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Joanna Korzeniowska

ORCID 0000-0001-5636-483X
Department of Ecology and Environmental Protection,
Institute of Biology and Earth Sciences,
University of the National Education Commission (Kraków, Poland)
korzeniowska.joanna.maria@gmail.com

History of Research on Heavy Metals in the Roadside Environment

Abstract

For a number of years, research has been conducted around the world to not only determine the concentration of heavy metals along traffic routes, but also to develop a dispersion pattern for emissions generated by transportation in areas adjacent to roads. The history of these studies is relatively brief, as it covers just over eighty years. However, this research is significant in terms of the development of motor vehicle exploitation over recent years and the negative impact of road transport on human, animal, and plant health. Substances originating from motor vehicles are qualified as highly harmful, and growing crops or living near roads makes us particularly susceptible to their impact.

At the beginning of the research targeting the impact of roads on the environment, scientists focused primarily on determining the content of lead and cadmium in soils and plants. Over time,

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as ecological awareness and technological progress accelerated, research on determining the content of metals in the environment expanded to other elements along with their impact on biodiversity and human health. The first works described the distance from the road as the main factor influencing roadside pollution. Subsequent years and observations led to the description of at least several factors that influence the dispersion of pollution along roads. Thanks to monitoring studies undertaken around the world for several decades, which quantify the content of heavy metals in soils and plants, it has become possible to observe changes in the concentration of metals in the roadside environment over the years and to compare the concentration of metals in soils and plants extracted from areas prior to the construction of roads (the so-called background areas) with the concentrations of metals in these components of the environment in later roadside areas.

Keywords: *research history, heavy metals, roadside environment*

Z historii badań nad metalami ciężkimi w środowisku przydrożnym

Abstrakt

Od szeregu lat na świecie prowadzi się badania mające na celu nie tylko określenie koncentracji metali ciężkich wzdłuż ciągów komunikacyjnych, lecz także opracowanie schematu rozprzestrzeniania się emisji pochodzących z transportu na terenach przyległych do dróg. Historia tych badań nie jest długa, bo dotyczy zaledwie ponad osiemdziesięciu lat. Jednak badania te są ważne z punktu widzenia rozwoju motoryzacji na przestrzeni ostatnich lat oraz negatywnego wpływu transportu drogowego na zdrowie ludzi, zwierząt i roślin. Substancje pochodzące z motoryzacji zalicza się do bardzo szkodliwych, a uprawy roślin czy mieszkanie w pobliżu dróg sprawiają, że jesteśmy szczególnie narażeni na ich oddziaływanie.

Na początku badań dotyczących wpływu dróg na środowisko naukowcy skupiali się przede wszystkim na określeniu zawartości ołowiu i kadmu w glebach i roślinach. Z czasem, w miarę wzrostu świadomości ekologicznej i postępu technologicznego, badania dotyczące określania zawartości metali w środowisku rozszerzyły się na inne pierwiastki wraz z podaniem ich wpływu na bioróżnorodność i zdrowie człowieka. Pierwsze prace opisywały odległość od drogi jako główny czynnik wpływający na zanieczyszczenia przydrożne. Kolejne lata i spostrzeżenia doprowadziły do opisywania co najmniej kilku czynników, które mają wpływ na rozprzestrzenianie się zanieczyszczeń wzdłuż dróg. Dzięki badaniom monitoringowym dotyczącym określenia zawartości metali ciężkich w glebach i roślinach, prowadzonym na całym świecie od kiludziesięciu lat, możliwym stało się zaobserwowanie zmian w koncentracji metali w środowisku przydrożnym na przestrzeni lat i porównanie koncentracji metali w glebach i roślinach pobranych z terenów sprzed budowy dróg (tzw. tłowych) z koncetracjami metali w tychże komponentach środowiska w późniejszych terenach przydrożnych.

Słowa kluczowe: *historia badań, metale ciężkie, środowisko przydrożne*

1. Introduction

Heavy metals pose a serious threat to the environment and human health, especially in areas exposed to pollution derived from road transport. The history of research on their presence and impact on the roadside environment dates back to the second half of the 20th century, when the negative effects of exhaust emissions and wear of car parts began to be noticed. This article presents the evolution of research on heavy metals in the context of the roadside environment, from the first observations of their presence in soil and plants to modern methods of monitoring and assessing the risks associated with them. Pollution of the environment by heavy metals, such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), copper (Cu), chromium (Cr), nickel (Ni) and zinc (Zn), poses a serious threat to human health as well as the quality of water, soil and vegetation. In particular, roadside environments, i.e. areas lying in the vicinity of roads, are particularly vulnerable to the presence of these substances, especially as a result of car exhaust emissions and precipitation containing heavy metal particles (Chmielewski et al. 2020; Genchi et al. 2020; Mitra et al. 2022).

2. Heavy metals in the natural environment

The term "heavy metals" refers to elements with a density greater than 5 g/cm^3 which are indispensable, toxic, or superfluous to living organisms. This term refers to all metallic elements with an atomic number greater than twenty. The source literature also includes the term "metals" or "trace metals". The term "trace metals" is not strictly defined and may refer to elements whose content in the Earth's crust is low (usually less than 0.1%) or to elements occurring in the environment in trace amounts (Adriano 1986; Kabata-Pendias, Pendias 1999).

Heavy metals are very widespread in the environment, occurring in all of its components: hydrosphere, biosphere (plants and animals) and pedosphere (soils). Increased concentrations of heavy metals in the environment pose a serious threat to the life and health of living organisms (Werkenthin et al. 2014; Popek et al. 2017; Dzikuć et al. 2018; Fidos and Rutkowska 2023).

According to Kabata-Pendias and Pendias (1999), four groups of metals with varying degrees of hazard posed for the natural environment can be distinguished:

- elements posing a very high degree of hazard: Cd, Hg, Pb, Cu, Tl, Sn, Zn, Cr, Sb, Ag, Au;
- elements posing high potential hazard: Bi, U, Mo, Ba, Mn, Ti, Fe, Se, Te;
- elements posing a medium degree of hazard: F, Be, V, Rb, Ni, Co, As, Li, Ge, In, B, Br, Cs, W, Al;
- elements posing low potential hazard: Sr, Zr, Ta, La, Nb.

It should be stressed here that potential contamination of the environment with individual heavy metals does not equate to their harmfulness for living organisms. The toxic impact of elements is dependent not only on the degree of environment contamination with the metal in question but is also related to the biochemical role of elements in metabolic processes. However, group one metals (Cd, Hg, Pb, Cu, Tl, Sn, Zn, Cr, Sb, Ag, Au) pose a serious risk of chemical imbalance in ecosystems when large quantities of them are found in the environment. Similarly, metals displaying a lower degree of hazard can be harmful if their environmental concentrations increase significantly.

