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Air pollution in the context of building structure and density in selected Polish cities

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ABSTRACT

The aim of the study was to determine the differentiation of mean annual concentrations of particulate matter PM2.5 and PM10, benzo(a)pyrene (BaP), nitrogen dioxide (NO_2), and benzene (C_6H_6) in 2018–2024 in the context of the structure and intensity of development in Gdańsk, Kraków, and Łódź. The analysis also accounted for reported pollutant emissions and mean annual wind speed. Data from GIOŚ, KOBiZE, and IMGW-PIB, as well as building data from BDOT10k were used. The highest mean annual concentrations of all analysed pollutants were recorded in Kraków, where the share of built-up area was 49%, and the lowest in Gdańsk, where this share was 22%. After accounting for differences between cities, significant positive correlations between reported emissions and concentration were found for BaP ($\rho = 0.90$), NO_2 ($\rho = 0.60$), and PM10 ($\rho = 0.55$). However, in the models accounting for the city effect, reported emissions were not significantly associated with the concentration of any of the analysed pollutants. The mean annual wind speed was highest in Gdańsk (3.98 m/s) and lowest in Kraków (3.08 m/s). The height structure of buildings differed between cities, but did not directly correspond to the observed differences in concentrations. The results indicate that the differentiation of mean annual air pollutant concentrations between cities co-occurs with differences in building intensity and wind speed. Due to the limited number of cities analysed, these relationships should not be interpreted as causal.

Keywords: air pollution, building structure, building intensity, Poland, particulate matter PM2.5, benzo(a)pyrene.

INTRODUCTION

Building structure is one of the factors affecting air quality in cities (EEA, 2020). The density and height of buildings modify local air circulation and the conditions for pollutant dispersion (Bochenek and Klemm, 2016; Fronczak, 2018). Intensive urbanization also affects the local climate, promoting the development of the urban heat island and limiting air exchange, which can lead to increased pollutant concentrations, especially during unfavourable meteorological conditions (Bui and Ngheim, 2025; Wang et al., 2021; Mohajerani et al., 2017).

The exposure to air pollution is one of the best-documented environmental health hazards. Epidemiological studies link it to respiratory diseases (asthma, lung cancer, COPD exacerbations, respiratory tract infections), cardiovascular diseases (heart attack, hypertension, ischemic heart disease, arrhythmias, heart failure), and nervous system diseases (stroke, memory and concentration impairment, accelerated aging of the nervous system), as well as cancers and pregnancy complications (Czernych et al., 2024; Czernych et al., 2023; Czubaj-Kowal et al., 2022; Dummer et al., 2023; Góra, 2024; Góra et al., 2026; Alexeeff et al., 2021; Zhong et al., 2025). A significant proportion of global deaths attributed to air pollution is linked to fossil fuel combustion (Lelieveld et al., 2023).

The burden of this problem falls on cities. In Poland, about 23.3 million people live in cities, accounting for over 61% of the country's population (Warsza, 2025). Progressive urbanisation and industrial development increase the share of anthropogenic surfaces, which modify local atmospheric conditions. A city creates a heterogeneous environment with sharp boundaries between built-up fragments and clear barriers to air flow (Albertsen, 2019), with its own topoclimate differing from the surroundings in thermal, humidity, wind, and aerosanitary parameters. These features are most pronounced in large agglomerations, although elevated concentrations and changes in wind speed and direction are also observed in smaller cities (Nidzgorska-Lencewicz and Mąkosza, 2016).

Urban development directly affects ventilation. The rough surface of the city causes a decrease in wind speed – on average by about 30% in city centres and by 15–20% in outer residential zones – increasing the frequency of atmospheric calms and hindering the removal of pollutants and heated air (Klemm, 2022). Dense and tall buildings form street canyons that promote the accumulation of pollutants, while the development of natural ventilation corridors limits the inflow of fresh air from outside the city (Bochenek and Klemm, 2016; Fronczak, 2018). This type of land use reinforces the urban heat island – higher air temperature is observed in the city than in the surrounding areas, resulting from a lack of greenery and the presence of heat-accumulating materials, primarily concrete and asphalt (Bokwa et al., 2015; Lin et al., 2024; Wang et al., 2021; Musiał et al., 2025).

