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ORIGINAL PAPER

Effect of selected environmental pollutants on hypertension in chosen regions of Poland*

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Abstract

Heavy metals are major pollutants in urban environments, affecting their inhabitants by having adverse effects on human health, and implicating as causes of many civilization diseases, for example cardiovascular disease. The main objective of our study was to evaluate the relationship between selected environmental pollutants, including mainly nitrogen dioxide, nitrogen oxide, benzo(a)pyrene, and others, on the risk of hypertension. Data on mortality, morbidity, and hospitalization rates by city, sex, age, and ICD-10 classification were obtained from ProfiBaza. Data from air quality monitoring stations were sourced from the Chief Inspectorate of Environmental Protection. We analyzed the annual mean values of 10 air pollutants from 2017 to 2019 in 30 Polish cities. Values from these datasets were combined, and the Pearson correlation and Lasso regression analyses were performed. A positive correlation was observed between MR, SMR, HR, SHR, and levels of Benzo(a)pyrene, PM_{10}, $PM_{2.5}$, and SO2. Stronger positive correlations between benzo(a)pyrene, PM_{10}, $PM_{2.5}$, and SO_2 with MR and SMR were found in males compared to females, while correlations with HR and SHR were lower in males than in females. The Lasso regression analysis revealed that HR (0.42) had the highest explanatory power, while SMR (0.05) scored the lowest. MR was most positively influenced by $PM_{2.5}$ (2.91), while HR was most strongly affected by PM_{10} (139.78) and As (56.71). A comprehensive concerted regulatory plan and a program of health-promoting interventions should be developed and implemented to reduce urban residents' exposure to environmental factors, inducing, among other problems, cardiovascular disorders, including hypertension. Public awareness of the above compounds and individual action strategies to mitigate their impact should be promoted. The ubiquity of these pollutants is a serious public health threat, and should be strictly controlled by all possible national and independent institutions, especially pro-health ones.

Keywords: environmental pollution, hypertension, external factors, analysis model, toxic/heavy metals

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INTRODUCTION

Cardiovascular diseases (CVDs) are at the forefront of mortality and morbidity in Poland. According to the Central Statistical Office, the number of CVD deaths in Poland in 2017 was 167 thousand (42%) – Statistical causes of death. And the Global Burden of Disease (GBD) study showed that in 2019, 174 thousand people died (Roth et al. 2020), showing a significant upward trend. In 2021 alone, 180,760 patients, or 473.7 for every 100,000 people, will die from CVD in Poland (Wojtyniak, Goryński 2022), while in Eastern Europe in 2022. 432.3 per 100,000 people (Mansah et al. 2023). At the same time, it is worth noting that hypertension alone comprises practically 70% of cases among all cardiovascular diseases (Heart Failure Health Problem Analysis 2014-2021). According to a report by the National Health Fund, there were about 10 million people living with hypertension in Poland in 2018 (May 17 World Hypertension Day).

Several data confirm a marked difference in the prevalence of CVD in the population by gender, accounting for 42% in men and 33% in women (May 17 World Hypertension Day 2024, Roth et al. 2015, Charkiewicz at al. 2019, Charkiewicz 2025). After eliminating differences in age structure, it turns out that CVDs represent by far the highest risk of death and further predispose to the development of other disease entities (Charkiewicz et al. 2021, 2022). Meanwhile, it is necessary to take into account still vulnerable subgroups, including the elderly, women, ethnic groups, people with cardiovascular incidents to account for the concentration of air pollution more or less extreme outflows of CVD (Charkiewicz, Backstrand 2020). By far among the most common cardiovascular diseases, hypertension is the most life-threatening (Heart Failure Health Problem Analysis 2014-2021, Mensah et al. 2022, Charkiewicz 2025*a*,*b*).

Meanwhile, when assessing the most common CVD risk factors, the environmental factor counts for more than 50% cases. Both the workplace and living environment are then definitely taken into account. Among the most common potential environmental pollutants, associated with the development of civilization, heavy metals, including at least lead, cadmium, mercury, copper, nickel, are considered as well as other dust particles in the air. There is a wealth of data confirming the negative impact of at least these toxic elements contributing potentially to hypertension, a predictor of subsequent cardiovascular subunits (Tibuakuu et al. 2018, Charkiewicz et al. 2023, 2024, Charkiewicz 2024, Charkiewicz et al. 2025).

In its World Air Quality Repor, a Swiss air quality technology company (IQAir) presented data from more than 40,000 air quality monitoring stations in 138 countries. It was found that only 17% of global cities meet the WHO pollution guidelines. In 2024, only 7 countries (Australia, Bahamas, Barbados, Estonia, Grenada, Iceland and New Zealand) met the annual $PM_{2.5}$ - 5 g m^{-3} guideline. The most polluted countries are: Chad (91.8 g m^{-3}), Bangladesh (78.0 g m^{-3}), Pakistan (73.7 g m^{-3}), the Democratic Republic of Congo (58.2 g m^{-3}) and India (50.6 g m^{-3}), exceeding the WHO $PM_{2.5}$ guideline by 10 to 18 times. And as many as 126 countries exceeded the $PM_{2.5}$ guideline of 5 g m^3. Byrnihat in India was the most polluted area in 2024 ($PM_{2.5}$ – 128.2 g m^{-3}). In the US, Los Angeles and Ontario and California were most polluted, while Washington was the cleanest. Data concerning Africa are difficult to obtain due to the scarcity of monitoring stations, meanwhile quite extensive areas of South America have been affected by the Amazon rainforest (IQAir World Air Quality Report 2024, State of Global Air Report 2024).

The main objective of our study was to evaluate the relationship between selected environmental pollutants, including mainly nitrogen dioxide, nitrogen oxide, benzo(a)pyrene, and others, on the risk of hypertension. Specific objectives included observations over several years with reference to the most polluted urban regions.