The heavy metals posing a very high environmental hazard and, at the same time, most often investigated in scientific studies are cadmium, lead, zinc, copper, and chromium.

2.1. Cadmium

Cadmium, even at extremely low concentrations in the body, is an element of high toxicity. Its toxicity impairs the function of the liver, kidney and other organs, reproductive function, leads to bone deformity and induces neoplastic lesions (especially of the kidneys and prostate gland), probably related to the induction of an inflammatory response in them. In cells, cadmium disrupts the metabolism of calcium, magnesium, iron, zinc, and copper. This element has also an adverse impact on the cardiovascular system. A case of mass cadmium poisoning occurred in Toyama province, Japan, near the Kamioka mine (Itai-Itai disease, Japanese for "severe pain"). Severe pain occurred in the spine and joints. As a result of the operation of metal ore mines, cadmium was released in significant quantities from 1910. The disease was first reported around 1912. In Toyama province, rice was grown in fields fertilised with sewage of high cadmium content. Rice field workers were found to have:

- osteomalacia (metabolic bone disease) resulting from the displacement of calcium by cadmium, leading to numerous fractures;
- nephropathy (kidney diseases);
- pain in the spine, limbs, joints and muscles;
- characteristic waddling gait (a disorder involving paresis of the muscles of the pelvic girdle and thighs, which causes hips to sway sideways when walking) (Kabata-Pendias, Pendias 1999; Inaba et al. 2005; Czeczot and Majewska 2010; Trojanowska and Świetlik 2012; Kaczyńska et al. 2015).

2.2. Lead

Absorption of lead into the body proceeds via the respiratory system, skin, and gastrointestinal tract. All lead compounds are poisonous. Chronic poisoning with lead and its salts which affects workers of printing houses, facilities producing batteries and lead paint, as well as metal smelters. Chronic poisoning affects the gastrointestinal and nervous systems. The main symptoms of lead poisoning are:

- lassitude, fatigue;
- muscle paralysis, a grey ring around the teeth;
- memory deterioration, neurological and mental disorders.

Lead compounds are particularly dangerous for young people, in whom the blood-brain barrier is not yet well-developed. At concentrations as low as 0.2 mg/kg in the blood, lead damages the central and peripheral nervous systems. In addition to the nervous system, lead adversely affects the functioning of kidneys, liver, circulatory and cardiovascular systems, and the respiratory system. It impairs reproductive function and calcium metabolism, whereby its excess in the body is the cause of bone deformities

(Kabata-Pendias, Pendias 1999; Ociepa-Kubicka and Ociepa 2012; Hou et al. 2013).

A disease caused by excessive lead intake is called lead poisoning (also plumbism or saturnism). In Poland, the best-known case of acute lead poisoning of children is the impact of the non-ferrous metal smelting plant in Katowice-Szopienice. The smelting plant operated from 1834 to 2008 (the lead smelter closed in the 1980s and a company recovering lead from batteries remained there). The filters installed in the smokestacks of the Szopienice plant were mock-ups, while 350 m from the factory walls the pollution of air with particles exceeded the norm by about a thousand times. Thousands of children living near the smelting plant were poisoned by lead and suffered lifelong effects of this poisoning. Many of those children did not live to the age of 50, developed mental illnesses, were developmentally retarded and had mobility problems. Furthermore, diseased residents gave birth to ill children and this lead poisoning caused enormous health damage felt for several generations. Between 1974 and 1975, owing to the efforts of Wiesława Wilczek, Bożena Hager-Małecka, and Jolanta Wadowska-Król, more than 4,500 children living in Szopienice were tested. In blood and urine tests, elevated lead content was found (exceeding permissible values severalfold), and the test results remained secret. Jolanta Wadowska-Król, a physician, wanted to disclose those results in her doctoral thesis, but she was not allowed to complete her work. Mrs Wadowska-Król demonstrated a heroic attitude and, acting together with the management of the smelting plant, managed to secure replacement housing for the residents of Szopienice and therapeutic stays in sanatoria (often lasting over 6 months) for sick children (Jędryka 2020).

2.3. Zinc

Zinc performs highly important functions in the human body, like the creation of enzymes which regulate the metabolic processes of proteins and carbohydrates, and regulates the operation of the cardiovascular, reproductive, and skeletal systems. Zinc deficits lead to skin diseases, as well as allergies and hair loss. Excessive zinc content damages health. At high concentrations, it is deposited in the kidneys and liver, causing anaemia, which is associated with decreased absorption of other elements such as iron, phosphorus, copper, and calcium. It is also considered a carcinogen (Kabata-Pendias, Pendias 1999; Ociepa-Kubicka and Ociepa 2012; Zhang et al. 2012).

2.4. Copper

The basic function of copper in the body is to participate in oxidative-reductive processes, where it occurs as a component of the coenzyme, regulating metabolism, iron transport, and collagen metabolism. Excess copper causes a decrease in haemoglobin concentration and damage to the liver and kidneys. Since copper is a zinc antagonist, its excess leads to zinc deficiency and, consequently, immunological deficiencies. The source of copper accumulation in the body is the consumption of plants and vegetables from areas exposed to heavy metal emissions. Common toxic symptoms following copper ingestion include kidney, liver, and capillary damage, diarrhoea, and intestinal cramps and pain (Kabata-Pendias, Pendias 1999; Gruca-Królikowska and Wacławek 2006; Araya, Olivares and Pizarro 2007).

2.5. Chromium

Chromium is essential for life in small amounts and plays an important role in the metabolic transformation of glucose, certain proteins, and fats. It is also a component of selected enzymes and stimulates the activity of other ones.

Exceeding physiological concentrations is an allergy and cancer inducing factor. Chromium compounds damage the gastrintestinal system, induce skin changes, and exhibit mutagenic, embryotoxic, and teratogenic effects. The carcinogenicity of chromate was revealed during the research on workers exposed to chromium compounds. Exposure to chromate contained in the atmosphere may cause nasal and bronchial cancer with a latent period of 10 to 15 years (Kabata-Pendias, Pendias 1999; Ociepa-Kubicka and Ociepa 2012; Coetzee, Bansal and Chirwa 2020).

3. Motor vehicle exploitation as a source of heavy metals

Motor vehicle exploitation is one of the human-made sources of heavy metals in the natural environment. The exploitation of vehicle fleets exerts a negative impact on individual components of the environment. It contributes to deteriorating air quality, pollution of soil, vegetation, groundwater, and surface water, and takes up land surface for transportation infrastructure and exposes a significant percentage of the population to excessive noise pollution (Gworek and Kwasowski 2001, Jankaitė et al. 2008).