The dispersion of pollutants also depends on meteorological conditions and terrain relief. Wind speed determines the rate of their transport, and direction determines the direction of movement; under weak wind, pollutant concentrations increase, while thermal inversions limit vertical transport and trap pollutants in the near-ground layer of the atmosphere, which often accompanies episodes of high particulate matter concentrations (Jasiński et al., 2021; Godłowska, 2019; Flaga et al., 2020). The season also matters in winter, low temperatures increase emissions from the municipal-residential sector, while in summer, high temperatures and strong sunlight favour the formation of secondary pollutants, including ozone (Chen et al, 2024).

Urban greenery and green-blue infrastructure can counterbalance these phenomena, as they lower temperature, improve air quality, and act as a barrier to pollutants (Ciapa and Śliwka, 2023; Barwise and Kumar, 2020). Their effectiveness, however, depends on the local spatial layout and on whether planning takes building development and ventilation into account at all.

Although the influence of city structure on air quality has been well described qualitatively, the quantitative relationships between the intensity and height of buildings and mean annual pollutant concentrations in Polish cities remain insufficiently understood (Hojnicki, 2012), especially when simultaneously accounting for emission volumes and meteorological conditions. Combining data – GIOŚ concentration measurements, KOBiZE emission reporting, and the BDOT10k spatial building database – allows these relationships to be examined for selected cities within one coherent framework.

The aim of the study was to determine the differentiation of mean annual concentrations of selected air pollutants in the context of the structure and intensity of urban development in Gdańsk, Kraków, and Łódź, taking into account reported pollutant emissions and mean annual wind speed.

MATERIALS AND METHODS

Study area

The analysis was conducted for three large urban agglomerations in Poland: Gdańsk, Kraków, and Łódź, which differ in terms of geographical, climatic, and urban conditions. The basic indicators for the analysed centres are presented in Table 1.

Gdańsk: The terrain is highly diverse, encompassing both depression areas in the Żuławy region and numerous moraine hills in the western part of the city (highest point: 180.1 m a.s.l.). The proximity of the Baltic Sea influences Gdańsk's climate, giving it transitional climate features and causing milder winters and cooler summers. The economy is based on the maritime, petrochemical, and electromechanical industries as well as modern services (GIOŚ, 2025a).

Kraków: Located in the Vistula valley and surrounded by higher terrain, which limits air mass exchange. On cold, windless days, temperature inversion occurs here, preventing smog dispersion. The region's economy has historically been based on heavy industry, metallurgy, and energy production (GIOŚ, 2025b).

Łódź: Situated on gently rolling terrain in central Poland, without distinct terrain barriers limiting air flow. The historic centre is characterised by dense tenement-house development, forming so-called "street canyons," which significantly hinder air circulation. The city's industry has undergone a transformation from textiles toward energy, machinery, and pharmaceutical industries (GIOŚ, 2025c).

Concentration, emission, and meteorological variables

Mean annual concentrations of particulate matter PM2.5 and PM10, benzo(a)pyrene (BaP), nitrogen dioxide (NO_2), and benzene (C_6H_6) from 2018–2024 were analysed. The data were obtained from the Chief Inspectorate of Environmental Protection (GIOŚ).

Measurements came from urban background monitoring stations: in Kraków (ul. Złoty Róg, Piastów estate; Φ 50.081197, λ 19.895358), in Gdańsk (ul. Lawendowe Wzgórze, ul. Grunwaldzka; Φ 54.328833, λ 18.568819), and in Łódź (ul. Gdańska, al. Jana Pawła II; Φ 51.754613, λ 19.43492).

Meteorological data on mean annual wind speeds from 2018–2024 were obtained from the Institute of Meteorology and Water Management – National Research Institute.

Emission data were compiled based on reports to the national database maintained by the National Centre for Emissions Management (KOBiZE) for 2018–2024. For each city, year, and pollutant, absolute emissions [$kg \cdot year^{-1}$] and two normalised metrics were analysed: emissions per city area [$kg \cdot km^{-2} \cdot year^{-1}$] and per built-up area [kg/km² of built-up area/year]. The emission–concentration comparison was performed for benzo(a)pyrene (BaP), C_6H_6, PM10, PM2.5, and NO_2. Sulphur oxides (SO_x/SO_2) were included in the descriptive emission analysis but excluded from the emission–concentration statistical comparisons due to the lack of a complete concentration measurement series for this gas in the database.