MATERIALS AND METHODS

Data

The ProfiBaza and the Chief Inspectorate of Environmental Protection databases contain information on mortality and morbidity. They also include a breakdown by district for the specified observation period, province, district, gender, age, disease entities according to ICD10 (International Statistical Classification of Diseases and Related Health Problems), number of deaths, number of hospitalizations, and other indicators (Polish National Institute of Public Health's). It was decided to select data on mortality, morbidity, and hospitalization by city, gender, age, and ICD-10 in accordance with the concept of the manuscript. Two mortality rates were used in the analyses, i.e. the mortality rate and the standardized mortality rate. The death rate (MR) describes the intensity of mortality in a given population directly by relating the number of deaths to the size of the population in which they occurred, i.e. the number of permanent residents of a given province or district. On the other hand, the SMR, the standardized death rate (when multiplied by 100), tells us by how many percent the number of deaths observed in a province/district is greater (or less) than the number of deaths that would be observed if the mortality intensity in each five-year age group were the same as in the country as a whole. The number of deaths (NoD), number of hospitalizations (NoH), hospitalization rate (HR), and standardized hospitalization rate (SHR) were analyzed, considering their potential impact on hypertension (according to the codes used by physicians to precisely identify different types of hypertensions: ICD I10-I15). With regard to inpatient prevalence, we also use actual and standardized indicators.

Data from air quality monitoring stations originated from the Chief Inspectorate of Environmental Protection (Measurement database – GIOŚ).

The measurement data bank provides very precise measurements with accurate selection of years, regions, individual molecules and even the frequency of measurements per day. We described 10 pollutant particles year mean values (Table 1) reported between 2017 and 2019 from 30 Polish cities (Białystok, Bielsko-Biała, Bydgoszcz, Częstochowa, Elbląg, Gdańsk, Gorzów Wielkopolski, Kalisz, Katowice, Kielce, Koszalin, Kraków, Legnica, Łódź, Lublin, Olsztyn, Opole, Płock, Poznań, Radom, Rybnik, Rzeszów, Szczecin, Tarnów, Toruń, Wałbrzych, Warszawa, Włocławek, Wrocław, Zielona Góra). Annual average values from measurement stations in each city were related to respective ProfiBaza rates. The list of airborne pollutants considered for analysis comprises arsenic (As), benzo(a)pyrene (BaP), cadmium (Cd), nickel (Ni), nitrogen dioxide (NO_2), nitrogen oxide (NO), lead (Pb), sulfur dioxide (SO_2), particulate matter with aerodynamic diameters ≤ 10 µm (PM_{10}), and particulate matter with aerodynamic diameters ≤ 2.5 µm ($PM_{2.5}$).

Table 1

Mean values from measurement stations between 2017 and 2019 from 30 Polish cities, and mean death and hospitalization numbers and ratios values

Pollutants	Mean
Arsenic	1.48
Benzo(a)pyrene	3.38
Cadmium	0.34
Nickel	1.87
Nitrogen dioxide	21.23
Nitrogen oxide	37.39
Lead	0.01
PM_{10}	29.82
$PM_{2.5}$	21.27
Sulfur dioxide	5.27
Epidemiological data	
Number of deaths	151.27
MR	17.56
SMR	0.78
Number of hospitalizations	1881.67
HR	197.12
SHR	0.96

Statistical analysis

Pearson correlation was performed between ProfiBaza's health outcome indicators and pollution measurement values using Statistica 13. Statistical significance was assessed using a two-tailed *t*-test with a sample size of 30.

To perform feature selection and enforce sparsity, a Lasso regression model was implemented with an α parameter of 0.1. Lasso regression applies L1 regularization, which penalizes large coefficients and effectively reduces some to zero, allowing for automatic feature selection and only features with nonzero coefficients were considered important. The relationship between selected features and the target variable was analyzed, and the most significant predictors were identified. Lasso regression were performed using python library scikit-learn version 1.2.2.

RESULTS

Table 1 shows the average values of individual elements, compounds and particles from the analyzed cities.