Road transport is responsible for the emissions of heavy metals such as: cadmium, copper, lead, antimony and zinc. In addition, it pollutes the environment with various waste materials, such as used vehicles, vehicle bodies, and discarded consumables, including oils, electrolytes, coolants, and materials used for washing and maintenance of vehicles (Button, Hensher 2003; Werkenthin et al. 2014).

Emissions from the exploitation of motor vehicles are disorganized and variable over time - pollutants are introduced into the atmosphere in a disorderly and impossible to quantify manner. In addition, the quantity of pollutants emitted in the adopted time intervals is variable (Turer 2005). When examining heavy metal emissions related to car traffic, the construction of the structural elements of cars and roads should be taken into account, as well as factors affecting the spatial dispersion of emitted heavy metals in areas adjacent to roads, such as traffic volume, distance from the road, road profile, configuration of the area adjacent to the road as well as the vegetation cover (Samecka-Cymerman et al. 2011; Radziemska et al. 2019; Skorbiłowicz et al. 2021; Isinkaralar et al. 2024).

Due to the imperfection of the combustion process and the properties of the fuels used, toxic substances are produced during engine operation, which are then emitted into the environment along with exhaust gases (Wang et al. 2003). These compounds may be divided into three groups:

- incomplete combustion derivatives: hydrocarbons, carbon monoxide, aldehydes;
- products of the oxidation of atmospheric nitrogen – NOx;
- products from the combustion of admixtures and impurities as well as other substances (dust and heavy metals: cadmium, chromium, copper, lead, nickel and zinc.

The elements Cd, Ni, Zn are components of oils and lubricants. In the process of catalytic converters wear, on the other hand, platinum is emitted into the environment (Whiteley, Murray 2003).

Car tires are the main source of Zn and a number of other elements which are emitted into the environment as a consequence of tire wear. In the dust derived from worn-out tires, scientists found the following elements to occur in smaller quantities: Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, and Pb (Weckwerth 2001).

Another structural element of cars that emits heavy metals into the environment as a result of wear is the braking system (Weckwerth 2001; Laschober et al. 2004). Brake linings include the following elements: Cd, Cr, Cu, Ni, Pb, Sb, and Zn. Considerable wear of brake linings occurs near roundabouts and intersections, i.e. places where driving speed becomes reduced (Hjőrtenkrans et al. 2006).

The chemical composition of road pavement and the metals derived from road pavement wear depend on binding agents (bitumen) and base materials (Lindgren 1996). The material derived from road pavement may include Cd, Cr, Cu, Hg, Ni, Pb, V, and Zn.

The spectrum of heavy metals related to motor vehicle exploitation shows time changes. Lead and cadmium were gradually withdrawn from fuel until 2021 in Algeria (Pierre et al. 2004). Since January 2000, lead has been disallowed as an antiknock agent for fuel in the European Union. Thus, lead is no longer an indicator of traffic pollution, and its place is replaced by other metals. The content of cadmium and lead in soils is only a historical residue from the fuel combustion process. They are still present, even though the concentration of these metals in the soil is no longer on the rise (Hjőrtenkrans et al. 2006).

In the course of technological innovation, brake linings made of asbestos were replaced with materials with better performance parameters and lower noxiousness for the environment. Metals such as Cu, Sb and Zn were mainly used for the production of brake linings. The result of applying the above-mentioned metals in the construction of brake linings was an increase in the concentration of copper and antimony in soils and roadside vegetation in recent years (Monaci et al. 2000; Hjőrtenkrans et al. 2006).

Hjőrtenkrans et al. (2006), based on the observed correlations between metals in the soil cover lying in the vicinity of roads, proposed the division of the heavy metals under study into three groups:

1. Group with the most significant correlations: Cu, Sb and Zn. Correlations between these metals indicate a common source of origin, i.e. transportation.

2. Metals whose presence in soils has a historical significance and is associated with the process of fuel combustion: Pb and Cd.

3. Metals associated with all sources related to transport without indicating their specific source: Cr and Ni.

The division of metals presented above is largely simplified, because at least several emission sources could be additionally listed for each of the groups. The emission of heavy metals into the environment is influenced by a number of environmental factors, which should be taken into account in order to determine the pollution dispersion model.

Hjőrtenkrans et al. (2006) conducted research aimed at determining the content of heavy metals in soils near roundabouts and road intersections in southern Sweden. One of the resources examined by the authors were galvanized surfaces of roadside equipment, i.e. lamps, barriers, fences, etc. They found that these galvanized roadside equipment items are the main source of Zn. The Mann-Whitney U test demonstrated that zinc concentrations for lanterns, which are characterized by varying sizes of galvanized surfaces, do not differ in a significant way. However, this test demonstrated that zinc concentrations were significantly higher for sites with galvanized fences and gates in comparison to sites with galvanized lamps. The explanation for this phenomenon is the fact that the corrosion of galvanized surfaces decreases in an aggressive road environment (Sederholm 2001).

4. History of research on heavy metals in soils and roadside vegetation

The first works investigating the content of heavy metals in the roadside environment dealt with lead content in soils and emerged in the late 1960s. They indicated concentrations of lead reaching values up to several dozen times higher than those currently observed. For example, Motto et al. (1970) established lead concentrations being twelve times higher near a road in New Jersey, Smith (1976) in soil in Maryland, U.S., while Lagerweff and Specht (1970) reported concentrations being four times higher in Cincinnati, Ohio. Some of the highest lead concentrations in the world were found by the following researchers in the course of their studies: Garcia-Miragaya et al. (1981) in the roadside soils of Caracas, Venezuela (up to 1620 mg/kg), Ajayi and Kamson (1983) in Lagos, Nigeria (2350–7270 mg/kg), Hoffman et al. (1989) in Germany (110–479 mg/kg), Onyari et al. (1991) in Nairobi (up to 2000 mg/kg) and Piron-Frenet et al. (1994) in France (195 mg/kg). It should be noted that the data cited above came from the 1970s and 1980s, when leaded gasoline (containing tetraethyllead as an antiknock agent), was commonly used worldwide. Until 2005, the concentration of lead in soils kept rising both in Poland and worldwide (in 2002 such fuel was available in 117 countries). Since 2005, the sale of ethylene has been banned in the European Union. It has been replaced by fuels in which the role of an antiknock additive is performed by lithium salts. The last country to phase out leaded gasoline was Algeria (2021).

In the 1970s and 1980s, a dynamic development of research methods took place, allowing for more accurate measurements of the concentration of heavy metals in various elements of the roadside environment, such as soil, groundwater, vegetation or living organisms. During this period, modern analytical techniques, such as mass spectrometry or atomic absorption spectroscopy, began to be applied, making it possible to precisely determine the concentration of individual metals in environmental samples. Thanks to these technologies, it became possible to detect not only lead, but also other metals, such as cadmium, arsenic, mercury or copper, which posed a serious threat to biodiversity in these ecosystems. The impact of these metals on human health was also studied, paying attention to their toxicity and the possibility of accumulation in plants and animals.