Analysis of building structure and intensity

The context of city development was addressed in two ways. The main analysis used macro-indicators (city area, share of built-up areas, green areas). The built-up area was calculated as the product of the city area and the share of built-up areas.

Table 1. Comparison of selected indicators in the analysed cities

Indicator	Gdańsk	Kraków	Łódź
Area [km²]	261.57	327	293
Share of city area in country area [%]	0.084	0.105	0.094
Green area [km²]	15	15	14
Forest area [km²]	9	5	9
Built-up areas of the city [%]	22	49	44
Population density [persons/km²]	1870	2480	2292

Note: For Gdańsk, the area of 261.57 km² excludes internal marine waters (PL-1992); the built-up share of 22% is based on the BDOT10k PTZB layer. Population density uses 489,160 residents as at 30 June 2025.

In the height-structure analysis, the Database of Topographic Objects (BDOT10k) was used, to categorise buildings in accordance with the Regulation of the Minister of Infrastructure on technical conditions to be met by buildings (Journal of Laws 2022, item 1225).

The following classes were distinguished:

a) low (N) – up to and including 12 m above ground level, or residential buildings up to and including 4 above-ground storeys;
b) medium-height (SW) – above 12 m up to and including 25 m above ground level, or residential buildings above 4 up to and including 9 above-ground storeys;
c) high (W) – above 25 m up to and including 55 m above ground level, or residential buildings above 9 up to and including 18 above-ground storeys;
d) high-rise (WW) – above 55 m above ground level.

The height structure of the cities was analysed using the pseudo-usable-area index (built-up floor area multiplied by the number of storeys), which precisely combines the area occupied by buildings with their vertical differentiation.

Statistical analysis

The relationships between reported annual emissions [kg/year] and concentration, and between wind speed and concentration, were assessed separately for 5 pollutants. In each pair, both variables were ranked and centered separately within each city, and a pooled within-city rank correlation coefficient ρ was then calculated. Converting emissions to the city area did not change their within-city ranks. Two-sided p-values were determined using an exact permutation test stratified by city. The Benjamini-Hochberg correction was applied separately for the five emission–concentration correlations and the five wind speed–concentration correlations; p_BH < 0.05 was considered significant. Separately, pooled Spearman correlations were calculated across the 21 city–year observations for absolute emissions, emissions per city area, and emissions per built-up area, using two-sided asymptotic p-values and Benjamini–Hochberg correction across the 15 tests.

Concentration models were then fitted separately for each pollutant. Concentration and reported annual emissions [kg/year] were transformed as ln(x + 1), and the models included emissions and wind speed. For NO_2, the NO_x/NO_2 emission category from the KOBiZE database was used as an approximate predictor. Robust HC3 standard errors were applied to the coefficients. P-values for emissions, wind speed, and year were corrected using the Benjamini-Hochberg method within the 5 models.

RESULTS

Air pollutant concentrations

The analysis showed clear and systematic differences between cities in terms of the studied indicators. Kraków recorded the highest mean annual values for all five analysed pollutants, and Gdańsk the lowest. These results are consistent with differences in the share of built-up areas, amounting to 22% in Gdańsk, 44% in Łódź, and 49% in Kraków. The highest values in Kraków reached, respectively: BaP – 3.47 ng/m³; C_6H_6 – 1.30 ng/m³; NO_2 – 41.22 ng/m³; PM10 – 33.26 µg/m³; PM2.5 – 22.86 µg/m³ (Figure 1 and Figure 3).

Reported emissions and mean annual concentrations

After accounting for differences between cities, positive emission–concentration correlations were significant for BaP (ρ = 0.90, p < 0.001, p_BH < 0.001), NO_2 (ρ = 0.60, p = 0.0093, p_BH = 0.0233), and PM10 (ρ = 0.55, p = 0.0183, p_BH = 0.0305). For C_6H_6 and PM2.5, correlations were not significant after correction (Figure 2).

In the pooled analysis of 21 city-year observations, the strongest emission-concentration correlation was observed for C_6H_6 and emissions per built-up area (ρ = −0.65, p = 0.0016, FDR = 0.0117). For NO_2 and emissions per city area, the correlation was ρ = −0.01 (p = 0.9733, FDR = 0.9733). The emissions-per-city-area metric met $|\rho| \geq 0.60$ in one comparison (C_6H_6), while absolute emissions met this threshold in one comparison (PM10). These pooled correlations combine within-city and between-city differences (Figure 3).