For group all individuals (Figure 1), NO_2 and NO exhibit the strongest

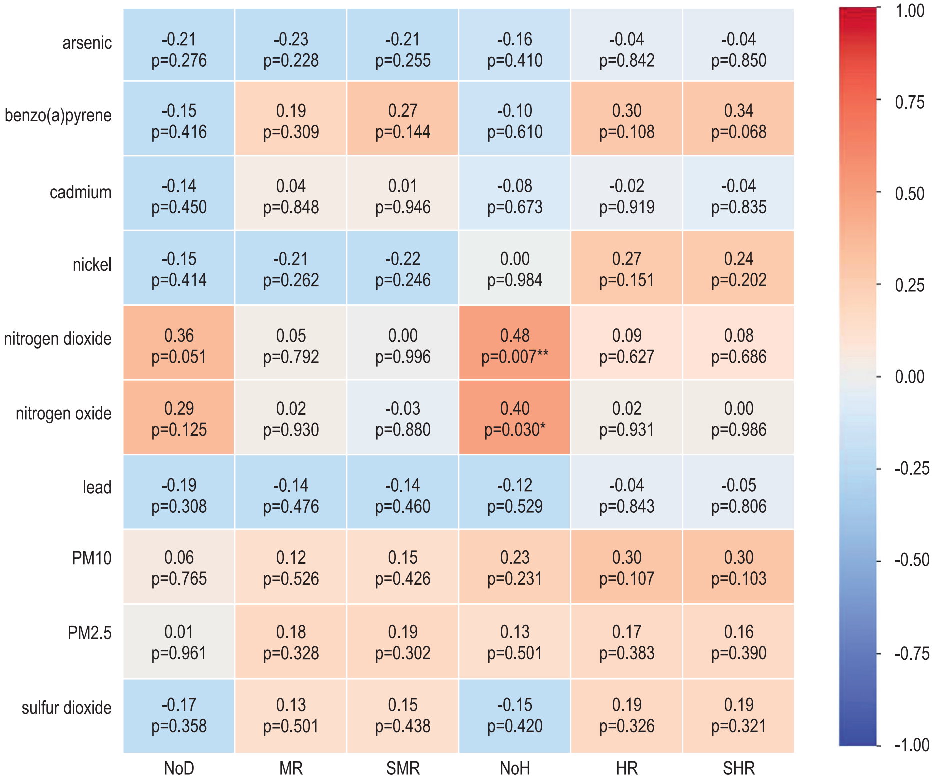


Fig. 1. Pearson correlation coefficients and p values between results from air pollution monitoring stations and hypertension (ICD I10-I15) mortality and hospitalization rates (NoD – number of deaths, MR – death rate, SMR – standardized death rate, NoH – number of hospitalizations, HR – hospitalization rate, SHR – standardized hospitalization rate) in all demographic groups, * p<0.05 and ** p<0.01

positive correlations with mortality and hospitalization outcomes, with coefficients ranging from 0.37 (NoD) to 0.50 (NoH) for NO_2 and 0.30 (NoD) to 0.41 (NoH) for NO. Benzo(a)pyrene shows stronger positive correlations with HR and SHR (e.g., 0.31 and 0.34 for SHR, respectively) than with MR and SMR (e.g., 0.20 and 0.29, respectively). PM_{10} and $PM_{2.5}$ show moderate positive correlations, particularly with hospitalization rates (e.g., 0.30 and 0.16 for HR, respectively). Conversely, arsenic, cadmium and lead display consistent negative correlations across all outcomes, although the correlations were not statistically significant. Nickel exhibits negative correlations for MR and SMR, and weak positive correlations with HR and SHR.

With benzo(a)pyrene PM_{10}, $PM_{2.5}$, and SO_2, higher positive correlations with MR and SMR, and lower correlations with HR and SHR in males than in females were observed (Figure 2).

Higher correlations were observed between MR and SMR versus BaP, Cd, PM_{10}, $PM_{2.5}$, SO_2 in age < 64 compared with the older group (Figure 3).

We observed moderate variability between cities in terms of SMR, SHR and pollution levels, but also a correlation between epidemiological and environmental data (Figure 4). The LASSO regression analysis results indicate the relative importance of various pollutants in predicting different metrics (MR, SMR, HR, and SHR). For MR, $PM_{2.5}$ (2.91) and BaP (1.35) exhibit the strongest positive associations, whereas Ni (-2.62) and Pb (-1.68) have notable negative impacts (Table 2). SMR shows weak associations, with BaP (0.03) and Ni (-0.02) having minimal influence. HR presents significant variations, with As (56.71), Ni (25.21), and PM_{10} (139.78) strongly influencing the outcome, while Pb (-98.42) and $PM_{2.5}$ (-67.24) demonstrate substantial negative effects. Finally, SHR indicates minor associations, with BaP (0.07) and Ni (0.02) having minimal influence. Overall model performance varies, with HR (0.42) showing the highest explanatory power and SMR (0.05) the lowest.

DISCUSSION

It is important to emphasize that residents exposed to pollutants, including heavy metals, often experience so-called smog episodes, such as respiratory infections, the development of coronary heart disease, stroke and myocardial infarction, memory/concentration issues, cognitive impairment and memory problems, the development of certain cancers (such as the respiratory system neoplasms), slower fetal development or more frequent birth defects in newborns, fertility disorders, and reduced immunity. Absorption of dust particles occurs mainly through direct ingestion, respiration and skin contact (Tibuakuu et al. 2018, Charkiewicz et al. 2019, 2023, 2024, Jahandari 2020, Skalny et al. 2021, Charkiewicz 2024, Charkiewicz et al.

A

	NoD	MR	SMR	NoH	HR	SHR
arsenic	-0.19 p=0.323	-0.06 p=0.759	-0.08 p=0.676	-0.16 p=0.408	-0.04 p=0.852	-0.05 p=0.810
benzo(a)pyrene	-0.10 p=0.591	0.29 p=0.117	0.28 p=0.129	-0.11 p=0.571	0.33 p=0.074	0.32 p=0.082
cadmium	-0.07 p=0.732	0.17 p=0.376	0.13 p=0.400	-0.10 p=0.610	-0.01 p=0.941	-0.04 p=0.832
nickel	-0.18 p=0.354	-0.26 p=0.163	-0.27 p=0.149	-0.02 p=0.920	0.21 p=0.254	0.21 p=0.276
nitrogen dioxide	0.45 p=0.014*	0.04 p=0.814	0.06 p=0.755	0.46 p=0.010*	0.05 p=0.803	0.06 p=0.752
nitrogen oxide	0.37 p=0.042*	0.04 p=0.851	0.04 p=0.814	0.37 p=0.044*	-0.04 p=0.821	-0.03 p=0.869
lead	-0.14 p=0.450	0.07 p=0.718	0.03 p=0.876	-0.13 p=0.480	-0.03 p=0.865	-0.06 p=0.772
PM10	0.13 p=0.488	0.16 p=0.396	0.16 p=0.399	0.20 p=0.286	0.31 p=0.090	0.31 p=0.101
PM2.5	0.11 p=0.552	0.26 p=0.167	0.26 p=0.165	0.11 p=0.577	0.18 p=0.352	0.17 p=0.379
sulfur dioxide	-0.11 p=0.573	0.24 p=0.195	0.22 p=0.253	-0.17 p=0.367	0.19 p=0.321	0.17 p=0.382