In the 1980s and 1990s, the first studies assessing the impact of heavy metal pollution on roadside ecosystems, including studies on the bioavailability of metals in the soil and their impact on soil microorganisms, as well as plants, were conducted. It was determined that heavy metals could not only accumulate in plants, but also enter the food chain, affecting animal and human health.

Modern research on heavy metals in the roadside environment employs advanced technologies, such as chemical sensors, electron microscopy and computer modelling, which allow for a more precise determination of the sources of pollution and its effects. A crucial area of research is also the assessment of the effectiveness of various methods of purifying the environment of heavy metals, such as bioremediation or phytoremediation, which uses plants to remove toxic metals from the soil (Coetzee, Bansal and Chirwa 2020). Research on the use of nanotechnology for the removal of heavy metals is also underway (Gong et al. 2021; Mitra et al. 2022).

These studies, which in most countries are carried out systematically (as part of environmental monitoring) and are constantly developing through:

– application of new research technologies (chemical analyses and devices);
– detailed elaboration of the research methodology;
– introduction and testing of new plant species as bioindicators of the state of the environment;
– determining the content of heavy metals other than lead or cadmium.

Currently, it is possible to determine the content of numerous metals, including platinum (Whiteley and Murray 2003).

Today, attention and research interest are drawn to metals such as molybdenum, vanadium and thallium, whose content in soils and roadside vegetation is increasing, in contrast to the content of Pb and Cd, which have remained constant in recent years (Karbowska 2016).

The researchers also focus on assessing the impact of heavy metal pollution on human health, especially in areas with high traffic volumes. Modern research has shown that long-term exposure to these substances can lead to various medical conditions, such as nervous system damage, cardiovascular diseases, as well as cancer (Mitra et al. 2022; Jomova et al. 2024).

5. Factors influencing the content of heavy metals in the roadside environment

In the 1960s, when the first works addressing pollution linked to road transport began to appear, the authors investigated the impact of distance from the road on the dispersion of heavy metals in soil and vegetation. It is only now that the research efforts are becoming focused on the influence of various environmental factors on the dispersion of pollution along roads. These factors include, among others: traffic volume, vehicle speed, road profile, configuration of the areas surrounding the road, land cover, size of emitted particles and meteorological conditions. Comparing literature data on the content of heavy metals in soil and vegetation is quite difficult, because a number of the above factors may determine the quantity of accumulated metals. These factors are of a very complex nature and are based on a number of variable parameters. Therefore, only a few selected factors may be considered significantly influential for the chemical composition as well as distribution of chemical elements.

5.1. Distance from the road

The distance from the road is one of the most important factors influencing the accumulation of heavy metals in soils and vegetation. Car traffic can bring about even a severalfold increase of the content of chemical elements in the soil and in vegetation compared to the content of those chemical elements in unpolluted areas (among others: Czarnowska 1974; Roszyk, Roszykowa 1975).

The distance from the road at which the influence of vehicular traffic ceases, and the concentrations of metals in soils and vegetation are similar to background values, has been determined. The distance over which heavy metals are emitted is usually determined to be 100–150 m away from the road (Curzydło 1988, Malczyk, Kędzia 1996; Słowik et al. 2006). However, some authors give a smaller range of traffic pollution dispersion, up to 50 meters (Czarnowska 1994; Maciejewska, Kwiatkowska-Malina 2001; Fakayode, Olu-Owolabi 2003).

There are also authors who believe that even at a distance of several hundred meters: over 300 m (in soils – Viard et al. (2004)) and over 1000 m from the road (in mosses – Zechmeister et al. (2005)), pollutants from road transport are still detectable.

Regardless of the maximum range of pollution, expressed by soil and plant enrichment coefficients in relation to reference areas, the highest level of accumulated metals (the highest values of enrichment coefficients) has always been observed at a distance of 0 to 10 meters.

5.2. Vehicle traffic intensity

The intensity of vehicle traffic is the second most often taken into consideration factor in the study of traffic pollution, next to distance. Most of the authors demonstrated that along roads with high traffic intensity, the content figures for metals in the soil and in vegetation were several times higher than along roads with medium or low traffic (Schröder et al. 2008; Ćwiąkała et al. 2019).

Similar conclusions were drawn by Korzeniowska and Panek (2008) – severalfold differences in traffic intensity contributed to statistically significant differences in the content of heavy metals in the common dandelion (Taraxacum officinale). These differences were observed at all distances from the road.

In the first works dealing with the intensity of vehicle traffic, in particular regarding Polish roads, the authors did not provide precise data regarding the number of passing vehicles. The information was provided only with a comment about very high, medium or low traffic intensity.

5.3. Configuration of the terrain surrounding the road

The configuration of the terrain surrounding the road means rising or descending terrain shapes, i.e. ones located above and below the road level. There are few scientific works which deal with the study of how terrain configuration impacts the level of accumulated metals along roads. Often, roads with an inclined profile cross areas of diverse configuration, while roads with a flat profile run across areas of plains. In the cases where the road runs through or past morphological forms such as: valley, basin, pass, natural and artificial excavations and protective screens, the surrounding area rises above its level "naturally" limiting the extent of pollutant dispersion in the situation described, heavy metals are deposited primarily near the road.

Panek and Zawodny (1993) determined that lead concentrations in the soil alongside a mountain road leading through the Sierra Nevada range in southern Spain, were higher in areas of descending terrain compared to rising terrain areas, at a distance of 50 from the road. Szarek-Łukaszewska et al. (2002) and Zechmeister et al. (2005) did not find statistically significant dependencies between the configuration of the surrounding terrain and the content of heavy metals in mosses. Only lead concentrations in soils and vegetation at all distances from the road were higher in areas of descending terrain compared to rising terrain areas, but these were not statistically significant differences.

5.4. Land cover adjacent to the road

Research by Curzydło (1988) and Trzaskoś and Dzida (1995) concerned the protective function of the forest as a natural screen for traffic pollution. They tested and selected appropriate tree species (including oak, maple, hornbeam, beech, alder, larch and linden) for use as "natural screens", absorbing pollutants from road transport. The research conducted demonstrated higher concentrations of metals in soil and forest vegetation than in areas of open terrain along roads.

Similar research along the Kraków–Zakopane road and in the area of Chyżne village was carried out by Korzeniowska et al. (2014; 2023). This study demonstrated that soil concentrations of zinc, copper and lead, found in the common dandelion (Taraxacum officinale) and in the European spruce (Picea abies; individual trees growing on pastures) were higher in forest areas compared to areas of pastures. This trend was visible within the sampling sites at a distance of up to 50 m from the road, and faded at a distance of 100 m. This fact should be associated with the filtering function of the forest, which probably stops traffic pollutants in the close proximity of the road, hampering their dispersion over greater distances.

