



Measurement report: Seasonal trends and chemical speciation of chromium(III/VI) in different fractions of urban particulate matter – a case study of Radom, Poland

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Abstract. The paper assesses chromium occurrence in urban particulate matter – PM₁₀, PM_{2.5}, PM₁, and PM_{0.25} – over a calendar year. The seasonality of both pseudo-total chromium content and its valence speciation are studied. Airborne aerosol was sampled in the city of Radom (Poland) using a Hi-Flow MOUDI model 130 cascade impactor from Copley. Cr_{tot} concentrations in the PM fractions investigated ranged from 0.08 to 4.09 ng m⁻³. The results point to a seasonality of Cr_{tot} concentration changes in PM. The concentration of Cr_{tot} in PM₁₀ was maximum in winter (2.23 ± 0.53 ng m⁻³ on average) and averaged 1.71 ± 0.83 ng m⁻³ in the whole measurement period. The average Cr(VI) concentration did not exceed 0.40 ng m⁻³ and was maximum in winter, too (max 1.354 ng m⁻³). The Cr(VI) share in PM in the particular seasons varied from a low in summer (9.1 % of Cr_{tot}) to a high in winter (40 % of Cr_{tot}). The carcinogenic risk for the urban residents based on the Cr(VI) concentration in PM₁₀ was below the US Environmental Protection Agency (EPA) threshold for significant risk (between 1 × 10⁻⁶ and 1 × 10⁻⁴) and amounted to between 1.11 × 10⁻⁶ and 5.78 × 10⁻⁶ for children and from 3.69 × 10⁻⁶ to 1.92 × 10⁻⁵ for adults. The non-carcinogenic health risk caused by the presence of Cr_{tot} was also lower than the safe level of 1 – the hazard quotient (HQ) values for both adults and children ranged from 1.32 × 10⁻² to 3.92 × 10⁻². The studies presented in the paper fill the research gap of Cr_{tot} and Cr(VI) measurements in particulate matter of different sizes in the air of a medium-sized city in central Poland.

1 Introduction

Air quality has continued to deteriorate lately, especially in urban and industrial areas. Particulate matter (PM) is a major pollutant whose substantial quantities are emitted into the air, adversely affecting both the climate and all parts of the environment (Fang et al., 2005; Wagner et al., 2008; Arhami et al., 2017). Particulate matter, considered one of the most dangerous environment pollutants (Park et al., 2009; Waheed et al., 2011; Izhar et al., 2016), has a complex and heterogeneous composition, dependent on the season, source of emissions, and weather conditions. Knowledge of the composition, concentration, and sources of particulate matter suspended in the air is of great importance to resi-

dents of urban–industrial areas, since breathing these particles can increase mortality or morbidity due to respiratory and pulmonary conditions. The particulate matter's coarse fraction (2.5–10 µm) is assumed to be of natural origin, while the fine fraction (0.1–2.5 µm, especially the particles of less than 1 µm) mostly comes from anthropogenic processes (Nocoń et al., 2018). The distribution of particulate matter particle sizes and their loading with different chemical compounds determine the aerosol's effect on human health and the environment. Particulate matter with grain diameters below 2.5 µm is particularly dangerous to living organisms as it penetrates alveoli pulmonis and thence potentially enters the bloodstream (Wagner et al., 2008; Pan et al., 2015). For this

reason, this particulate matter fraction is the most common object of environmental studies (Feng et al., 2009; Rogula-Kozłowska et al., 2013a; Zajusz-Zubek and Mainka, 2015; Li et al., 2016; Sah et al., 2019; Xie et al., 2019; Anake et al., 2020; Wu et al., 2021; Wang et al., 2023) (Table S1 in the Supplement). Researchers frequently examine PM_{10} too (e.g., Richter et al., 2007; Catrambone et al., 2013; Huang et al., 2014a; Pandey et al., 2017; Rubio et al., 2018; Conca et al., 2020). The finer fractions, e.g., PM_1 , are investigated far more seldom (Rogula-Kozłowska et al., 2013b; Zajusz-Zubek et al., 2015; Zajusz-Zubek et al., 2017). Scientists rarely assay two (PM_{10} and $PM_{2.5}$ in Canepari et al., 2009; Dos Santos et al., 2009; Jan et al., 2018; Gunchin et al., 2021) or more grain fractions (PM_1 , $PM_{2.5}$, and PM_{10} in Samara and Voutsas, 2005; Rogula-Kozłowska et al., 2013b; Rogula-Kozłowska, 2015) in parallel.

Various organic and inorganic compounds are also transported together within the particulate matter, some of which are toxic. Special attention is paid to heavy metals (Wagner et al., 2008; Pan et al., 2015; Samara et al., 2016) that may contribute to oxidative DNA damage and in effect cause carcinogenic lesions (Somers, 2011; IARC, 2012; Arhami et al., 2017). Chromium occurs in the air in two valence states – Cr(III) and Cr(VI) – which greatly vary in their physical and chemical properties and toxicity. Chromium(III) is a microelement necessary for living organisms, whereas chromium(VI) is toxic and classified as a carcinogen (Katz, 1991; Barceloux and Barceloux, 1999; Kotaś and Stasicka, 2000). Epidemiological research has shown a close connection between chromium(VI) exposure and lung cancer (IARC, 2012). Chromium presence in air has been studied a lot given its toxicity (Nriagu and Nieboer, 1988; Nusko and Heumann, 1997; Świetlik et al., 2011; Tirez et al., 2011; Torkmahalleh et al., 2013; Huang et al., 2014a, b; Kang et al., 2016; Widziewicz et al., 2016; Molik et al., 2018; Nocoń et al., 2018). Regionally, natural sources account for 30 %–40 % of total chromium emissions (Pacyna, 1986; Kotaś and Stasicka, 2000). Authors report that fuel combustion in stationary sources is the chief source of Cr emissions in Europe and more than a half of all anthropogenic sources (Pacyna et al., 2007). In Poland, the burning of fuels is responsible for 60 % of all the Cr emissions to the environment (Ministry of Climate and Environment, 2022).