B

arsenic	-0.21 p=0.273	-0.25 p=0.188	-0.23 p=0.219	-0.15 p=0.414	-0.03 p=0.879	-0.02 p=0.904
benzo(a)pyrene	-0.16 p=0.401	0.23 p=0.213	0.27 p=0.151	-0.09 p=0.640	0.35 p=0.062	0.35 p=0.056
cadmium	-0.15 p=0.426	-0.01 p=0.962	0.00 p=0.983	-0.07 p=0.720	-0.04 p=0.852	-0.04 p=0.847
nickel	-0.15 p=0.422	-0.21 p=0.254	-0.20 p=0.280	0.01 p=0.972	0.25 p=0.178	0.25 p=0.182
nitrogen dioxide	0.35 p=0.058	0.01 p=0.940	-0.06 p=0.972	0.50 p=0.005*	0.09 p=0.637	0.08 p=0.661
nitrogen oxide	0.28 p=0.139	-0.02 p=0.910	-0.04 p=0.845	0.41 p=0.023*	0.03 p=0.888	0.02 p=0.910
lead	-0.20 p=0.297	-0.17 p=0.363	-0.16 p=0.391	-0.11 p=0.566	-0.04 p=0.842	-0.03 p=0.855
PM10	0.05 p=0.796	0.13 p=0.504	0.15 p=0.432	0.24 p=0.200	0.30 p=0.104	0.30 p=0.104
PM2.5	0.00 p=0.994	0.17 p=0.373	0.18 p=0.337	0.14 p=0.455	0.16 p=0.392	0.16 p=0.399
sulfur dioxide	-0.18 p=0.340	0.12 p=0.541	0.13 p=0.478	-0.14 p=0.461	0.20 p=0.286	0.21 p=0.776

Colour scale: 1.00, 0.75, 0.50, 0.25, 0.00, -0.25, -0.50, -0.75, -1.00

Fig. 2. Pearson correlation coefficients and p values results from air pollution monitoring stations and hypertension (ICD I10-I15) mortality and hospitalization rates (NoD – number of deaths, MR – death rate, SMR – standardized death rate, NoH – number of hospitalizations, HR – hospitalization rate, SHR – standardized hospitalization rate) by gender (a: female, b: male) demographic groups, * $p<0.05$ and ** $p<0.01$

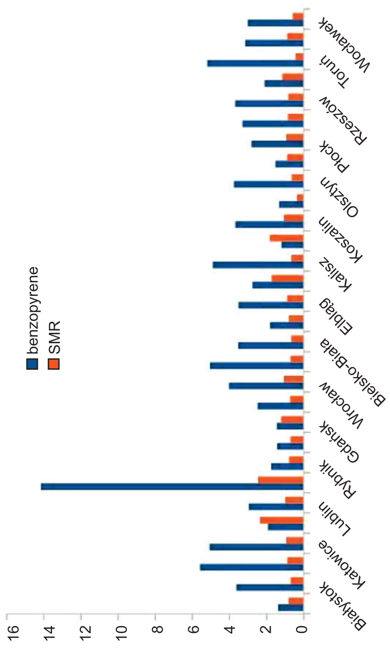
A

	NoD	MR	SMR	NoH	HR	SHR
arsenic	-0.21 p=0.262	-0.28 p=0.136	-0.27 p=0.143	-0.16 p=0.410	-0.03 p=0.888	-0.02 p=0.901
benzo(a)pyrene	-0.18 p=0.332	0.08 p=0.664	0.17 p=0.356	-0.09 p=0.634	0.32 p=0.085	0.37 p=0.046*
cadmium	-0.16 p=0.399	0.00 p=0.981	-0.01 p=0.946	-0.08 p=0.672	-0.02 p=0.928	-0.04 p=0.851
nickel	-0.15 p=0.423	-0.20 p=0.294	-0.20 p=0.281	0.00 p=0.993	0.26 p=0.168	0.23 p=0.231
nitrogen dioxide	0.34 p=0.063	0.06 p=0.765	0.01 p=0.964	0.48 p=0.007**	0.09 p=0.633	0.08 p=0.692
nitrogen oxide	0.27 p=0.146	0.03 p=0.883	0.02 p=0.926	0.40 p=0.031*	0.02 p=0.924	0.01 p=0.976
lead	-0.21 p=0.274	-0.20 p=0.287	-0.21 p=0.272	-0.12 p=0.532	-0.03 p=0.873	-0.04 p=0.846
PM10	0.03 p=0.892	0.04 p=0.844	0.08 p=0.687	0.23 p=0.222	0.31 p=0.099	0.32 p=0.089
PM2.5	-0.02 p=0.904	0.11 p=0.567	0.13 p=0.507	0.13 p=0.493	0.17 p=0.376	0.17 p=0.379
sulfur dioxide	-0.20 p=0.295	0.05 p=0.808	0.07 p=0.694	-0.14 p=0.448	0.20 p=0.284	0.21 p=0.264

B

	NoD	MR	SMR	NoH	HR	SHR
arsenic	-0.19 p=0.304	-0.14 p=0.462	-0.12 p=0.518	-0.15 p=0.414	-0.06 p=0.766	-0.05 p=0.774
benzo(a)pyrene	-0.11 p=0.575	0.33 p=0.079	0.38 p=0.041*	-0.11 p=0.570	0.27 p=0.146	0.28 p=0.130
Cadmium	-0.12 p=0.544	0.08 p=0.682	0.04 p=0.814	-0.08 p=0.677	-0.02 p=0.915	-0.04 p=0.818
nickel	-0.16 p=0.401	-0.21 p=0.266	-0.23 p=0.230	-0.01 p=0.943	0.28 p=0.141	0.26 p=0.167
nitrogen dioxide	0.39 p=0.036*	0.04 p=0.851	-0.02 p=0.934	0.49 p=0.006**	0.09 p=0.633	0.08 p=0.677
nitrogen oxide	0.31 p=0.099	0.00 p=0.992	-0.05 p=0.809	0.40 p=0.029*	0.01 p=0.957	0.00 p=0.999
lead	-0.17 p=0.373	-0.04 p=0.848	-0.04 p=0.830	-0.12 p=0.526	-0.05 p=0.803	0.00 p=0.755
PM10	0.11 p=0.574	0.22 p=0.235	0.23 p=0.228	0.22 p=0.249	0.29 p=0.124	0.28 p=0.134
PM2.5	0.06 p=0.748	0.22 p=0.254	0.20 p=0.297	0.13 p=0.488	0.11 p=0.545	0.11 p=0.569
sulfur dioxide	-0.13 p=0.479	0.23 p=0.224	0.22 p=0.233	-0.17 p=0.374	0.16 p=0.403	0.15 p=0.443