Only a few authors, like e.g. Malczyk and Kędzia (1996), do not confirm the filtering role of the forest. They found no statistically significant differences between the content of metals (Pb and Cd) in the soil in forested and open areas. They believed that in the vicinity of roads forests do not create a sufficiently good barrier to the dispersion of pollution and suggested that weather conditions such as wind speed and direction, as well as air turbulence, are more important for the range over which traffic pollution exerts its influence.

5.5. Road profile

Zechmeister et al. (2005) in their research conducted in the Austrian Alps, demonstrated the existence of statistically significant differences in the concentration of copper, zinc and antimony in Pleurozium schreberi moss between roads with different profiles.

They stated that the more inclined the road profile, the higher the concentrations of the above-mentioned metals. This fact should be associated with more intensive engine exploitation along uphill and downhill sections and with greater wear of brake linings and car tires, which is confirmed by the works of: Świetlicki et al. (1996); Laschober et al. (2004); Hjőrtenkrans et al. (2006).

The research conducted by Korzeniowska et al. (2014; 2019), along selected sections of the Kraków–Zakopane road, carried out in the years 2005–2015, confirmed that the average soil concentrations of metals were higher alongside sections with an inclined profile than alongside flat sections of the road. In the case of plants, on the other hand, the trend was the opposite.

5.6. Absolute altitude

It is commonly known that with the increase in the altitude, the content of metals in soils and vegetation rises (Grodzińska et al. 1994; Zechmeister 1995).

High precipitation, the quantity of which is strongly correlated with the deposition of metals, especially lead and zinc, contributes to the increase in the concentration of metals along with the elevation of the terrain (Zechmeister 1995).

Mountain ecosystems are mainly contaminated with long-range emissions, which may refer to the Kraków–Zakopane road, for which the height difference between the lowest and highest points is 428 m above sea level (333 m above sea level – Raba valley and 761 m above sea level in the Stare Wierchy and Obidowiec ranges).

Currently, in Poland, research on changes in the content of metals in soils and vegetation in conjunction with rising absolute altitude in the

Tatra National Park was conducted by Korzeniowska, Krąż and Dorocki (2020; 2021). In addition, Dorocki and Korzeniowska (2023) carried out similar research on the southern slope of Jaworzyna Krynicka Mountain. The research conducted by them confirmed the results of Zechmeister (1995), i.e. an increase in the concentration of lead in soils with the rising altitude above sea level and the influence of long-range emissions on the increased content of heavy metals in soils and vegetation in selected mountain areas.

5.7. Meteorological conditions

A highly important factor influencing the dispersion of metals in the environment is the prevailing wind direction. The literature data points to the conclusion that the location of the road in relation to the dominant wind direction has an impact on the propagation of traffic pollution, which is particularly important for exposed road sections running across convex landforms such as mountain ridges and in valleys where the wind direction coincides with the direction of the valleys (Piron-Frenet et al. 1994; Masoudi et al. 2012). Viard et al. (2004) and Masoudi et al. (2012) found higher metal contents in the soil on the windward side compared to the leeward side.

In 2018–2022, Korzeniowska and Panek (2019; 2023) carried out research to determine the impact of the prevailing wind direction on the amount of metal concentration in soils and vegetation along road No. 7 in the area of Chyżne village. The prevailing wind direction in the area under study was the south-westerly direction, which influenced the size of metal accumulation in the soils described and roadside vegetation. The influence of the dominant wind direction on the amount of metal concentration (Cr, Ni and Zn) was found at a distance of 100, 300 and 500 meters from the road. Variations in the concentration of metals in the soil on the windward and leeward side were determined. The content of chromium, nickel and zinc in the soils under study was higher on the windward side of the road compared to the concentrations of metals on the windward side (Korzeniowska 2023).

6. Summary

Research on heavy metals in the roadside environment has evolved in recent years, and their results have allowed for the development of effective methods of monitoring and reducing pollution. However, there are still many challenges related to the long-term impact of heavy metals on human health and ecosystems. As new technologies develop in the transport industry and changes in sources of pollutant emissions occur, further research on the impact of heavy metals on the environment and the innovation of new, effective strategies for their reduction will be necessary. Further advances in the monitoring of air, water and soil quality, as well as in the regulation of heavy metal emissions, will be crucial in minimizing their negative impact on the roadside environment and human health.

References

Adriano, Domy C. 1986: *Trace elements in the terrestrial environment*. New York: Springer Verlag. 533 pp. ISBN 9781475719079. DOI: 10.1007/978-1-4757-1907-9.

Ajayi, A.; Kamson, O. 1983: Determination of lead in roadside dust in Lagos City by atomic absorption spectrophotometry. *Environment International* 9(5), pp. 397–400. DOI: 10.1016/0160-4120(83)90132-0.

Araya, Magdalena; Olivares, Manuel; Pizarro, Fernando 2007: Copper in human health. *International Journal of Environment and Health* 1(4), pp. 608–620. DOI: 10.1504/IJENVH.2007.018578.

Button, Kenneth J.; Hensher, David A. 2003: *Handbook of transport and the environment*. Amsterdam: Elsevier. ISBN 978-0-080-44103-0. DOI: 10.1108/9781786359513.

Chmielewski, Jarosław; Gworek, Barbara; Florek-Łuszczki, Magdalena; Nowak-Starz, Grażyna; Wójtowicz, Bożena; Wójcik, Tomasz; Żeber-Dzikowska, Ilona; Strzelecka, Agnieszka; Szpringer, Monika 2020: Heavy metals in the environment and their Impact on human health. *Przemysł Chemiczny* 99(1), pp. 50–57. DOI: 10.15199/62.2020.1.3.

Coetzee, Johan J.; Bansal, Neetu; Chirwa, Evans M.N. 2020: Chromium in environment, its toxic effect from chromite-mining and ferrochrome industries, and its possible bioremediation. *Exposure and Health* 12(1), pp. 51–62. DOI: https://doi.org/10.1007/s12403-018-0284-z.

Curzydło, Józef 1988: Ołów i cynk w roślinach i glebach w sąsiedztwie drogowych szlaków komunikacyjnych. *Zeszyty Naukowe Akademii Rolniczej im. Hugona Kołłątaja w Krakowie* 127 (Rozprawa habilitacyjna). ISSN 0239-8109, pp. 70.

Czarnowska, Krystyna 1974: The accumulation of heavy metals in soils and plants in Warsaw Area (exemplified by grasses and mosses). *Polish Journal of Soil Science* 7(2), pp. 117–122.