Nriagu et al. (1988) report an average atmospheric concentration of Cr starting from 1 ng m^{-3} in rural areas and increasing to 10 ng m^{-3} in polluted urban areas. Świetlik and Trojanowska (2022) review the average Cr in the urban air of diverse regions globally. Given the commonly encountered pollution levels worldwide, Cr_{tot} in the urban air averaged $13 \pm 2 \text{ ng m}^{-3}$, whereas Cr_{tot} in heavily polluted areas was many times higher, $350 \pm 70 \text{ ng m}^{-3}$ (Świetlik and Trojanowska, 2022). Average Cr(VI) concentration is far lower – 0.5 ng m^{-3} (Seinfeld and Pandis, 2006). It is normally higher close to industrial sources (Proctor et al., 2021). According to the US Environmental Protection Agency (EPA) National

Air Toxics Assessment in 2017, the median, mean, and maximum Cr(VI) concentrations in the United States were 0.03, 0.1, and 3.18 ng m^{-3} , respectively (Proctor et al., 2021).

To assure legal protection against atmospheric chromium in Poland, reference values were set as follows: 20 and $2.5 \text{ } \mu\text{g m}^{-3}$ for Cr(III) and Cr(VI) compounds and 4.6 and $0.4 \text{ } \mu\text{g m}^{-3}$ for Cr(VI) over 1 h and 1 year, respectively (Regulation of the Minister of the Environment, 2010).

Although chromium occurrence in urban air has been extensively studied and a range of publications have appeared recently (Catrambone et al., 2013; Widziewicz et al., 2016; Nocoń et al., 2018), investigations of total Cr occurrence and its valence speciation in particulate matter of different particle sizes are still limited. We have only examined Cr(III/VI) speciation in total suspended particulate (TSP) matter before (Świetlik et al., 2011). Our current study is designed to (i) assess chromium occurrence and speciation in urban particulate matter fractions of varied particle sizes (PM_{10} , $PM_{2.5}$, PM_1 , $PM_{0.25}$); (ii) examine the fluctuations and seasonality of Cr concentrations over 1 year; and (iii) estimate health risk caused by inhalation exposure to airborne Cr in two different exposure schemes – (1) the risk that comes from the Cr_{tot} ambient concentrations and (2) the risk that comes exclusively from Cr(VI) species. Radom is an interesting location for such research as the atmospheric chromium levels are a result not only of an aged urban structure relying on private hard-coal heating, considerable road transit, and the operation of multiple metalworking factories, but also of tanneries that have been clustered in the region for more than 70 years.

These are the results of the first-ever hexavalent chromium (Cr(VI) measurements in the particulate matter of different sizes in the air of a medium-sized city in central Poland.

2 Experimental

2.1 Sampling area and the collection of PM samples

The airborne particulate matter was sampled in Radom, a medium-sized town (a population of 196 000, an area of 112 km^2) in central Poland, 100 km south of Warsaw. The local sources of chromium emissions are road traffic, coal burning in homes, coal-fired municipal heating plants, tanneries, and multiple metalworks. The sampling points of the suspended airborne particulate matter were located on the University of Radom premises. The area is adjacent to a housing estate with a prevalence of private houses heated with traditional coal furnaces, but it is not subject to the immediate impact of local sources of industrial emissions or streets with heavy traffic.

The airborne particulate matter was sampled in spring (variable weather: cool, sunny, wet; heating campaign until the middle of April), summer (sunny, warm weather), autumn (variable weather: sunny–warm or cool–wet; heating campaign from the middle of October), and winter (cold,

overcast, and wet weather; heating campaign). Averaged weather conditions for each weekly sampling cycle are presented in Table S2. A Hi-Flow MOUDI model 130 cascade impactor from Copley was used, positioned at a height of 1.5 m above the ground level. It enabled the separation of four grain fractions of atmospheric dust: PM_{10} , $PM_{2.5}$, PM_1 , and $PM_{0.25}$. The grain fractions of atmospheric particulate matter were sampled from February 2020 to April 2021 in 29 weekly cycles. A total of 116 samples were collected. The sampling time averaged $70 \text{ h} \pm 4 \text{ h}$. The sampling rate was maintained at approximately $6 \text{ m}^3 \text{ h}^{-1}$. The airborne particulate matter was collected on cellulose filters (POCH). The filters were weighed before and after sampling; the precision was 0.01 mg (Microbalance MX5 Mettler Toledo) in a temperature- and relative-humidity-controlled environment ($20 \pm 3^\circ\text{C}$ and $50 \pm 10\%$, respectively). Then the filters were stored in a plastic CD case. Before the analysis, the filters with the deposit were sectioned into four equal parts. The samples were only withdrawn when there was no precipitation.

2.2 The determination of the contents of the particular airborne particulate matter fractions

The concentrations of the specific particulate matter fractions were calculated by dividing the difference between filter weight prior to and following the exposure by the mean airflow at the time of atmospheric aerosol sampling.

2.3 The determination of pseudo-total chromium

In order to assay Cr_{tot} by means of graphite furnace atomic absorption spectrometry (GF-AAS), the particulate matter samples collected on filters were mineralized using microwave energy. A quarter of the deposited filter was placed in a 100 mL Teflon vessel with 5 mL 65 % HNO_3 and 3 mL 30 % H_2O_2 . The samples were digested in a microwave oven (Milestone MLS 1200 Mega) according to the following program: (1) 6 min, 250 W; (2) 1 min, 0 W; (3) 6 min, 400 W; (4) 6 min, 650 W; (5) 6 min, 250 W; and (6) 5 min, ventilation. After the digestion, the solutions were filtered through a $0.45 \mu\text{m}$ Millex-HV syringe filter (Millipore), transferred into a polypropylene volumetric flask, and diluted to 25.0 mL with deionized water.

