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Air pollution in the context of the structure and intensity of urban development: The case of Kraków

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ABSTRACT

The physical form of a city is one of the factors that shape the concentrations of air pollutants measured within it, yet the quantitative relationship between the intensity of development and measured concentrations remains poorly documented for Polish cities. The aim of this study was twofold: to determine the variation in mean annual concentrations of five air pollutants – benzo(a)pyrene (BaP), benzene (C_6H_6), NO_2, PM_{10} and $PM_{2.5}$ – in Kraków in 2018–2024 in relation to reported emissions and meteorological conditions, and to characterise the structure and intensity of the city's development as the spatial context of those concentrations. Data comprised annual concentrations from the State Environmental Monitoring network, emissions reported to the National Centre for Emissions Management, and building data from the Database of Topographic Objects for 90,563 buildings in 18 districts. Relationships and trends were assessed by Spearman rank correlation with Benjamini–Hochberg correction; development was described by the pseudo-usable floor area, that is the building footprint area multiplied by the number of storeys. In 2024 all five pollutants were lower than in 2018, the largest decrease being for BaP (−83.8%). Significant monotonic decreases, and significant positive emission–concentration relationships, were obtained for BaP ($\rho = -1.00$ and 0.96) and PM_{10} ($\rho = -0.96$ and 0.93); none of the 15 meteorology–concentration pairs was significant. Low-rise and medium-rise buildings account for almost identical shares of the pseudo-usable floor area (43.68% and 43.51%), although building counts alone would indicate a decisive predominance of low-rise development (88.45%). Building intensity ranges from 10,019 m²/ha in Stare Miasto to 701 m²/ha in Nowa Huta. The picture of urban structure therefore depends strongly on the aggregation method, which should be taken into account wherever building indicators are used as proxies for dispersion conditions.

Keywords: air pollution, benzo(a)pyrene, building intensity, BDOT10k, urban form.

INTRODUCTION

Air quality in large urban agglomerations is shaped not only by the volume of pollutants released into the atmosphere, but also by the physical form of the city itself. Built-up areas modify the radiation balance, the roughness of the underlying surface and the pattern of airflow,

and thereby determine how effectively pollutants are dispersed. Ongoing and intensive urbanisation restricts air exchange, which may lead to increased pollutant concentrations, particularly under unfavourable meteorological conditions [1–3].

The magnitude of urban emissions depends primarily on the number of inhabitants and on the scale of industrial and transport-related sources [4, 5]. The location of large point sources, such as waste incineration plants, is itself a planning decision in which environmental criteria, including the dispersion of emissions, are weighed against technical and economic ones [6]. Road transport, in turn, is a source of particulate matter not only through exhaust emissions but also through the wear of road surfaces, tyres and brakes and the resuspension of street dust; the residues removed by street sweeping, which consist of this material, show seasonal variation in particle-size distribution and nanofraction content [7] and annual variation in heavy-metal content [8], and their fine fractions constitute a waste stream that requires recovery [9]. Urbanised areas consist largely of concrete and asphalt surfaces which, owing to their low albedo, accumulate considerable amounts of heat. Combined with vehicle traffic, greenhouse gas emissions and the heating of buildings, this produces an urban heat island. Warmer air within the city generates a local low-pressure system, so that air flows in from the outskirts, preventing pollutants from being removed and favouring the accumulation of smog [10, 11].

Kraków belongs to the group of European cities characterised by very high concentrations of atmospheric pollutants [12, 13]. The problem of designing urban ventilation has been the subject of research since the nineteenth century, and has gained particular importance in view of the strong anthropogenic transformation of the environment: increased emissions, soil sealing and the expansion of built-up areas. A growing urban population contributes to the degradation of the urban fabric and to uncontrolled development, and thus to the modification of climatic elements such as sunshine duration, temperature, humidity and wind speed. The resulting phenomena – the urban heat island, arising from a positive net radiation balance, and reduced exchange of air and of the pollutants it contains, caused by compact development – directly affect the quality of life and the health of inhabitants [14–16].