Czarnowska, Krystyna 1994: Akumulacja niektórych metali ciężkich w glebach uprawnych i w liściach selera w pobliżu dróg wylotowych z Warszawy. *Roczniki Gleboznawcze* 45(3/4), pp. 59–75.

Czeczot, Hanna; Majewska, Monika 2010: Cadmium – exposure and its effects on health. *Farmacja Polska* 66(4), pp. 243–250. URL: https://www.ptfarm.pl/pub/File/Farmacja%20Polska/2010/04-2010/02%20%20Kadm.pdf (accessed on: 8.03.2024).

Ćwiąkała, Michał; Korzeniowska, Joanna; Kraszewski, Cezary; Rafalski Leszek 2019: Testing the concentration of trace metals in soils near roads with varied traffic intensity. *Roads and Bridges. Drogi i Mosty* 18(2), pp. 127–134. DOI: 10.7409/rabdim.019.008.

Dorocki, Sławomir; Korzeniowska, Joanna 2023: Soil contamination with metals in mountainous: A case study of Jaworzyna Krynicka in the Beskidy Mountains (Poland). *International Journal of Environmental Research and Public Health* 20, 5150. DOI: 10.3390/ijerph20065150.

Dzikuć, Maciej; Adamczyk, Janusz; Piwowar, Arkadiusz 2018: Problems associated with the emissions limitations from road transport in the Lubuskie Province (Poland). *Atmospheric Environment* 160, pp. 1–8. DOI: 10.1016/j.atmosenv.2017.04.011.

Fakayode, Sayo; Olu-Owolabi, Bamidele 2003: Heavy metal contamination of roadside top soil in Osogbo, Nigeria; Its relationship to traffic density and proximity to highways. *Journal of Environmental Geology* 44(2), pp. 50–157. DOI: 10.1007/s00254-002-0739-0.

Fidos, Maciej; Rutkowska, Beata 2023: Accumulation of selected trace elements in soil and roadside trees – case study. *Soil Science Annual* 74(1), pp. 163082. DOI: 10.37501/Soilsa/163082.

Garcia-Miragaya, J.; Castro, S.; Paolini, J. 1981. Lead and zinc levels and chemical fractionation In roadside soils of Caracas, Venezuela. *Water, Air and Soil Pollution* 15, pp. 285–297.

Genchi, Giuseppe; Carocci, Alessia; Lauria, Grazantionio; Sinicropi, Maria S.; Catalano, Alessia 2020: Nickel: Human health and environmental toxicology. *International Journal of Environmental Research and Public Health* 17(3), pp. 679. DOI: 10.3390/ijerph17030679.

Gong, Zhaoyuan; Chan, Hiu T.; Chen, Qilei; Chen, Hubiao 2021: Application of nanotechnology in analysis and removal of heavy metals in food and water resources. *Nanomaterials* 11(7), 1792. DOI: 10.3390/nano11071792.

Grodzińska, Krystyna; Szarek, Grażyna; Godzik, Barbara; Braniewski, Stanisław; Chrzanowska, Elżbieta 1994: Mapping air pollution in Poland by measuring heavy metal concentration in mosses. *Climate and Atmospheric Deposition Studies in Forests* 19, pp. 197–209.

Gruca-Królikowska, Sylwia; Wacławek, Witold 2006: Metals in the environment. Part 2. Effect of heavy metals on plants. *Chemistry-Didactics-Ecology-Metrology* 11(1–2), pp. 41–56. URL: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-efc9e9ab-613b-4409-a468-c7c303fff07a (accessed on: 10.02.2024).

Gworek, Barbara; Kwasowski, W. 2001: Influence of motorization on an environment. [In:] Barbara Gworek, Andrzej Mocka (eds.), *Obieg pierwiastków w przyrodzie. Monografia*. Vol 1. Warszawa: Instytut Ochrony Środowiska. ISBN 8385805761, pp. 39–48.

Hjőrtenkrans, David; Bergbäck, Bo; Häggerud, Agneta 2006: New metal emission patterns in road traffic environments. *Environmental Monitoring and Assessment* 117, pp. 85–98. DOI: 10.1007/s10661-006-7706-2.

Hoffman, G.; Scholl, W.; Trenkle, A. 1989: Soil pollution by motor vehicles: Lead, cadmium, de-icing salt and chlorohydrocarbons. *Environment Pollution* 19, pp. 103–108.

Hou, Shuangxing; Yuan, Lianfang; Jin, Pengpeng; Ding, Bojun; Qin, Na; Li, Li; Liu, Xuedong; Wu, Zhongliang; Zhao, Gang; Deng, Yanchun 2013: A clinical study of the effects of lead poisoning on the intelligence and neurobehavioral abilities of children. *Theoretical Biology and Medical Modelling* 10(13), pp. 1–9. DOI: 10.1186/1742-4682-10-13.

Inaba, Takeya; Kobayashi, Etsuko; Suwazono, Yasushi; Uetani, Mirei; Oishi, Mitsuhiro; Nakagawa, Hideaki; Nogawa, Koji 2005: Estimation of cumulative cadmium intake causing Itai–itai disease. *Toxicology Letters* 159(2), pp. 192–201. DOI: 10.1016/j.toxlet.2005.05.011.

Isinkaralar, Oznur; Świsłowski, Paweł; Isinkaralar, Kaan; Rajfur, Małgorzata 2024: Moss as a passive biomonitoring tool for the atmospheric deposition and spatial distribution pattern of toxic metals in an industrial city. *Environmental Monitoring and Assessment* 196(513). DOI: 10.1007/s10661-024-12696-x.

Jankaitė, Audronė; Baltrėnas, Pranas; Kazlauskienė, Agnė 2008: Heavy metal concentrations in roadside soils of Lithuania's highways. *Geologija* 50(4), pp. 237–245. DOI: 10.2478/v10056-008-0049-7.

Jędryka, Michał 2020: *Ołowiane dzieci. Zapomniana epidemia*. Warszawa: Wydawnictwo Krytyki Politycznej. ISBN 978-83-66586-05-5, 256 pp.

Jomova, Klaudia; Alomar, Suliman; Nepovimova, Eugenie; Kuca, Kamil; Valko, Marian 2024: Heavy metals: toxicity and human health effects. *Archives of Toxicology*, pp. 1–57. DOI: 10.1007/s00204-024-03903-2.

Kabata-Pendias, Alina; Pendias, Henryk 1999: *Biogeochemia pierwiastków śladowych*. Warszawa: PWN. ISBN 8301128232, 400 pp.

Kaczyńska, Agata; Zajączkowski, Miłosz; Grzybiak, Marek 2015: Cadmium toxicity in plants and humans. *Annales Academiae Medicae Gedanensis* 45, pp. 65–70. URL: https://ppm.edu.pl/info/article/GUMaa6e3c724cdd42e1a0667e7e257c3240/ (accessed on: 26.04.2024).