A Perkin-Elmer 3100 AAS graphite furnace system equipped with HGA 600 and an AS-60 autosampler were used for the determination of pseudo-total chromium concentration. The standard chromium solution (J.T. Baker Inc.) at a concentration of $1000 \mu\text{g mL}^{-1}$ served to calibrate the device. The limit of detection (LOD) (instrumental) was found to be $0.2 \mu\text{g L}^{-1}$ of Cr or 0.03 ng m^{-3} expressed as the concentration of Cr in the air. The quality of the chromium results was characterized with a recovery test of the CRM BCR-701 (river sediment). It was found to be $259 \pm 18 \text{ mg kg}^{-1} Cr_{\text{tot}}$

($n = 3$), while the certified value is $272 \pm 20 \text{ mg kg}^{-1}$; hence the recovery for extractable Cr was 95.2 %.

2.4 The determination of chromium(VI)

The filters with the collected airborne particulate matter were extracted as per a modified US EPA 3060A standard by means of alkaline digestion (US EPA, 1996). The modification was necessary given the low chromium(VI) contents in the suspended particulate matter samples. For this purpose, a quarter of the exposed filter was placed in the Teflon vessel, and 5 mL of 0.056 M Na_2CO_3 / 0.08 M NaOH was added and extracted in a microwave oven, MLS 1200 Mega (3 min, 400 W). The leachates were then centrifuged (MPW 342) and filtered through a $0.45 \mu\text{m}$ Millex-HV syringe filter (Millipore) into 10 mL test tubes.

Cr(VI) in the leachates was determined using the technique of catalytic cathodic stripping voltammetry with the adsorption of Cr(III)–DTPA complexes (CCSV–DTPA) (Li and Xue, 2001). The voltammograms were recorded with a trace analyzer, model 394, connected to a hanging mercury drop working electrode, model 303A SMDE (EG&G Princeton Applied Research Electrochemical).

The supporting electrolyte (5 mL water, 500 μL saturated solution of KNO_3 , 200 μL 0.1 M AcONa, 200 μL 0.1 M DTPA) and a 100 μL sample of Cr(VI) extract were transferred into an electrochemical cell, pH was adjusted to 6.00 ± 0.05 , and the solution was purged for 4 min with high-purity argon. Deposition on a mercury drop was carried out for 60 s at -0.95 V . Then the stirring was discontinued and an equilibration time of 10 s was allowed. The differential pulse scan was carried out from -0.95 to -1.65 V ; the pulse height was 50 mV and the rate 6 mV s^{-1} . The peak corresponding to the reduction of the adsorbed Cr(III)–DTPA complex appeared at -1.20 to -1.30 V . The chromium(VI) concentration was assayed using the technique of double spike–standard addition (2–10 μL , depending on the expected analyte concentration) with a concentration of $0.2 \text{ mg L}^{-1} Cr(VI)$. LOD (instrumental) was found to be $2.9 \mu\text{g L}^{-1}$ or 0.010 ng m^{-3} expressed as the concentration of Cr(VI) in the air. CMR061-030 (sandy loam) was used as the certified reference material to validate the analytical procedure. It was found to equal $239.3 \text{ mg kg}^{-1} Cr(VI)$ ($n = 3$), and the certified value was $241.00 \pm 9.00 \text{ mg kg}^{-1}$, hence the recovery of 99.3 %. The recovery is high enough (Cr – 95.2 %; Cr(VI) – 99.3 %) and our results are not related to the enforcement analysis, which is why the data presented in this report are uncorrected for sample recovery efficiency.

3 Results and discussion

3.1 The mass concentration of PM

The concentrations of the following particulate matter fractions were assayed: PM_{10} , $PM_{2.5}$, PM_1 , and $PM_{0.25}$. The

Table 1. The concentrations of PM in the urban atmosphere.

	PM ₁₀ [μg m ⁻³]	PM _{2.5} [μg m ⁻³]	PM ₁ [μg m ⁻³]	PM _{0.25} [μg m ⁻³]
Spring				
Min	5.2	3.1	2.4	1.3
Max	62.7	48.6	36.6	20.6
Mean	25	19	15	7.5
SD	21	17	13	7.2
Summer				
Min	22.4	16.9	12.7	6.6
Max	43.3	33.1	22.9	12.0
Mean	28.6	22.1	16.3	8.3
SD	7.9	6.2	4.1	2.0
Autumn				
Min	31.1	23.6	17.9	7.6
Max	68.2	59.2	45.1	27.6
Mean	53	44	34.3	15.9
SD	10	10	8.3	5.5
Winter				
Min	23.1	19.0	15.4	7.0
Max	60.9	51.8	45.4	24.2
Mean	45	39	32	15.8
SD	13	12	10	6.0

World Health Organization (WHO) claims that there is no evidence of a safe exposure level or threshold below which there are no adverse effects of exposure to particulate matter (WHO, 2013).

In Radom, the PM₁₀ concentration ranged widely from 5.2 to 68.2 μg m⁻³ (40 ± 17 μg m⁻³ on average). The PM_{2.5} concentrations were lower, from 3.1 to 59.2 μg m⁻³ (33 ± 15 μg m⁻³ on average). The concentrations of finer particulate matter were in the following ranges: PM₁ from 2.4 to 45.4 μg m⁻³ (26 ± 13 μg m⁻³ on average) and PM_{0.25} from 1.3 to 27.6 μg m⁻³ (12.6 ± 6.6 μg m⁻³ on average) (Table 1). Comparable concentrations of urban PM_{2.5} have been reported by other authors, e.g., Budapest (Hungary) 23 μg m⁻³, Istanbul (Türkiye) 40 μg m⁻³ (Szigeti et al., 2013), Tehran (Iran) 33 ± 11 μg m⁻³ (Arhami et al., 2017), and Katowice (Poland) 31 μg m⁻³ (Rogula-Kozłowska et al., 2013a).

These concentrations were far lower than those reported in our earlier study of TSP matter – from 36 to 282 μg m⁻³, average 110 μg m⁻³ (Świetlik et al., 2011).