Fig. 3. Correlations between results from air pollution monitoring stations and hypertension (ICD I10-I15) mortality and hospitalization rates (NoD – number of deaths, MR – death rate, SMR – standardized death rate, NoH – number of hospitalizations, HR – hospitalization rate, SHR – standardized hospitalization rate) by age (a: age <64, b: age>= 65)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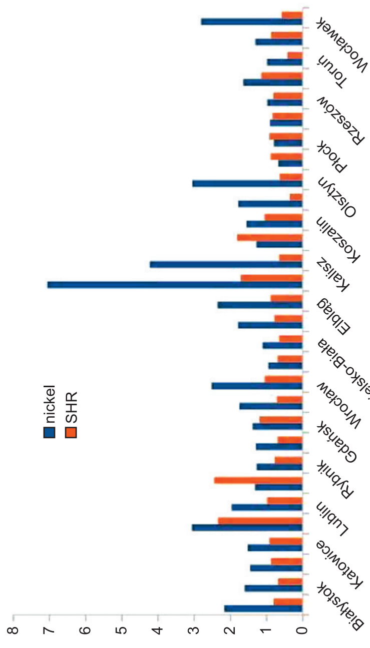
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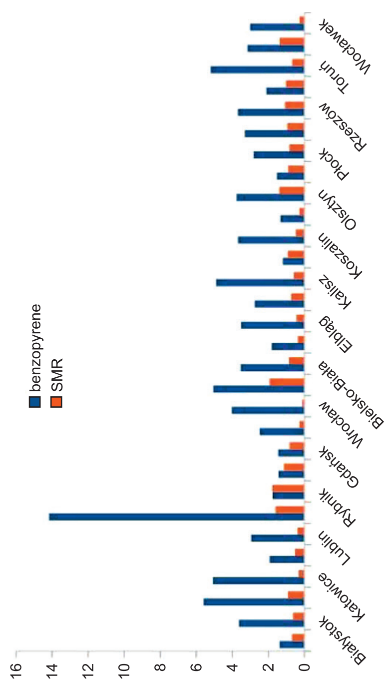
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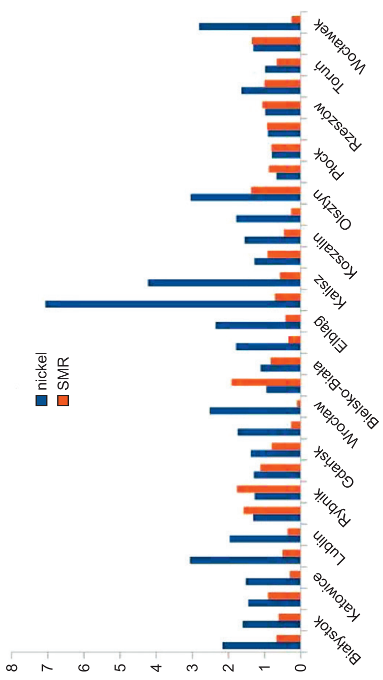
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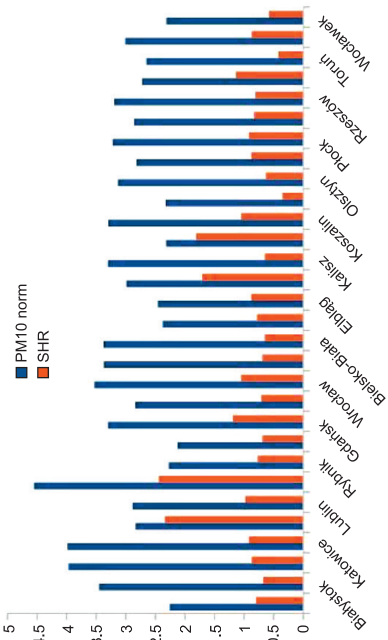
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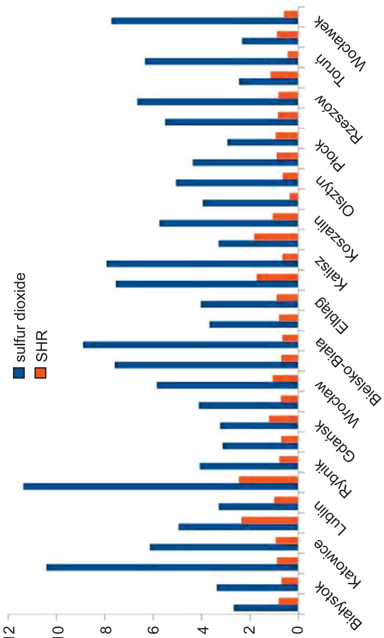
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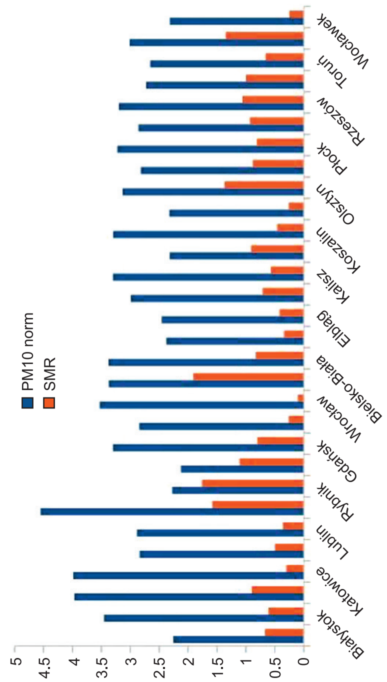
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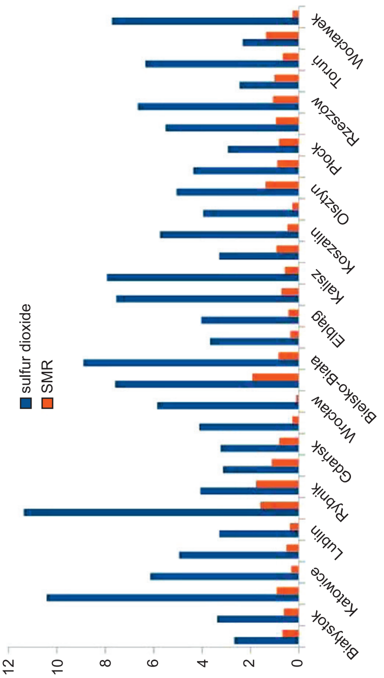
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Rybnik
Gdansk
Wrocław
Bielsko-Biała
Elbląg
Kalisz
Koszalin
Olsztyn
Płock
Rzeszów
Toruń
Włocławek