Influence of wind speed

The mean annual wind speed in 2018–2024 was higher in Gdańsk (3.98 m/s) than in Kraków

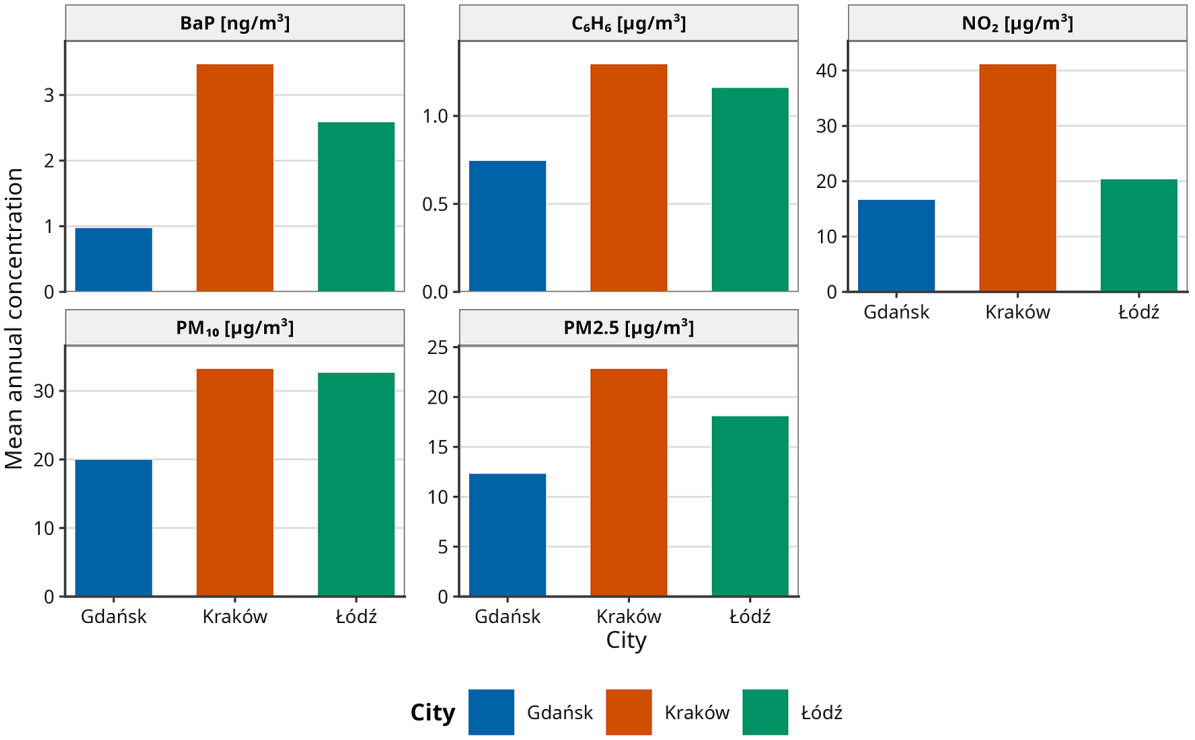


Figure 1. Mean concentrations of BaP, C_6H_6, NO_2, PM_{10}, and $PM_{2.5}$ in Gdańsk, Kraków, and Łódź from 2018 to 2024. Each bar shows the mean of 7 annual values for one city. PM_{10} and $PM_{2.5}$ are shown in separate panels. Panels use pollutant-specific y-axis scales; BaP is shown in ng/m³, and the remaining pollutants in µg/m³