The average PM₁₀ and PM_{2.5} concentrations in autumn (53 ± 10; 44 ± 10 μg m⁻³) and winter (45 ± 13; 39 ± 12 μg m⁻³) were in excess of the national (40 and 20 μg m⁻³, respectively) and European (40 and 25 μg m⁻³, respectively) air quality standards (Regulation of the Minister of the Environment, 2012; Directive 2024/2881). A relatively high share of the PM_{2.5} respirable fraction relative

to PM₁₀ was found in the measurement period, 81 % on average. Zajusz-Zubek and Mainka (2015) report a similar share of PM_{2.5} (88 %), although the particulate matter concentrations measured by them were somewhat lower: PM₁₀ 25.58 μg m⁻³ and PM_{2.5} 22.93 μg m⁻³ (PM₁ concentration – 18.44 μg m⁻³) (Zajusz-Zubek and Mainka, 2015). The literature states PM_{2.5} in most European locations constitutes 50 % to 70 % of PM₁₀ (WHO, 2013).

Seasonality had a great influence on the concentrations of particulate matter suspended in urban air (Fig. S1 in the Supplement). During the winter season, the concentrations of each fraction were nearly double those in summer. In the autumn, however, slightly higher concentrations of PM₁₀, PM_{2.5}, and PM₁ were recorded compared to the winter season (on average by 12 %). Only PM_{0.25} concentrations were steady in autumn and winter and stood at 15.9 ± 5.5 and 15.8 ± 6.0 μg m⁻³, respectively (Table 1).

The high airborne particulate matter concentrations in the urban area investigated during the winter season suggest municipal emissions including coal burning in household furnaces were the chief source of particulate matter pollution.

The higher suspended particulate matter concentrations in the winter season have also been found by others, e.g., Rogula-Kozłowska et al. (2013a) report PM_{2.5} concentrations in Zabrze and Katowice (Poland) that usually range between 10 and 20 μg m⁻³ and are far greater in winter, from 50 to 110 μg m⁻³ (Rogula-Kozłowska et al., 2013a). The higher suspended particulate matter concentrations in winter (pointing to a greater share of fuel combustion sources) have been noted by other authors, too (Krzemińska-Flowers et al., 2006; Widziewicz et al., 2016).

It should be pointed out that particulate matter pollution has been substantially reduced in Poland in recent years, owing to the application of state-of-the-art, efficient, and environmentally friendly technological solutions. The continuing modernization of the energy, heating, and industrial sectors – such as the EU Clean Air Program (since 2018) and provincial anti-smog resolutions (since 2017) – along with improved fuel quality regulations (established by the Minister of Industry and the Minister of Climate and Environment regarding the quality of solid fuels since 2018), has led to a consistent reduction in the amount of particulate matter pollution emitted into the air each year (EU Clean Air Program, 2025; Regulation of the Minister of Industry and the Minister of Climate and Environment, 2022).

3.2 Chromium concentration

Given the environmental aspect of this study, the environmentally available chromium content Cr_{tot} (pseudo-total concentration of Cr) in the PM samples was assayed. All the results for Cr_{tot} concentrations in PM₁₀, PM_{2.5}, PM₁, and PM_{0.25} are listed in Table S3.

Cr_{tot} concentrations in the particulate matter fractions studied ranged from 0.08 to 4.09 ng m⁻³. Like in the case

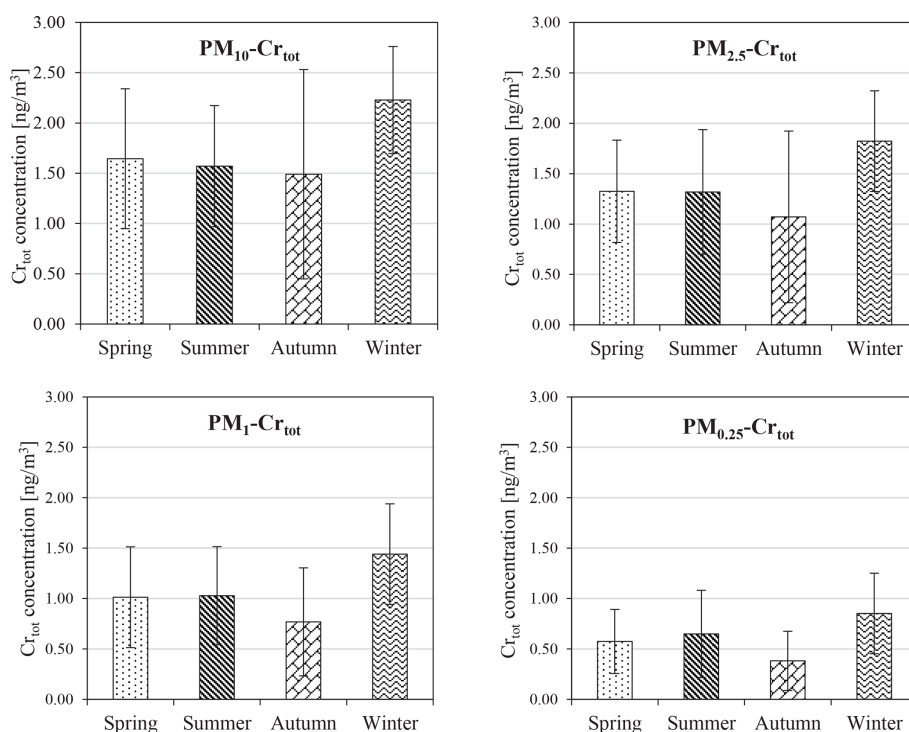


Figure 1. The concentrations of pseudo-total chromium in PM₁₀, PM_{2.5}, PM₁, and PM_{0.25} depending on the seasons.

of particulate matter concentrations, the results were several times lower than the chromium concentrations given in our previous work for the non-industrial zone (15 ng m^{-3} on average), when we studied TSP matter (Świetlik et al., 2011). In Poland, the concentrations of Cr in the PM, similarly to the particulate matter concentrations, decrease every year thanks to the use of state-of-the-art, efficient, and environmentally friendly technological solutions.

The results indicate a marked impact of the winter season on Cr_{tot} concentrations in all the PM fractions (Fig. 1).