Karbowska, Bożena 2016: Presence of thallium in the environment: sources of contaminations, distribution and monitoring methods. *Environmental Monitoring and Assessment* 188(640). DOI: 10.1007/s10661-016-5647-y.

Korzeniowska, Joanna 2023: Heavy metal content in the soil along the road no. 7 near Chyżne. *Atmosphere* 14(1). DOI: 10.3390/atmos14010002.

Korzeniowska, Joanna; Krąż, Paweł 2020: Heavy metals content in the soils of the Tatra National Park near lake Morskie Oko and Kasprowy Wierch – A case study (Tatra Mts, Central Europe). *Minerals* 10(12), 1120, 14 pp. DOI: 10.3390/min10121120.

Korzeniowska, Joanna; Krąż, Paweł; Dorocki, Sławomir 2021: Heavy metal content in the plants (Pleurozium schreberi and Picea abies) of environmentally important protected areas of the Tatra National Park (the Central Western Carpathians, Poland). *Minerals* 11, 1231. DOI: 10.3390/min11111231.

Korzeniowska, Joanna; Panek, Ewa 2008: Heavy metal concentrations in dandelion Taraxacum officinale alongside the road of various traffic density in the Podhale Region. *Polish Journal Environmental Studies* 17(3A), pp. 303–306.

Korzeniowska, Joanna; Panek, Ewa 2019: Trace metal concentrations in Pleurozium schreberi and Taraxacum officinale along the road no. 7. *Ecological Chemistry and Engineering S* 26(4), pp. 651–663. DOI: 10.1515/eces-2019-0047.

Korzeniowska, Joanna; Panek, Ewa; Baran, Agnieszka 2014: Testing of selected phytoindicators for assessment of trace metals (Cd, Cr, Cu, Ni, Pb and Zn) traffic pollution along the road Cracow–Zakopane. *Logistyka* 4, pp. 4486–4495. URL: https://www.academia.edu/29614332/Testing_of_Selected_Phytoindicators_for_Assessment_of_Trace_Metals_Cd_Cr_Cu_Ni_Pb_and_Zn_Traffic_Pollution_Along_The_Road_Cracow_Zakopane (accessed on: 10.01.2024).

Lagerweff, John; Specht, A.W. 1970: Contamination of roadside soil and vegetation with cadmium, nickel, lead and zinc. *Environmental Science & Technology* 4(7), pp. 583–586. DOI: 10.1021/es60042a001.

Laschober, Christian; Limbeck, Andreas; Rendl, Josef; Puxbaum, Hans 2004: Particulate emissions from on-road vehicles in the Kaisermühlen-tunnel (Vienna, Austria). *Atmospheric Environment* 38, pp. 2187–2195. DOI: 10.1016/j.atmosenv.2004.01.017.

Lindgren, Åsa 1996. Asphalt wear and pollution transport. *Science of The Total Environment* 189–190, pp. 281–186. DOI: 10.1016/0048-9697(96)05220-5.

Maciejewska, Alina; Kwiatkowska-Malina, Jolanta 2001: Contamination of soil with heavy metals along highways as well as In the city of Warsaw. [In:] Barbara Gworek, Andrzej Mocka (eds.), *Obieg pierwiastków w przyrodzie. Monografia.* Vol. 1. Warszawa: Instytut Ochrony Środowiska. ISBN 8385805761, pp. 49–54.

Malczyk, Piotr; Kędzia, W. 1996: Metale ciężkie w glebach leśnych wzdłuż drogi wylotowej Bydgoszcz–Inowrocław. *Roczniki Gleboznawcze* 47(3/4), pp. 203–211.

Masoudi, Neda; Ghajar, Mojtaba; Bahmanyar, M.A. 2012: Distribution of lead, cadmium, copper and zinc in roadside soil of Sari-Ghaemshahr road, Iran. *African Journal of Agricultural Research* 7(2), pp. 198–204. DOI: 10.5897/AJAR11.1771.

Mitra, Saikat; Chakraborty, Arka J.; Tareq, Abu M.; Emran, Talha B.; Nainu, Firzan; Khusro, Ameer; Idris, Abubakr M.; Khandaker, Mayeen U.; Osman, Hamid; Alhumaydhi, Fahad A.; Simal-Gandara, Jesus 2022: Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University – Science* 34(3), pp. 101865. DOI: 10.1016/j.jksus.2022.101865.

Monaci, Fabrizio; Moni, Fahmida; Lanciotti, Eudes; Grechi, Daniele; Bargagli, Roberto 2000: Biomonitoring of airborne metals in urban environments: new tracers of vehicle emission, in place of lead. *Environmental Pollution* 107(3), pp. 321–327. DOI: 10.1016/S0269-7491(99)00175-X.

Motto, Harry; Daines, Robert; Chilko, Daniel; Motto, Carlotta 1970: Lead in soils and plants. Its relationship to traffic volume and proximity to highways. *Environmental Science & Technology* 4, pp. 231–237. DOI: 10.1021/es60038a009.

Ociepa-Kubicka, Agnieszka; Ociepa, Ewa 2012: Toxic effects of heavy metals on plants, animals and humans. *Inżynieria i Ochrona Środowiska* 15(2), pp. 169–180. URL: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-LODD-0002-0015 (accessed on: 24.04.2024).

Onyari, John; Wandiga, S.; Njenga, G.; Nyatebe, J. 1991: Lead contamination in street soils of Nairobi City and Mobasa Island, Kenya. *Bulletin of Environmental Contamination and Toxicology* 46, pp. 782–789. DOI: 10.1007/BF01689968.

Panek, Ewa; Zawodny, Zbigniew 1993: Trace metals in the roadside mountain soils of Sierra Nevada, Spain. *Environmental Geochemistry and Health* 15(4), pp. 229–235. DOI: 10.1007/BF00146746.

Pierre, Tatiana; Dias, Lúcia; Maia, Sandra; Curtius, Adilson 2004: Determination of Cd, Cu, Fe, Pb and Tl in gasoline as emulsion by electrothermal vaporization inductively coupled plasma mass spectrometry with analyte addition and isotope dilution calibration techniques. *Spectrochimica Acta Part B: Atomic Spectroscopy* 59, pp. 551–558. DOI: 10.1016/j.sab.2003.12.025.

Piron-Frenet, Maryvonne; Bureau, F.; Pineau, Alain 1994: Lead accumulation in surface roadside soil. Its relationship to traffic density and meteorological parameters. *Science of The Total Environment* 144(1–3), pp. 297–304. DOI: 10.1016/0048-9697(94)90449-9.