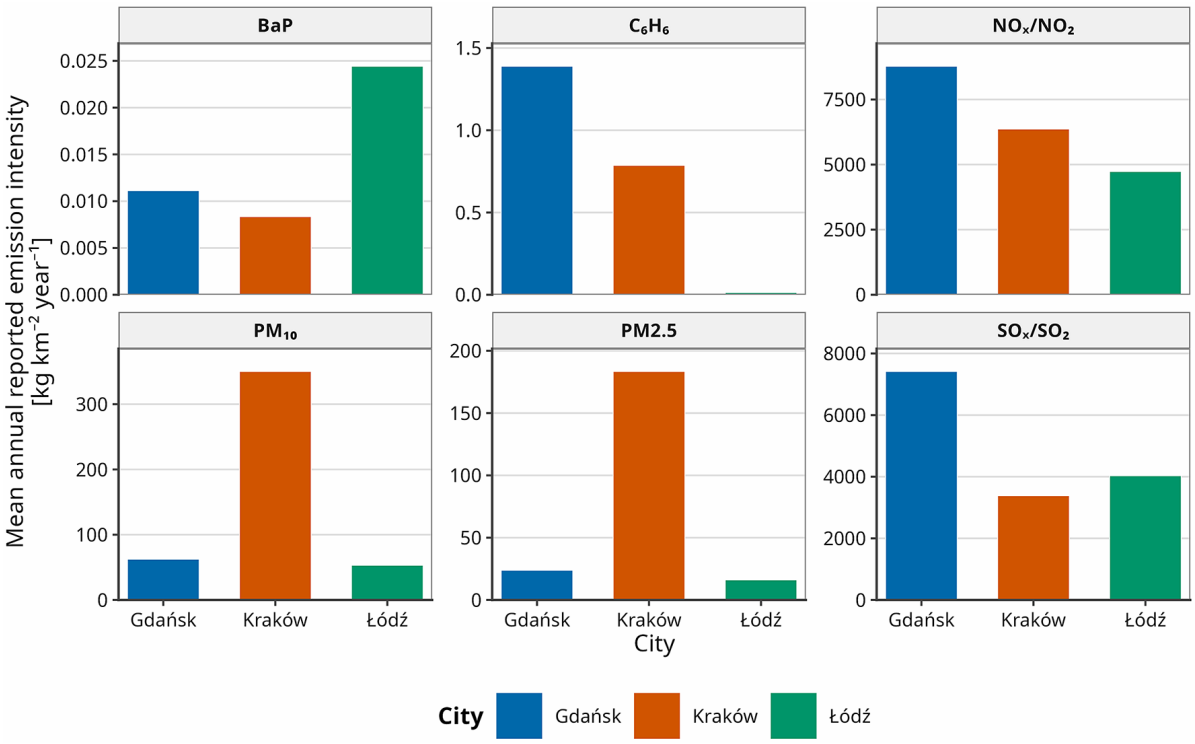


Figure 2. Mean intensity of emissions reported to KOBiZE by city and pollutant from 2018 to 2024. Each bar shows the mean of 7 annual values for one city. Annual emission intensity was calculated as reported annual emission divided by city area (Gdańsk: 261.57 km², Kraków: 327 km², Łódź: 293 km²) and then averaged across years. Panels use independent y-axis scales. NO_x/NO_2 and SO_x/SO_2 retain the categories used in the KOBiZE data