The maximum Cr_{tot} concentration relating to PM₁₀ was found in winter ($2.23 \pm 0.53 \text{ ng m}^{-3}$ on average), whereas it averaged $1.71 \pm 0.83 \text{ ng m}^{-3}$ in the entire measurement period. The mean Cr_{tot} concentrations relating to PM₁₀ in Radom were similar to those determined in other cities in Europe in urban areas: Edinburgh (UK) 1.6 ng m^{-3} (Heal et al., 2005), Katowice (Poland) 2.39 ng m^{-3} (Rogula-Kozłowska, 2015), and Rome (Italy) $2\text{--}5 \text{ ng m}^{-3}$ (Catrambone et al., 2013).

The PM_{2.5} fraction contains approximately 80 % of the total chromium content. A similar correlation was observed for the PM concentration in the winter season, where 86 % of PM₁₀ was the PM_{2.5} fraction (Table 1). The PM_{2.5} fraction is assumed to be the result of emissions from anthropogenic sources (Nocoń et al., 2018). The sampling point was located near a busy street and a housing estate of single-family homes (from the west and southwest) and far away from an industrial zone (approx. 8–10 km from the south and south-

west). Considering that Radom is a city with prevailing westerly winds, especially in autumn and winter (Weather Spark, 2025), it can be supposed that municipal emissions, mainly stationary coal combustion sources, and road traffic are probably the main factors influencing the measured chromium concentrations.

Cr_{tot} concentrations in PM_{2.5}, PM₁, and PM_{0.25} were 1.38 ± 0.69 , 1.06 ± 0.55 , $0.61 \pm 0.39 \text{ ng m}^{-3}$, respectively (Table S3). The mean chromium concentrations relating to PM_{2.5} in Radom were similar to those determined in other cities in Poland and globally: Zabrze $1.7 \pm 1.9 \text{ ng m}^{-3}$ (Rogula-Kozłowska et al., 2013a), Warsaw $1.2 \pm 1.4 \text{ ng m}^{-3}$ (Majewski and Rogula-Kozłowska, 2016), Wrocław $1.6 \pm 0.8 \text{ ng m}^{-3}$ (Zwoździak et al., 2013), Łódź $2.82 \pm 0.34 \text{ ng m}^{-3}$ (PM₃, Krzemińska-Flowers et al., 2006); Budapest (Hungary) 1.4 ng m^{-3} (Muránszky et al., 2011), Istanbul (Türkiye) 2.8 ng m^{-3} (Szigeti et al., 2013), and Rome (Italy) 3.72 ng m^{-3} (Canepari et al., 2009). The concentrations are far greater in industrial areas, e.g., Guangzhou (China) 7.693 ng m^{-3} (Feng et al., 2009), Ewekoro (Nigeria) 11.4 ng m^{-3} (Anake et al., 2020), Agra (India) 19.3 ng m^{-3} (Sah et al., 2019), and Nanjing (China) 26.61 ng m^{-3} (Li et al., 2016).

In spring and summer, Cr_{tot} concentrations for the particulate matter fractions were similar and averaged: PM₁₀ – 1.64 ± 0.70 and $1.57 \pm 0.60 \text{ ng m}^{-3}$, PM_{2.5} – 1.33 ± 0.51 and $1.32 \pm 0.62 \text{ ng m}^{-3}$, PM₁ – 1.01 ± 0.50 and $1.03 \pm 0.49 \text{ ng m}^{-3}$, and PM_{0.25} – 0.57 ± 0.32 and

$0.65 \pm 0.43 \text{ ng m}^{-3}$, respectively (Table S3). They were maximum in winter: PM_{10} $2.23 \pm 0.53 \text{ ng m}^{-3}$, $\text{PM}_{2.5}$ $1.82 \pm 0.50 \text{ ng m}^{-3}$, PM_1 $1.44 \pm 0.50 \text{ ng m}^{-3}$, and $\text{PM}_{0.25}$ $0.85 \pm 0.40 \text{ ng m}^{-3}$ (Fig. 1). The higher Cr_{tot} concentrations in winter are corroborated by other authors (Krzemińska-Flowers et al., 2006; Zwoździak et al., 2013; Widziewicz et al., 2016).

Based on the differences in Cr_{tot} concentrations in the particular fractions (PM_{10} and $\text{PM}_{2.5}$; $\text{PM}_{2.5}$ and PM_1 ; PM_1 and $\text{PM}_{0.25}$), its concentrations in the fractions were calculated as follows: $\text{PM}_{2.5-10}$, $\text{PM}_{1-2.5}$, $\text{PM}_{0.25-1}$, and $\text{PM}_{0.25}$ (Table S4). Regardless of the season, Cr_{tot} content was always highest in the finest fraction, $\text{PM}_{0.25}$ (Fig. S2).

3.3 The speciation of chromium

Chromium speciation was also assayed in all the fractions of airborne particulate matter. Cr(VI), as a particularly harmful metal, is classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen (IARC, 2023). Authors have reported that most airborne Cr(VI) (60 %–70 %) comes from anthropogenic sources (e.g., metallurgy, refractory production, or chemical processing industries) (Kang et al., 2016; Wang et al., 2020). Emissions associated with solid fuel combustion are of great significance as well (Nriagu and Pacyna, 1988). Combustion processes, mostly of anthropogenic origin, or gas-to-particle conversions of atmospheric substances produce small aerosol particles, whereas larger particles are formed by mechanical processes, such as wind erosion of soil or dust emission from public traffic (Nusko and Heumann, 1997). Cr(VI) presence in Radom's airborne aerosol may be chiefly a result of municipal (fuel burning in heating plants and household furnaces) and road traffic emissions. Industrial emissions are of lesser importance as the industrial sources are located far away from the sampling points (about 8–10 km).