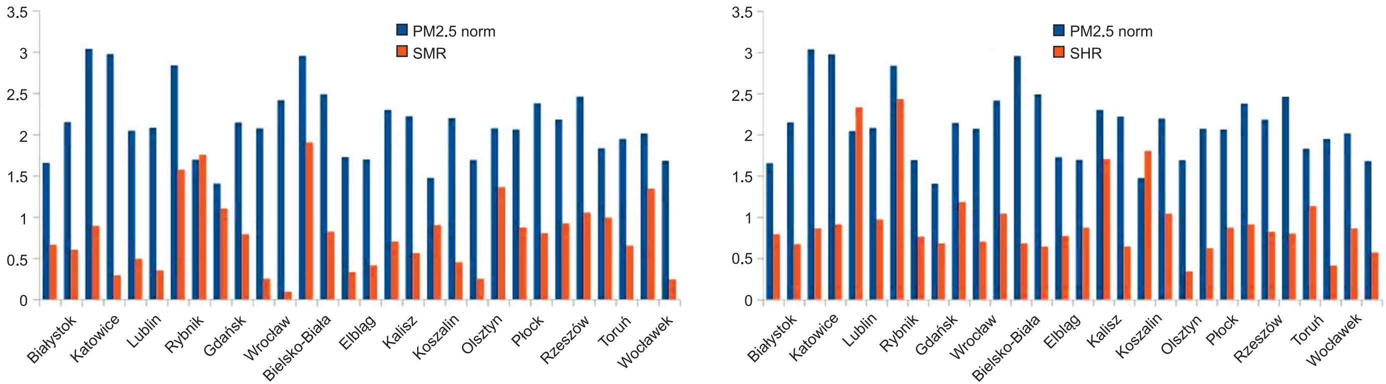

Fig. 4. Comparison of MR and SMR values for airborne pollutants with positive correlation values in all demographic groups (all age groups and genders). Y axis represents mean values from measurement stations

Table 2

Model and feature coefficients in the LASSO regression analysis

Metrics	Model coefficient	Pollutant	Feature coefficient
MR			
	0.20	arsenic	-1.26
		benzo(a)pyrene	1.35
		cadmium	0.28
		nickel	-2.62
		nitrogen oxide	-1.65
		lead	-1.68
		PM_{10}	-1.05
		$PM_{2.5}$	2.91
		sulfur dioxide	0.77
SMR			
	0.05	benzo(a)pyrene	0.03
		nickel	-0.02
HR			
	0.42	arsenic	56.71
		benzo(a)pyrene	-13.62
		nickel	25.21
		nitrogen dioxide	17.67
		nitrogen oxide	-23.35
		lead	-98.42
		PM_{10}	139.78
		$PM_{2.5}$	-67.24
		sulfur dioxide	18.08
SHR			
	0.10	benzo(a)pyrene	0.07
		nickel	0.02

2025*a*,*b*). The State of Global Air 2024 reports confirmed that air pollution is responsible for 28% deaths from obstructive pulmonary disease (48%), ischemic heart disease (28%), stroke (27%), lung cancer (19%), type II diabetes (18%). Nearly 490,000 deaths caused by air pollution can be determined in regions such as South Asian countries and East, West, Central and Southern Africa. These are the areas experiencing the highest burden of air pollution-related diseases. Among the populations exceeding one billion, India (2.1 million deaths) and China (2.3 million deaths) stand out, together accounting for 54% of the total global disease burden. Other high-impact countries in South Asia include Pakistan (256,000 deaths), Myanmar

(101,600 deaths) and Bangladesh (236,300 deaths) in South Asia. And deaths due to air pollution in Southeast Asia mainly occur in Indonesia (221,600 deaths), Vietnam (99,700 deaths) and the Philippines (98,209 deaths). In Africa, deaths caused by air pollutants were reported in Nigeria (206,700 deaths) and Egypt (116,500 deaths) (State of Global Air Report 2024).

The literature, including research reports, describes negative effects of heavy metals as well as other environmental pollutants being responsible for cardiovascular disease (Roth et al. 2015, Charkiewicz et al. 2019, Roth et al. 2020). The WHO estimates suggest that nearly 90% of the global population is severely exposed to levels of air pollution well above air quality guidelines (AQG) – State of Global Air Report (2024). More than 50% of the health burden is related to CVD (Brook et al. 2017). For $PM_{2.5}$ and PM_{10} particulate matter, the WHO introduced new recommendations in 2021. The maximum concentration for the $PM_{2.5}$ fraction is now: 15 μg m^{-3} daily and 5 μg m^{-3} annual average. Meanwhile, for PM_{10}, 45 μg m^{-3} daily and 15 μg m^{-3}, respectively. These are values relating to outdoor air quality (Indoor Particulate Matter. Environmental Health & Safety).