Popek, Robert; Łukowski, Adrian; Bates, Christopher; Oleksyn, Jacek 2017: Accumulation of particulate matter, heavy metals, and polycyclic aromatic hydrocarbons on the leaves of Tilia cordata Mill. in five Polish cities with different levels of air pollution. *International Journal of Phytoremediation* 19(12), pp. 1134–1141. DOI: 10.1080/15226514.2017.1328394.

Radziemska, Maja; Mazur, Zbigniew; Bes, Agnieszka; Majewski, Grzegorz; Gusiatin, Zygmunt M.; Brtnicky, Martin 2019: Using mosses as bioindicators of potentially toxic element contamination in ecologically valuable areas located in the vicinity of a road: a case study. *International Journal of Environmetal Research and Public Health* 16, pp. 3963. DOI: 10.3390/ijerph16203963.

Roszyk, Eligiusz; Roszykowa, Stefania 1975: Ołów w glebach i roślinach w pobliżu dróg na terenie Wrocławia. *Roczniki Gleboznawcze* 26(1), pp. 177–185.

Samecka-Cymerman, Aleksandra; Kolon, Krzysztof; Kempers, Alexander J. 2011: Taxus baccata as a bioindicator of urban environmental pollution. *Polish Journal of Environmental Studies* 20(4), pp. 1021–1027. URL: https://www.pjoes.com/pdf-88647-22506?filename=22506.pdf (accessed on: 17.02.2024).

Schröder, Winfried; Pesch, Roland; Englert, Cordula; Harmens, Harry; Suchara, Ivan; Zechmeister, Harald; Thöni, Lotti; Maňkovská, Blanka; Jeran, Zvonka; Grodzinska, Krystyna; Alber, Renate 2008: Metal accumulation in mosses across national boundaries: Uncovering and ranking causes of spatial variation. *Environmental Pollution* 151, pp. 377–388. DOI: 10.1016/j.envpol.2007.06.025.

Sederholm, Bror 2001: *Klassificering av korrosiviteten hos olika bromiljoer genom mätning av korrosionshastigheten hos kolstal och zink*. Report 2001:1. Stockholm: Swedish Corrosion Institute.

Skorbiłowicz, Mirosław; Skorbiłowicz, Elżbieta; Rogowska, Weronika 2021: Heavy metal concentrations in roadside soils on the Białystok–Budzisko route in Northeastern Poland. *Minerals* 11, pp. 1290. DOI: 10.3390/min11111290.

Słowik, Tomasz; Piekarski, Wiesław; Tarasińska, Joanna 2006: Analiza statystyczna wpływu odległości i głębokości poboru próbek od drogi na zawartość niektórych jonów metali ciężkich w glebie. *Inżynieria Rolnicza* 6(81), pp. 275–283. URL: https://bibliotekanauki.pl/articles/290566 (accessed on: 14.01.2024).

Smith, William H. 1976: Lead contamination of the roadside ecosystem. *Journal of the Air Pollution Control* 26(8), pp. 753–765. DOI: 10.1080/00022470.1976.10470310.

Szarek-Łukaszewska, Grażyna; Grodzińska, Krystyna; Braniewski, Stanisław 2002: Heavy metal concentration in the moss Pleurozium schreberi in the Niepołomice forest, Poland: changes during 20 years. *Environmental Monitoring and Assessment* 79, pp. 231–237. DOI: 10.1023/a:1020226526451.

Świetlicki, Erik; Puri, Sanjiv; Hansson, Hans-Christen; Edner, Hans 1996: Urban air pollution source apportionment using a combination of aerosol and gas monitoring techniques. *Atmospheric Environment* 30, pp. 2795–2809. DOI: 10.1016/1352-2310(95)00322-3.

Trojanowska, Marzena; Świetlik, Ryszard 2012: Heavy metals cadmium, nickel and arsenic environmental inhalation hazard of residents of Polish cities. *Environmental Medicine* 15(2), pp. 33–41. URL: https://www.environmed.pl/pdf-114524-43932?filename=Heavy%20metals%20cadmium_.pdf (accessed on: 22.04.2024).

Trzaskoś, Maria; Dzida, Małgorzata 1995: Metale ciężkie w glebie na łąkowo-pastwiskowych terenach przyległych do autostrady. *Zeszyty Problemowe Postępów Nauk Rolniczych* 421a, pp. 361–365.

Turer, Dilek 2005: Effect of non-vehicular sources on heavy metal concentrations of roadside soils. *Water, Air and Soil Pollution* 166, pp. 251–264. DOI: 10.1007/s11270-005-7378-5.

Viard, Bénédicte; Pihan, François; Promeyrat, Sandrine; Pihan, Jean-Claude 2004: Integrated assessment of heavy metal (Pb, Zn, Cd) highway pollution: bioaccumualtion in soil, Graminaceae and land snails. *Chemosphere* 55, pp. 1349–1359. DOI: 10.1016/j.chemosphere.2004.01.003.

Wang, Ya-Fen; Huang, Kuo-Lin; Li, Chun-Teh; Mi, Hsiao-Hsuan; Luo, Jih-Haur; Tsai, Perng-Jy 2003: Emissions of fuel metals content from diesel vehicle engine. *Atmospheric Environment* 37(33), pp. 4637–4643. DOI: 10.1016/j.atmosenv.2003.07.007.

Weckwerth, Gerd 2001: Verification of traffic emitted aerosol components in the ambient air of Cologne (Germany). *Atmospheric Environment* 35, pp. 5525–5536. DOI: 10.1016/S1352-2310(01)00234-5.

Werkenthin, Moritz; Kluge, Björn; Wessolek, Gerd 2014: Metals in European roadside soils and soil sollution – A review. *Environmental Pollution* 189, pp. 98–110. DOI: 10.1016/j.envpol.2014.02.025.

Whiteley, Jason D.; Murray, Francis 2003: Autocatalyst-derived platinum, palladium and rhodium (PGE) in infiltration basin and wetland sediments receiving urban runoff. *Science of the Total Environment* 317, pp. 121–135. DOI: 10.1016/j.scitotenv.2004.09.030.

Zechmeister, Harald 1995: Correlation between altitude and heavy metal deposition in the Alps. *Environmental Pollution*, pp. 89: 73–80. DOI: 10.1016/0269-7491(94)00042-C.

Zechmeister, Harald; Hohenwallner, Daniela; Riss, Alarich; Hanus-Illnar, Andrea 2005: Estimation of element deposition derived from road traffic sources by using mosses. *Environmental Pollution* 138, pp. 238–249. DOI: 10.1016/j.envpol.2005.04.005.

Zhang, Xiuwu; Yang, Linsheng; Li, Yonghua; Li, Hairong; Wang, Wuyi; Ye, Bixiong 2012: Impacts of lead/zinc mining and smelting on the environment and human health in China. *Environmental Monitoring and Assessment* 184(4), pp. 2261–2273. DOI: 10.1007/s10661-011-2115-6.