Cr(VI) concentrations in the urban air of Radom were quite varied and ranged from undetectable levels ($< \text{LOD}$) to 1.354 ng m^{-3} (Table S3). Average Cr(VI) concentrations did not exceed 0.400 ng m^{-3} in the entire measurement period, though, and equalled the following: PM_{10} – 0.38 ng m^{-3} ; $\text{PM}_{2.5}$ – 0.32 ng m^{-3} ; PM_1 – 0.26 ng m^{-3} ; and $\text{PM}_{0.25}$ – 0.16 ng m^{-3} . Similar Cr(VI) concentrations in airborne particulate matter are reported by other authors – Wilmington (USA) $0.5\text{--}1.0 \text{ ng m}^{-3}$ ($\text{PM}_{2.5}$) (Khlystov and Ma, 2006), New Jersey (USA) $0.86\text{--}1.56 \text{ ng m}^{-3}$ (PM_{10}) (Huang et al., 2014b), and Beijing (China) $0.006\text{--}0.266 \text{ ng m}^{-3}$ ($\text{PM}_{2.5}$) (Wang et al., 2023) – although higher concentrations are also found, e.g., the Flemish region (Belgium) $1.2\text{--}5.2 \text{ ng m}^{-3}$ (PM_{10}) (Tirez et al., 2011).

Our investigation has shown 78 %–90 % of total Cr(VI) content (depending on the season) was found in $\text{PM}_{2.5}$ (83 % on average). Like in the case of Cr_{tot} , a distinct effect of the heating in the winter season on Cr(VI) concentrations in

PM could be noted. This was true of all the grain fractions (Fig. 2).

Cr(VI) concentrations were maximum in winter (the heating campaign) and averaged the following: PM_{10} – $0.84 \pm 0.43 \text{ ng m}^{-3}$; $\text{PM}_{2.5}$ – $0.70 \pm 0.39 \text{ ng m}^{-3}$; PM_1 – $0.58 \pm 0.31 \text{ ng m}^{-3}$; and $\text{PM}_{0.25}$ – $0.36 \pm 0.21 \text{ ng m}^{-3}$. Maximum Cr(VI) concentrations in PM_{10} reached 1.354 ng m^{-3} . For the sake of legal protection against airborne chromium(VI), a reference value of $0.4 \mu\text{g m}^{-3}$ (for 1 year) was introduced in Poland (Regulation of the Minister of the Environment, 2010). The World Health Organization (WHO) recommends the baseline limit of hexavalent chromium with an excess lifetime risk (RR values) of 1 : 10 000, 1 : 100 000, and 1 : 1 000 000 to be 2.5, 0.25, and 0.025 ng m^{-3} , respectively (WHO, 2000).

Regardless of the particulate matter fraction, chromium(VI) accounted for approximately 20 % of Cr_{tot} content in the particulate matter (PM_{10} – 19.3 %; $\text{PM}_{2.5}$ – 19.9 %; PM_1 – 21.1 %; $\text{PM}_{0.25}$ – 22.4 %) during the whole measurement period (Table 2). However, Cr(VI) share in the particular seasons varied. It was minimum in summer, averaging 9.1 % and somewhat greater in spring (11.3 %), and it rose to 22.7 % (from 18.1 % to 26.9 %) in the autumn. It was maximum in winter, constituting 40 % of total chromium on average (from 37.6 % to 42.6 %). Our results are not different from those reported in the literature; e.g., Bell and Hipfner (1997) and Talebi (2003) claim that circa 20 % airborne chromium was Cr(VI), while Nusko and Heumann (1997) give approximately 30 %. Tirez et al. (2011) reported that, in the case of $\text{PM}_{2.5}$ from coal combustion, the share of Cr(VI) ranged from 6 % to 43 % of the total Cr (Tirez et al., 2011). Torkmahalleh et al. (2013) state the average Cr(VI) to total Cr ratios varied from 1 % to 30 %, whereas Kang et al. (2016) say the concentration of Cr(VI) measured accounted for 0.7 % to 9.4 % of the total chromium level, which is a low percentage compared to values in other urban areas around the world.

Cr(III) averaged 79.3 % of Cr_{tot} (Table 2). It was maximum in summer (90.9 % on average) and a little lower in spring (88.7 %). It was minimum in winter, 60.3 % of the total chromium content (Fig. S3).

Based on the difference in Cr(VI) concentrations assayed in PM_{10} , $\text{PM}_{2.5}$, PM_1 , and $\text{PM}_{0.25}$, its concentrations in $\text{PM}_{2.5-10}$, $\text{PM}_{1-2.5}$, $\text{PM}_{0.25-1}$, and $\text{PM}_{0.25}$ were calculated (Table S4). Like in the case of Cr_{tot} , regardless of the season, Cr(VI) concentrations were normally maximum in the finest fraction, $\text{PM}_{0.25}$ (Fig. S4). Some authors report that fine particulate matter, which can be carried over long distances, contains more Cr(VI) (Wang et al., 2023).

Attempts at correlating Cr_{tot} concentrations in PM_{10} with its values in finer fractions – $\text{PM}_{2.5}$, PM_1 , and $\text{PM}_{0.25}$ – brought interesting results. The coefficients of determination (R^2) are relatively high: 0.9512 (for $\text{PM}_{10}\text{--}\text{PM}_{2.5}$), 0.8678 (for $\text{PM}_{10}\text{--}\text{PM}_1$), and 0.6283 (for $\text{PM}_{10}\text{--}\text{PM}_{0.25}$), mean $R^2 = 0.8158$ (Fig. S5).