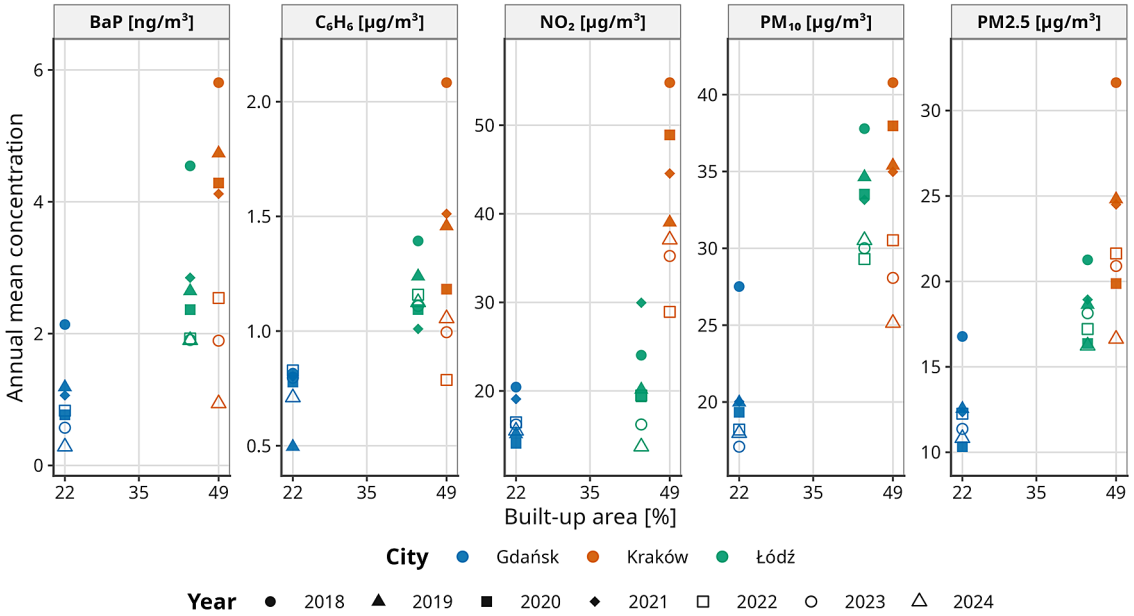


Figure 3. Share of built-up areas and mean annual pollutant concentrations. The chart is descriptive in nature, as it covers only three cities

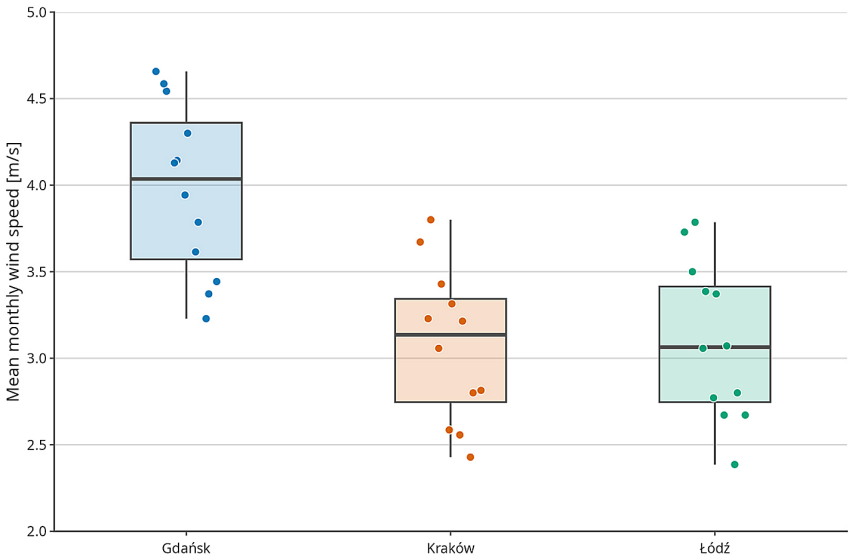


Figure 4. Relationship of mean monthly wind speed

(3.08 m/s) and Łódź (3.10 m/s; Figure 4). The combined analysis of data from all cities was dominated by between-city differences and did not provide a reliable assessment of within-city relationships. After ranking the data separately within each city, no relationship between concentration and wind speed was significant after the Benjamini-Hochberg correction. The lowest corrected p-value was obtained for NO_2 ($p_BH = 0.1464$). The analysis is exploratory in nature, as the exact permutation test assumes exchangeability of successive years within a city.

Relationships between building intensity and pollution (regression models)

Models were fitted separately for BaP, C_6H_6, NO_2, PM10, and PM2.5. Each model included 21 observations from 3 cities and 7 years. After accounting for wind speed, year, and a fixed city effect, reported annual emissions [kg/year] were not significantly associated with the concentration of any pollutant (all $p_BH \geq 0.5454$). The negative relationship with year remained significant for BaP, NO_2, PM10, and PM2.5, and the negative relationship with wind speed for BaP and PM10.

Influence of building intensity on mean annual air pollutant concentrations

The building structure of the analysed cities was characterized based on data from the Database of Topographic Objects BDOT10k (GUGiK, 2025), a nationwide spatial database containing the geometry and basic descriptive attributes of buildings. The analysis used the LICZ_KONDY attribute, which specifies the number of storeys of a building, used to assign objects to height classes. The building classification followed the categories set out in the Regulation of the Minister of Infrastructure (Minister of Development and Technology, 2022) on technical conditions to be met by buildings and their location, distinguishing low (N), medium-height (SW), high (W), and high-rise (WW) buildings.

