353	1.126	0.460	3.877
Si	45.423	40.174	41.446	55.257	58.958	40.746	39.780	42.813	45.574	7.403	39.780	58.958
Sr	0.157	0.098	0.145	0.093	0.096	0.184	0.102	0.131	0.126	0.034	0.093	0.184
Ti	2.237	1.427	2.770	2.067	1.969	2.314	1.337	2.326	2.056	0.478	1.337	2.770
Tm	<dl	<dl	<dl	<dl	<dl	<dl	<dl	0.898	0.898	*	<dl	0.898
V	0.065	<dl	<dl	<dl	<dl	<dl	0.032	0.075	0.057	0.023	<dl	0.075
Y	0.022	<dl	0.033	0.015	0.020	0.022	<dl	0.022	0.022	0.006	<dl	0.033
Zn	1.056	0.130	1.388	0.356	0.111	0.842	0.134	1.664	0.710	0.616	0.111	1.664
Zr	0.583	0.303	0.508	0.326	0.453	0.609	0.303	0.331	0.427	0.128	0.303	0.609

* Denotes the value that cannot be determined since can be calculated only when there are not less than two valid numeric values.

the control points. This suggests that the average elemental composition of the dust is not influenced by the control point type. To assess the impact of human activity on element concentrations in road dust, we conducted an analysis of enrichment factors (, (Table 3).

Road dust collected in an unrestricted area (F) with a fraction size of less than 0.1 mm was found to be highly enriched in Ca, Cr, Cu, Ni, Pb, S, and Zr. Dust collected from an area shielded by noise barriers (S) showed enrichment in Zn. These findings suggest that these elements have an anthropogenic origin, possibly from flue gases, as noted by (Aguilera et al. 2021, Rogula-Kozłowska et al. 2013, Adamiec et al. 2023), and may be present in. Furthermore, significant concentrations of Mn, Ti, and Y were found in dust from the area unobstructed by terrain barriers (F), while Ca and S were prominent in the downhill area (E). The likely source of this dust is the abrasion of vehicle tires (Dziubak 2021). Higher enrichment factors (EF) for Fe, K, Rb, Si, and Sr were observed in road dust at control point F compared to points S and E. It is noteworthy that dust collected at control points S and E showed similar levels of enrichment for these elements. The blowing of fine particles of roadside soil into the vicinity of the road lane occurs more frequently at the unrestricted point (F), influenced by atmospheric conditions, such as wind force, and vehicle speed. These factors increase air circulation, causing fine dust particles located around the road to become airborne (Juda-Rezler and Toczko 2016). Transportation-related dust pollutants can impact the environment up to 500 meters from traffic routes (Badyda 2010, Hajok et al. 2017). Therefore, it can be concluded that dust with a fraction <0.1 mm, collected from the road surface at an unresticted control point (F), exhibits higher levels of enrichment in Ca, Cr, Fe, K, Ni, Rb, Si, and Sr compared to dust from points shielded by an off-road barrier (S) or from exits (E).

Conclusion

The elemental composition of dust with a fraction <0.1 mm was analyzed at three control points (S, F, E). The mass shares of Al, Cr, Fe, K, Rb, S, Sr, Ti and Y were found to be comparable across the sites. The highest mass shares of road dust in the space shielded by noise barriers (S) were observed for K, Mn, Pb, Rb, Si, Ti, Zn and Zr, while at point F, the highest mass shares were found for Ca, Cr, V and Y. At the exits (E), the highest mass shares were for Al, Cu, Fe, S, Sr and Y. The mass proportion of Ca, Cu, Mn, Pb, Si, V, Zn and Zr in road dust varied depending on the control point type. Road dust collected

Table 2. The p values of the Welch's t-test for the equality of means for dust with a fraction size of <0.1 mm from three control points (E, WP, Z).

Elements	S-F	F-E	S-E
Al	0.21	0.95	0.20
Ca	0.26	0.91	0.33
Cr	0.36	0.67	0.71
Cu	0.61	0.50	0.30
Fe	1.00	0.60	0.59
K	0.23	0.44	0.65
Mn	0.51	0.59	0.99
Pb	0.37	0.49	0.75
Rb	0.29	0.16	0.45
S	0.41	0.50	0.90
Si	0.40	0.75	0.60
Sr	0.81	0.82	0.96
Ti	0.73	0.85	0.91
V	0.56	0.82	0.51
Y	0.73	0.61	0.32
Zn	0.21	0.40	0.32
Zr	0.28	0.20	0.83

Table 3. coefficients for the elements marked in road dust with a fraction <0.1 mm, depending on the control point (S, F, E). The the enrichment class, according to (Yongming et al., 2006), is denoted using Harvey balls for each cell, ○ for minimal enrichment (EF ≤ 2), ◔ for moderate enrichment (2 < EF ≤ 5), ◑ for significant enrichment (5 < EF ≤ 20), ◕ for very high enrichment (20 < EF ≤ 40) and ● for extremely high enrichment (EF > 40).

Elements	EF_S	EF_F	EF_E
Ca	◕ 23	● 46	◕ 24
Cr	● 74	● 126	● 82
Cu	● 287	● 423	● 348
Fe	◑ 12	◑ 20	◑ 14
K	◔ 5	◑ 7	◔ 5
Mn	◑ 20	◕ 31	◑ 19
Ni	○ 0	● 41	◑ 11
Pb	● 64	● 73	● 56
Rb	◑ 12	◑ 15	◑ 9
S	◕ 29	◕ 60	◕ 36
Si	◔ 4	◑ 7	◔ 4
Sr	◑ 11	◑ 17	◑ 11
Ti	◑ 19	◕ 32	◑ 19
V	◑ 15	◑ 16	◑ 14
Y	◕ 23	◕ 36	◕ 25
Zn	● 772	● 485	● 460
Zr	● 66	● 86	● 51

only at sites shielded by a field barrier (S) contained Pd, while Tm was found near a highway/expressway exits (E). Ni was present at points F and E.

Furthermore, road dust with a fraction less than 0.1 mm, collected in the area not restricted by the terrain barrier (F), exhibited extremely high levels of Ca, Cr, Cu, Ni, Pb, S and Zr. Conversely, dust from the area shielded by noise barriers (S) was enriched in Zn, indicating an anthropogenic origin, most likely from exhaust gases. Manganese (Mn), Titanium (Ti), and Yttrium (Y) showed very high enrichment at point F, which is not restricted by the terrain barrier. Calcium (Ca) and Sulfur (S) show high enrichment at the exit area (E). These elements may have originated from vehicle tire abrasion. Road dust at receptor F was more enriched in Iron (Fe), Potassium (K), Rubidium (Rb), Silicon (Si), and Strontium (Sr) compared to points S and E. The enrichment factor (EF) values at points S and E were similar.

In general, dust with a fraction <0.1 mm, collected from the road surface at the control point not restricted by noise barriers (F), exhibited stronger enrichment in Ca, Cr, Fe, K, Ni, Rb, Si and Sr compared to the control point shielded by an off-road barrier (S) or at the exit (E). This is likely due to the process of winding fine particles of roadside soil into the vicinity of the road lane.

The research conducted expanded knowledge on dust emissions generated near road lanes, particularly in areas with noise barriers. This information can be used to improve measures aimed at reducing dust emissions near roads and to promote environmentally friendly solutions, such as plant-based noise barriers.

It is important to note that the information provided on road dust is not exhaustive. Further research on this material is recommended, especially since this topic is still not sufficiently recognized in Poland and requires a substantial analysis.

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