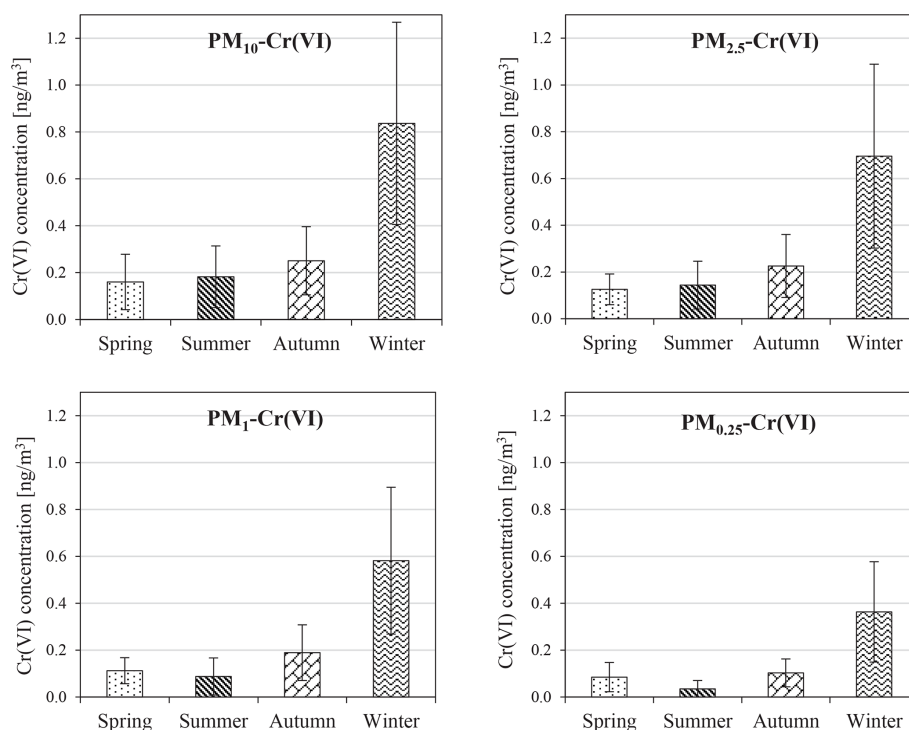


Figure 2. The concentrations of Cr(VI) in PM₁₀, PM_{2.5}, PM₁, and PM_{0.25} depending on the seasons.

Table 2. The percentage share of chromium speciation.

Season	PM ₁₀		PM _{2.5}		PM ₁		PM _{0.25}	
	Share of Cr(VI) [%]	Share of Cr(III) [%]	Share of Cr(VI) [%]	Share of Cr(III) [%]	Share of Cr(VI) [%]	Share of Cr(III) [%]	Share of Cr(VI) [%]	Share of Cr(III) [%]
Spring	9.8	90.2	9.5	90.5	11.1	88.9	14.8	85.2
Summer	11.6	88.4	10.9	89.1	8.5	91.5	5.3	94.7
Autumn	18.1	81.9	21.1	78.9	24.6	75.4	26.9	73.1
Winter	37.6	62.4	38.1	61.9	40.4	59.6	42.6	57.4
Average value	19.3	80.7	19.9	80.1	21.1	78.9	22.4	77.6

The correlation was even better for valence speciation. A clear dependence could be observed between the total Cr(VI) content in PM₁₀ and Cr(VI) content in finer fractions: PM_{2.5}, PM₁, and PM_{0.25} (Fig. S6). In this event, the coefficients of determination were greater than for Cr_{tot}: $R^2 = 0.9852$ (for PM₁₀–PM_{2.5}), 0.9715 (for PM₁₀–PM₁), and 0.9273 (and PM₁₀–PM_{0.25}), and the average R^2 was 0.9613.

3.4 The health risk of inhalation exposure to chromium

The health risk of respiratory exposure to chromium was estimated in the airborne particulate matter investigated. The model of risk assessment recommended by the US Environmental Protection Agency (US EPA, 2009) was applied. The risk for both adults and children was estimated. The exposure concentration (EC) [$\mu\text{g m}^{-3}$] of non-carcinogenic and

carcinogenic chromium was calculated according to Eq. (1):

$$EC = \frac{C_{\text{Cr}} \cdot ET \cdot EF \cdot ED}{AT_n}, \quad (1)$$

where C_{Cr} is the average concentration of Cr_{tot} or Cr(VI) in atmospheric particulate matter [$\mu\text{g m}^{-3}$], ET is exposure time [h d^{-1}], EF is exposure frequency [d yr^{-1}], ED is exposure duration [years], and AT_n is the averaging time of exposure [hours].

The acceptable carcinogenic risk ranges from 1×10^{-6} (1 per 1 000 000) to 1×10^{-4} (1 per 10 000) (US EPA, 1989). A carcinogenic risk value above the upper limit (1×10^{-4}) suggests that chromium(VI) in atmospheric particulate matter poses a substantial risk of carcinogenic effects in the future from lifetime exposure, while values below the lower limit (1×10^{-6}) do not pose a significant risk. A hazard

Table 3. Carcinogenic and non-carcinogenic risk from chromium via inhalation exposure to the airborne particles of PM₁₀.

Season	Carcinogenic risk – CR			Non-carcinogenic risk – HQ		
	Cr(VI) [ng m ⁻³]	Children	Adults	Cr _{tot} [ng m ⁻³]	Children	Adults
Average concentration of chromium in PM ₁₀ in each season						
Spring	0.1604	1.11 × 10 ⁻⁶	3.69 × 10 ⁻⁶	1.64	1.57 × 10 ⁻²	1.57 × 10 ⁻²
Summer	0.1823	1.26 × 10 ⁻⁶	4.19 × 10 ⁻⁶	1.57	1.51 × 10 ⁻²	1.51 × 10 ⁻²
Autumn	0.2508	1.73 × 10 ⁻⁶	5.77 × 10 ⁻⁶	1.38	1.32 × 10 ⁻²	1.32 × 10 ⁻²
Winter	0.8369	5.78 × 10 ⁻⁶	1.92 × 10 ⁻⁵	2.23	2.14 × 10 ⁻²	2.14 × 10 ⁻²
Av.		2.47 × 10 ⁻⁶	8.21 × 10 ⁻⁶		1.64 × 10 ⁻²	1.64 × 10 ⁻²
Maximum chromium concentration in PM ₁₀ throughout the measurement period						
	1.3544	9.24 × 10 ⁻⁶	3.12 × 10 ⁻⁵	4.09	3.92 × 10 ⁻²	3.92 × 10 ⁻²

quotient (HQ) below 1 suggests no significant risk of non-carcinogenic effects. If HQ is equal to or more than 1, the non-carcinogenic effects are possible in the future.

As recommended by the US EPA 2009 (Part F), a residential scenario could consist of inhalation exposure for up to 24 h d⁻¹ up to 350 d yr⁻¹ for 6 to 30 years. The residential exposure parameters used in this study are listed in Table S5 (US EPA, 2009; US EPA, 2014).