According to Polish legislation, air quality is assessed annually in Poland in terms of its pollution by 12 substances: sulfur dioxide, nitrogen dioxide, carbon monoxide, benzene and ozone, PM_{10} and $PM_{2.5}$ particulate matter, and pollutants determined in PM_{10}: Pb, As, Cd, Ni and BaP (Polish Regulation of April 27, 2001). And a significant problem remains mainly in the winter season, exceeding the standards for concentrations of PM_{10} and $PM_{2.5}$ particulate matter and BaP. In contrast, in the summer season, there are excessive concentrations of tropospheric ozone. Only isolated cases of exceeding the standards of nitrogen dioxide concentrations are observed, in which the main cause is emissions from motor traffic in the center of cities or on major roads located near the measuring stations (Air protection – Ministry of Climate and Environment).

In the USA, the Clean Air Act, proposed by the Environmental Protection Agency (EPA), entered into life, resulting in the issuing of the National Urban Air Quality Standards (NAAQS). It addressed 6 common pollutants, including lead and PM ($PM_{2.5}$, “fine PM,” and PM_{10}, “coarse PM”) (State of Global Air Report 2024). Poland does not have such a wide variety of racial or ethnic minorities (especially African Americans) that show an increased risk for CVD, as noted in many studies in the USA (Coogan et al. 2012, Aaron et al. 2016, State of Global Air Report 2024).

A study by Li et al. (2020) also found that pulse pressure was negatively associated with exposure to air pollution, but the results were inconclusive and unfortunately related to rural areas in developing regions of central China. As the authors pointed out, long-term exposure to $PM_{2.5}$, PM_{10} or NO_2 was also associated with behavioral factors, including poor diet, drinking and smoking, and even with strenuous physical activity (Li et al. 2020). Meanwhile, studies reported in US urban centers have shown sharp increases in blood pressure, mainly through acute exposure to $PM_{2.5}$, PM_{10} and NO_2 (Byrd et al. 2016, State of Global Air Report 2024).

Our analysis showed negative correlations between all analyzed parameters with As, Cd and Pb, while Ni showed negative correlations with MR and SMR. A study conducted in Iran showed moderate levels of ecological risk in 16 cities due to the 6 elements analyzed: Cd, Co, Cr, Ni, Pb and Zn (Jahandari 2020). Meanwhile, in other cities, heavy metal pollution also shows trends of high levels of contamination, sometimes resulting potentially in the occurrence of many diseases (Adimalla 2019, Zhaoyong et al. 2019, Živančev et al. 2019, Jahandari 2020). On the other hand, concentrations determined in Serbia have shown a gradual decline in $PM_{2.5}$ since 2015 (Renewables and Environmental Regulatory Institute). The KORA study conducted in Germany showed a link between $PM_{2.5}$ and a higher incidence of hypertension. And each additional increase in $PM_{2.5}$ of 1 µg m^{-3} indicated a tendency toward a higher incidence of high blood pressure and isolated systolic hypertension (Babisch et al. 2014).

Aging of the body itself was also noted and correlated with long-term exposure in our observation. Similar results were obtained in the ESCAPE project with 11 European cohorts, and the determined increase in mortality was nearly 13% due to acute coronary events vs. exposure to $PM_{2.5}$. It was observed then that people over 60 years of age have the highest risks of cardiovascular disease (Cesaroni et al. 2014).

Furthermore, our study showed higher morbidity among women and mortality among men associated with pollution exposure (Figure 2), contrary to what has been reported in the USA (Kaufman et al. 2016), Gothenburg, Sweden (Stockfelt et al. 2017), or China (Zhang et al. 2017). Meanwhile, among farmers in Iowa and North Carolina in the US, exposure to $PM_{2.5}$ was specifically associated with increased cardiovascular mortality only in men (Weichenthal et al. 2014).

In accordance with EU requirements, 12 mines will be closed in Poland, as part of the National Energy and Climate Plan (NERP). In 2015. The European Commission presented the "Clean Energy for All Europeans" Strategy for an Energy Union, which is designed to ensure that Europe and its citizens are decarbonized. The documents provide a base for the EU member states for the development of their national contribution to the Energy Union, and are intended to respond to the challenges of climate change and to intensify the fight against climate change and its effects (Poland's National Energy and Climate Plan for the years 2021-2030, European Green Bond Regulation (UE) 11.12.2018 r.). The current goal of the European Commission's European Green Deal (EGD) is to reduce air pollution to a level that does not significantly affect health by 2050. Currently, the share of the EU urban population exposed to air pollution concentrations for 2022 is: $PM_{2.5}$ <1%, PM_{10} – 9%, NO_2 <1%, BaP – 13% and SO_2 < 1%. The EEA (European Environment Agency) report estimates that 96% of the EU's urban population is exposed to dangerous concentrations of fine particulate matter ($PM_{2.5}$) – Europe's air quality status (2024).

In 2022, the Serbian government accepted the Air Protection Program (for 2022-2030) as a national strategy to reduce health damage caused by poor air quality by 50% compared to 2015 (Renewables and Environmental Regulatory Institute).

It is worth mentioning that military-related metal emissions with their potential subsequent excessive escalation also play a significant role in health risks for military personnel. The metals are deposited in soil, posing a serious threat to the agricultural industry and subsequently the food and feed industry (Tibuakuu et al. 2018, Charkiewicz et al. 2023, Charkiewicz 2024, Charkiewicz et al. 2025). Toxic exposure to heavy metals in Poland remains an important public health concern, mainly in the metallurgical, steel, arms, mechanical, agricultural, and other industries. Also, recent increased military and shooting range activities have been to cause an increased body's lead content among Polish soldiers (mainly due to inhalation of shooting fumes) – Jahandari (2020), Skalny et al. (2021), Charkiewicz (2025).