Building structure was assessed using three methods of aggregating building data, based on the number of objects, built-up area, and pseudo-usable area determined as the product of built-up area and number of storeys. The use of different aggregation methods leads to different representations of the share of individual building height classes (Table 2). Among the analysed methods, the pseudo-usable-area index was adopted for further analyses, as it most fully describes building intensity by simultaneously accounting for built-up area and the number of storeys of buildings (Figure 5).

Building intensity indicators

The analysis of building structure using the pseudo-usable-area index showed clear differences between the analysed cities. In Gdańsk, medium-height buildings dominate (46.68%), while the share of low buildings is 38.60%. At the same time, among all analysed cities, Gdańsk has the highest share of high-rise (WW) buildings, which account for 2.14% of the total pseudo-usable area. In Kraków, the shares of low (43.53%) and medium-height (43.62%) buildings are nearly identical, indicating a more balanced height structure. In Łódź, in turn, the largest share belongs to low buildings (48.45%), while the share of medium-height buildings is the smallest among the analysed cities (39.03%). Detailed results are presented in Table 2.

An interesting observation is the small variation in the share of high (W) buildings, which is around 12% in all cities, suggesting a similar scale of development of this group of objects. Much larger differences concern the relationship between low and medium-height buildings and the share of high-rise buildings, which determine the intensity of space development.

DISCUSSION

The results obtained indicate a clear differentiation of mean annual concentrations of the analysed pollutants between Gdańsk, Kraków, and

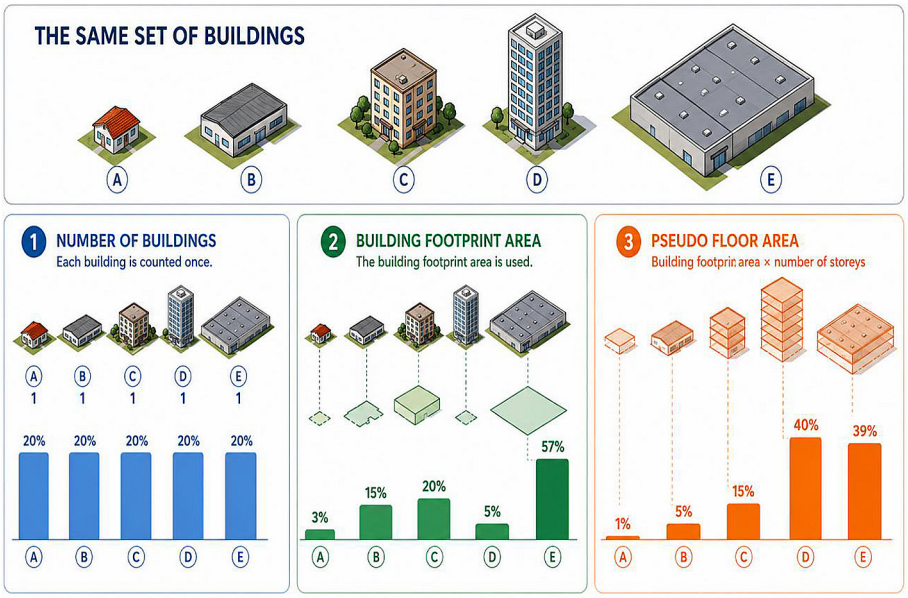


Figure 5. Comparison of three methods for determining the share of building height classes: number of objects, built-up area, and pseudo-usable area

Table 2. Share of building height classes determined based on the pseudo-usable area of buildings in the analysed cities

City	N	SW	W	WW
Gdańsk	38.60%	46.68%	12.58%	2.14%
Kraków	43.53%	43.62%	12.79%	0.06%
Łódź	48.45%	39.03%	12.01%	0.52%

Note: Legend: N – low buildings, SW – medium-height, W – high, WW – high-rise.

Łódź. The highest values of all five pollutants were recorded in Kraków, characterised by the highest share of built-up area (49%), the lowest in Gdańsk, where this share was 22%, while Łódź (44%) held an intermediate position. Analysis of the results indicates a co-occurrence of greater building intensity with higher pollutant concentrations. However, it should be noted that the analysis covered only three cities, and therefore this relationship cannot be separated from other city-differentiating features, in particular terrain relief, the nature of emission sources, and anemological conditions. The relationship obtained thus describes a co-occurrence of phenomena, not a causal relationship.