The non-carcinogenic health risk for chromium was evaluated by means of the hazard quotient (HQ) using Eq. (2):

$$HQ = \frac{EC}{RfC_{Cr} \cdot 1000}, \tag{2}$$

where RfC_{Cr} is the inhalation reference concentration for Cr [mg m⁻³]. Cancer risk (CR) was calculated using Eq. (3):

$$CR = EC \cdot IUR_{Cr}, \tag{3}$$

where IUR_{Cr} is the inhalation unit risk for Cr(VI) [(μg m⁻³)⁻¹]. The values of RfC_{Cr} and IUR_{Cr} were cited from the Regional Screening Level (RSL) tables for US EPA Region 9 (US EPA, 2022).

The estimated potential non-carcinogenic (HQ) and carcinogenic (CR) risks of inhalatory exposure to Cr_{tot} and Cr(VI) present in PM₁₀ for urban residents are shown in Table 3. Both were maximum in winter, when Cr_{tot} concentrations become highest. In light of the standard interpretation, however, regardless of the season, the carcinogenic risk to residents based on Cr(VI) concentration in PM₁₀ was below the US EPA threshold for significant risk (between 1 × 10⁻⁶ and 1 × 10⁻⁴) and amounted to between 1.11 × 10⁻⁶ and 5.78 × 10⁻⁶ for children and from 3.69 × 10⁻⁶ to 1.92 × 10⁻⁵ for adults. Even in the case of maximum Cr(VI) concentration in PM₁₀ during the winter season, the estimated carcinogenic risk to the population of Radom was lower than the upper limit: CR = 9.24 × 10⁻⁶ for children and CR = 3.12 × 10⁻⁵ for adults. However, although the risk of cancer in children is generally low, this

can be misleading because exposure during development can have disproportionately dramatic effects in adulthood.

The estimated non-carcinogenic inhalation risk from chromium for the residents of Radom was also low. The HQ values calculated based on the total Cr concentration in PM₁₀ were lower than the safe level (HQ = 1) and ranged from 1.32 × 10⁻² to 2.14 × 10⁻², indicating little non-carcinogenic risk from chromium. The non-carcinogenic health risk based on the maximum Cr_{tot} concentration in PM₁₀ was low, too, as it was not more than 1 (Table 3). These risk values are no different from those found in the literature; e.g., HQ in Italy was in the range of 1.5 × 10⁻²–5.4 × 10⁻² (Diana et al., 2023).

EU air quality directives do not provide for separate normative values for chromium. Directive 2024/2881 specifies quality objectives for arsenic, cadmium, lead, mercury, nickel, and polycyclic aromatic hydrocarbons (PAHs) but does not cover chromium (Directive 2024/2881). Within the framework of EU policy, chromium(VI) is regulated mainly in the context of occupational safety – the binding occupational exposure limit has been set at 0.005 mg m⁻³ by 2025 (Directive 2017/2398). For comparison, the highest obtained concentration of Cr(VI) in PM₁₀ (1.3544 ng m⁻³) is almost 3 orders of magnitude lower than this value. Consequently, the estimated health risk of chromium is low and does not raise significant health concerns.

In conclusion, the estimated potential non-carcinogenic (HQ) and carcinogenic (CR) risk of inhalatory exposure to Cr and Cr(VI), respectively, present in PM₁₀ for the urban residents of Radom indicates that risks of adverse health effects from chromium and chromium(VI) exposure in Radom are relatively low and comply with the applicable WHO and EU regulatory framework (WHO, 2021; Directive 2017/2398).

4 Conclusion

The mean concentrations of PM_{10} ($40 \pm 17 \mu\text{g m}^{-3}$) and $\text{PM}_{2.5}$ ($33 \pm 15 \mu\text{g m}^{-3}$) in the city of Radom were above the national (40 and $20 \mu\text{g m}^{-3}$, respectively) and European (40 and $25 \mu\text{g m}^{-3}$, respectively) levels. The total chromium content in PM_{10} ranged widely from 0.56 to 4.09 ng m^{-3} and averaged $1.71 \pm 0.83 \text{ ng m}^{-3}$. The mean Cr(VI) concentration in PM_{10} was 0.38 ng m^{-3} in the entire measurement period. Chromium(VI) accounted for circa 20 % of Cr_{tot} content in the particulate matter. The seasonality of Cr_{tot} and Cr(VI) concentration changes could be noted. The concentrations were maximum in the winter (heating) season – 2.23 and 0.84 ng m^{-3} , respectively – most likely as a result of a greater share of the air being polluted by fuel combustion sources in the air emissions of this type of pollution. The share of Cr(VI) in PM in the individual seasons varied as well: it was minimum in summer (9.1 % of Cr_{tot}) and maximum in winter (40 % of Cr_{tot}).

Out of the airborne particulate matter fractions investigated ($\text{PM}_{2.5-10}$, $\text{PM}_{1-2.5}$, $\text{PM}_{0.25-1}$, $\text{PM}_{0.25}$), both Cr_{tot} and Cr(VI) concentrations were maximum in the finest fraction – $\text{PM}_{0.25}$. Toxicity related to transition metals is greater for fine than for coarse dust since, once they penetrate the respiratory system, the finest particles reach pulmonary alveoli, where 60 %–80 % of a transmitted element enters the blood (Rogula-Kozłowska, 2013b). The health risk to urban residents, both carcinogenic and non-carcinogenic, is estimated to be highest in winter as Cr_{tot} and Cr(VI) concentrations reach their top values. Regardless of the season, however, these risk levels to the residents of Radom were within the acceptable risk range.

Research into the forms of atmospheric Cr is limited, and atmospheric Cr(VI) needs to be further investigated.

Data availability. Data sets are available at <https://doi.org/10.5281/zenodo.14808852> (Łożyńska et al., 2025).

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Author contributions. MŁ – data curation, formal analysis, methodology, writing – original draft, writing – review and editing, conceptualization, investigation, validation; MT – data curation, methodology, writing – original draft, writing – review and editing, conceptualization, investigation, validation; AM – data curation, methodology, visualization, investigation; RŚ – conceptualization, methodology, project administration, supervision.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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