When starting his second term as the American president in 2025, Donald Trump emphasized that he intended to have metal refining facilities built at Pentagon military bases. This strategic decision can be implemented as part of a plan to increase domestic production of critical minerals. Despite this, Of course, the guidelines stemming from the Clean Air Act and the Clean Water Act will still apply (Scheyder, Renshaw 2025). While the planned large-scale business ventures would result in big savings for the USA, all preventive measures must be considered for protection of the environment, the workers themselves, and the residents of the surrounding regions (Tibuakuu et al. 2018, Charkiewicz et al. 2023, Charkiewicz 2024, Charkiewicz et al. 2025). Regular checkups of workers, strict safety measures and treatment standards, taking into account the latest knowledge, will be necessary. Monitoring measures could then protect workers from consequences of the toxic effects of heavy metals and other dust particles, including the risk of causing CVDs, such as hypertension. A correctly designed and implemented preventive program could reduce the negative effects of inhalation or adsorption of heavy metals as well as other dust particles (Charkiewicz et al. 2019, Charkiewicz 2025).

As a well-known cardiologist Valentin Fuster points out, this widespread and intense global epidemic of cardiovascular diseases must be stopped in a very significant and strategic way. A wide-ranging plan composed of 12 strategic actions, with close monitoring of their results, has been proposed. It is suggested that efforts must be made by governments and government organs, global health organizations, communities, business institutions, and most importantly, patients themselves. Food processing agencies, the pharmaceutical industry and manufacturers of diagnostic tools for the use of rapid prevention will also play an important role (Fuster 2014). Such activities are always relevant even in a smaller area and in a specific risk group, for example the metal industry employees (Charkiewicz 2025).

PREVENTIVE MEASURES

There is still a lack of specific guidelines directly related to occupational health and safety in this occupational group, and a lack of targeted individual or group prevention programs for people exposed to the pollution mentioned above. Primary prevention requires measures to ensure that our environment is safe and healthy for the entire population. A comprehensive regulatory plan and a program of health-promoting interventions should be developed and implemented to reduce the exposure of workers in the metallurgical or arms industry, as well as the dangers of exposure to heavy metals and other pollutants causing *inter alia* cardiovascular diseases, including hypertension (Charkiewicz et al. 2019, Charkiewicz 2025, Skalny et al. 2021).

The fact that programs exist not only at the local level but also on the global stage prompts policymakers to adopt broadly applicable policies and ensure their effective implementation (Fuster 2014, May 17 World Hypertension Day 2024, Charkiewicz 2025). Above all, any action is expected to trigger the planning of new or adjustment of existing health programs as well as the operation of health care systems so as to reduce the risk of hypertension (Roth et al. 2015).

In the external environment, effective prevention relies on appropriate methods such as land decontamination, reforestation, drinking-water filtration, and continuous pollution monitoring. At the individual level, preventive measures may include regular biomarker testing (e.g., blood, urine, hair, and nails), increased exposure to fresh air, routine ventilation of indoor environments, promotion of healthy dietary habits, and regular physical activity. Such an approach enables comprehensive strategies to deliver personalized care while safeguarding public health (Tibuakuu et al. 2018, Charkiewicz et al. 2023, Charkiewicz 2025*a*).

To reduce the negative health effects of the presence of harmful dust and other volatile substances, it is recommended to make amendments to lifestyle (Münzel et al. 2022). We recommend personal strategies and educational measures:

– stay indoors during periods of peak pollution, limiting your presence in regions with the highest pollution levels;
– wear special masks (N95);
– choose outdoor physical activity in a forest or outside the city;
– use air cleaners and special filters at home, in your car, and at work;
– check the dedicated online applications and official sources of information for pollution levels on a given day or during a planned period of the year (especially autumn and winter);

– use the most modern generation of furnaces in your household;
– have blood tests or other biomarkers performed appropriately at different times of the year.

CONCLUSIONS

A review of the literature from the past decade indicates limited direct evidence linking the pollutants examined in this study to hypertension, particularly in populations residing in polluted regions. However, short-term exposure to air pollution has been associated with increased cardiovascular disease risk, including hypertension.

Benzo(a)pyrene showed stronger positive correlations with HR and SHR. Ni exhibits negative correlations for MR and SMR and weak positive correlations with HR and SHR. Benzo(a)pyrene PM_{10}, $PM_{2.5}$, and sulfur dioxide demonstrated higher positive correlations with MR and SMR and lower correlations with HR and SHR in males. Higher correlations were observed between MR or SMR with BaP, Cd, PM_{10}, $PM_{2.5}$, SO_2 in the age < 64 group.

A comprehensive, coordinated regulatory strategy and a program of health-promoting interventions are needed to reduce urban residents' exposure to environmental factors associated with cardiovascular disease, including hypertension. Environmental health policy should therefore adopt a broad, integrated approach to patient care. Increasing public awareness of these air-borne pollutants and implementing corresponding preventive actions are essential, as their widespread presence constitutes a major public health challenge requiring strict oversight by national and independent public-health institutions.

Limitations of study

Although a larger and more accurate model would ideally span at least five to ten years, this study presents a three-year analysis prior to the COVID-19 pandemic (up to 2019), when more complete public data were available. Limitations also included the lack of detailed lifestyle and family history data, restricting deeper analyses of individual factors and more elaborate analytical models.

Author contributions

A.E.C. – methodology, P.K. – software (data curation, formal analysis), A.E.C. – conceptualization, investigation, project administration, P.K. – resources; software, A.E.C. – supervision, visualization, writing – original draft preparation, A.E.C. and P.K. writing – review and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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