An important meteorological element differentiating the analysed cities was wind speed, whose correlations with concentrations were negative for all pollutants. In the models accounting for the city effect, wind speed and a declining trend in mean annual concentrations remained significant predictors, while the emissions reported to the national database did not reach the significance threshold. The direction of these relationships corresponds to the role attributed to dispersion and ventilation conditions in studies of Polish cities (Godłowska, 2019; Flaga et al., 2020; Bochenek and Klemm, 2016). The observed decrease in concentrations should be linked to factors that vary over time, since the share of built-up area remained constant during the analysed period.

The reported emissions showed a varied relationship with the concentrations of the analysed pollutants. After accounting for the differences between cities, positive emission–concentration correlations were significant for BaP ($\rho = 0.90$), NO_2 ($\rho = 0.60$), and PM10 ($\rho = 0.55$). However, in models accounting for the city effect, reported annual emissions were not significantly associated with the concentration of any of the analysed pollutants. This discrepancy may result, among other things, from the scope of the KOBiZE data, which covers entities subject to reporting obligations. These data do not fully reflect all sources shaping air quality in the city, including municipal-residential and traffic emissions. For this reason, reported emissions should not be treated as a complete measure of the total emission pressure in the analysed areas.

The analysed cities also differed in the height structure of their buildings. In Gdańsk, medium-height buildings predominate (46.68%), with simultaneously the highest share of high-rise buildings; in Łódź, low buildings dominate (48.45%), while in Kraków, the shares of low (43.53%) and medium-height (43.62%) buildings are nearly identical. Kraków, with the highest concentrations, is therefore not characterised by the most vertical building structure, while the highest share of high buildings occurs in Gdańsk, where the lowest concentrations were recorded. The height differentiation of buildings may affect ventilation conditions and promote the formation of the street-canyon effect and the urban heat island (Bochenek and Klemm, 2016; Nidzgorska-Lencewicz and Mąkosza, 2016); however, in the analysed sample, it did not directly reflect the gradient of concentrations between cities. Kraków's basin location favours the occurrence of thermal inversions (Bokwa et al., 2015), and the dense tenement-house development of Łódź may limit air exchange and the functioning of ventilation corridors (Bochenek and Klemm, 2016). Building intensity is thus only one of the factors shaping pollution levels, alongside meteorological conditions, terrain relief, and emission volume (Godłowska, 2019; Flaga et al., 2020).

Persistently high concentrations are of significant importance from a public health perspective, as epidemiological analyses link long-term exposure to fine particulate matter with respiratory diseases and cancers (Czubaj-Kowal et al., 2022; Dummer et al., 2023; Hassanipour et al., 2023; Zhang et al., 2023; Zhao et al., 2022), and a significant proportion of global deaths attributed to air pollution is linked to fossil fuel combustion (Tsekeri et al., 2026; Lelieveld et al., 2023). The analysis conducted indicates that in the studied sample, the differentiation of mean annual concentrations between cities is best reflected by building intensity

and dispersion conditions, rather than the volume of reported emissions. This argues for including in spatial policy tools that limit pollutant accumulation, including the protection of ventilation corridors, control of building intensity, and the development of green-blue infrastructure (Fronczak, 2018; Ciapa and Śliwka, 2023), treated as a complement to measures aimed at reducing emissions.

CONCLUSIONS

Mean annual concentrations of key pollutants (BaP, C_6H_6, NO_2, PM10, PM2.5) are related to the degree of urbanisation. The highest critical values were recorded in densely built-up Kraków (49% urbanised area), and the lowest in structurally looser Gdańsk (22%).

Wind speed is the strongest predictor of decreasing particulate matter concentrations. A dense, canyon-like architectural layout (typical of older tenement buildings) blocks pollutant dispersion much more strongly than dispersed high-rise development, underscoring the importance of protecting urban air corridors. Registered industrial emissions (KOBiZE) do not explain the urban background burden. Poor air quality is primarily due to "grey" (unregistered) anthropogenic activity: unregistered low-stack municipal-residential emissions and road traffic.

Despite noticeable downward trends resulting from implemented thermomodernisation programs, concentrations in the most burdened centres still drastically exceed EU standards. Due to the limited number of cities analysed, the relationships obtained should be interpreted as a co-occurrence of the studied features, not as causal relationships.

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