As a result of the considerable roughness of the urban surface, wind speed is markedly reduced. In the city centre the reduction averages 30%, decreasing to 15–20% in outlying housing estates. At the same time, winds of 4–5 m/s are weakened while weak winds are accelerated as they are channelled between buildings, and the frequency of calm conditions increases. The dynamic interaction between buildings and airflow also causes strong deflection of wind direction. The modification of the wind field above the city results from the pressure difference between the city and its surroundings, caused by changes in air density, which in turn is related to the heat surplus in the city. Under conditions of weak atmospheric circulation, an urban heat island develops together with an associated system of breeze-type winds directed towards the city interior. Transport corridors and valley floors running from the extra-urban zone towards the centre allow air from outside to penetrate the city, and appropriately planned ventilation corridors with low surface roughness and a high proportion of greenery, which acts as a filter and a cooling agent, make it possible to exploit the urban breeze [17, 18].

Exposure to air pollution is among the best-documented environmental health hazards. Epidemiological studies confirm that it contributes to diseases of the respiratory system (asthma, lung cancer, exacerbations of COPD, respiratory tract infections), the circulatory system (myocardial infarction, arterial hypertension, ischaemic heart disease, arrhythmias, heart failure) and the nervous system (stroke, impaired memory and concentration, accelerated ageing of the nervous system), as well as to cancers and complications of pregnancy [19–24]. A substantial proportion of the global deaths attributed to air pollution is associated with the combustion of fossil fuels [25].

The dispersion of pollutants also depends on meteorological conditions and relief [26]. Wind speed determines the rate of transport and wind direction the direction of displacement; under weak winds concentrations increase, whereas thermal inversions limit vertical transport and retain pollutants in the near-surface layer of the atmosphere, which frequently accompanies episodes of high particulate concentrations. The season is also relevant: in winter, low temperatures increase emissions from the municipal and residential sector, whereas in summer high temperatures and strong insolation favour the formation of secondary pollutants, including ozone. Urban

greenery and blue-green infrastructure may counteract these phenomena by lowering temperature, improving air quality and acting as a barrier to pollutants, although their effectiveness depends on the local spatial layout and on whether planning takes development and ventilation into account at all [27].

Although the influence of urban structure on air quality has been well described in qualitative terms, the quantitative relationships between the intensity and height of development and mean annual pollutant concentrations in Polish cities remain insufficiently documented, particularly when the magnitude of emissions and meteorological conditions are considered simultaneously [28]. Combining concentration measurements from the State Environmental Monitoring network, emission reporting to KOBiZE and the spatial building database BDOT10k makes it possible to describe both dimensions for a single city within one coherent framework, and to establish how far the available data allow their relationship to be assessed.

The aim of this study is twofold. The first objective is to determine the variation in mean annual concentrations of five air pollutants – benzo(a)pyrene, benzene, NO_2, PM_{10} and $PM_{2.5}$ – in Kraków in 2018–2024, and to establish whether the changes were monotonic and whether they were associated with reported emissions or with meteorological conditions. The second objective is to characterise the structure and intensity of urban development in Kraków by building-height class and by district, as the spatial context in which those concentrations are measured. The study does not test a statistical relationship between building structure and concentrations, because the two sets of data have no common spatial or temporal unit.

MATERIALS AND METHODS

Study area

Kraków lies in the broad, latitudinally oriented valley of the Vistula, on the southern slope of the Kraków-Częstochowa Upland and the northern slopes of the Carpathian Foothills. This location modifies the meteorological factors that govern pollutant concentrations: wind speed, the intensity and vertical extent of air mixing, precipitation, atmospheric stability and air temperature. From the perspective of pollutant dispersion, urban development constitutes above all an obstacle to the free flow of air. In Kraków the built-up area occupies the floor of the Vistula valley and extends onto the elevated landforms situated to the north and south of it, but does not reach the level of the surrounding plateaux, where suburban and extra-urban areas with dispersed development are found. The reduction of wind speed by buildings, known as the curtain or sheltering effect, is relevant to pollutant dispersion only within a certain range of wind speeds recorded outside the city.

The position of Kraków at the junction of three physico-geographical regions is reflected in its diversified relief. The city centre occupies the Vistula valley, which belongs to the Sandomierz Basin, as does the Nowa Huta district with its metallurgical plant. The southern margins of the city extend onto the Wieliczka Foothills and the northern ones onto the Polish Uplands. In the western part of the city the Vistula valley is obstructed by the tectonic horsts of the Kraków Gate mesoregion, which naturally shelters the city from westerly winds – the most frequent wind direction in Poland. The difference in elevation between the valley floor and the nearby plateaux amounts to approximately 100 m. The city is thus surrounded on three sides by elevated landforms, which contributes to the considerable frequency of calm conditions and low wind speeds. Although Kraków does not lie in a mountainous area and the local relief appears moderate, processes typical of mountain and foothill areas shape the local climate and mesoclimate of the city and its surroundings: thermal inversions, katabatic flows and cold-air pools [29, 30].

The basic indicators characterising Kraków are summarised in Table 1.

Table 1. Basic indicators of Kraków

Indicator	Kraków
Area [km^2]	327
Share of the country's area [%]	0.105
Green areas [km^2]	15
Forests [km^2]	5
Built-up areas [%]	49
Population density [inhab./km^2]	2480

Note: Source – Statistics Poland (GUS), 2025.

Concentration, emission and meteorological variables

The analysis covered annual pollutant concentrations and their relationships with reported emissions and meteorological conditions in Kraków in the years 2018–2024. All analyses were carried out at the level of calendar years. Five pollutants were examined: BaP (benzo[a]pyrene), C_6H_6 (benzene), NO_2, PM_{10} and $PM_{2.5}$; seven annual values were available for each of them.

Concentrations were measured at urban background monitoring stations of the State Environmental Monitoring network operated by the Chief Inspectorate of Environmental Protection [13]: in Kraków, ul. Złoty Róg and os. Piastów (φ 50.081197°, λ 19.895358°). Annual concentrations were calculated as the mean of 12 monthly values. Emission data were obtained from the National Database on Emissions of Greenhouse Gases and Other Substances (Krajowa baza) maintained by the National Centre for Emissions Management (KOBiZE) [31] under the Act of 17 July 2009 on the system for managing emissions of greenhouse gases and other substances [32]. Entities using the environment – in Polish law, the operators of installations and of other activities that release substances into the air, who are obliged to report – submit their emissions to the database annually for the preceding calendar year. The reporting obligation does not extend to households, so emissions from individual heating appliances, which are the dominant source of BaP and a substantial source of particulate matter in Polish cities [22], are not represented directly. Emissions reported for the area of Kraków were analysed for five categories corresponding to the measured concentrations; SO_x/SO_2 was considered only descriptively because no corresponding concentration series was available. The meteorological variables – mean air temperature, mean wind speed and total precipitation – were obtained for the years 2018–2024 from the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

Emissions were expressed in kg per km^2 of city area per year. The emission–concentration and meteorology–concentration relationships, as well as trends over time, were assessed using Spearman rank correlation. Two-sided p-values were determined exactly, taking into account all possible orderings of the seven years.

The p-values were corrected using the Benjamini–Hochberg (BH) procedure separately within each family of tests presented: emission–concentration (5 tests), meteorology–concentration (15 tests) and concentration trends (5 tests). Corrected values are denoted pBH, and pBH < 0.05 was treated as statistically significant. Because only seven years were available, no models including the year and the three meteorological variables simultaneously were fitted. With seven observations, the exact two-sided test yields $p < 0.05$ only for $|\rho| \geq 0.786$ ($p = 0.048$), so the analysis can detect only strong monotonic associations; a non-significant result is therefore not evidence of the absence of a relationship and is not interpreted as such.

Building structure and intensity

A detailed analysis of the building height structure was conducted using data from the Polish Database of Topographic Objects (BDOT10k) [33]. The analysis covered 90,563 buildings located within the boundaries of Kraków's 18 districts. The building geometries, footprint areas and the LICZ_KONDY attribute, which specifies the number of above-ground storeys, were used.

The buildings were assigned to four height classes: low-rise (N) – up to and including 4 above-ground storeys; medium-rise (SW) – from 5 to 9 above-ground storeys; high-rise (W) – from 10 to 18 above-ground storeys; and very high-rise (WW) – more than 18 above-ground storeys. The adopted ranges correspond to the storey-number criteria included in the classification established by the Regulation of the Minister of Development and Technology on the technical requirements to be met by buildings and their location [34]. Owing to the absence of a consistent building-height attribute, the classification was operationally based on the number of storeys.

For buildings for which the number of storeys recorded in BDOT10k was zero, a minimum value of one storey was assumed. This prevented buildings with a non-zero footprint area from contributing no value to the building-intensity indicator.

The building structure was assessed using three measures: the number of buildings, the building footprint area and the pseudo-usable floor area. The latter was calculated as the product of the building footprint area and the number of storeys, and was treated as an approximate

measure of the vertical intensity of development rather than as the actual usable floor area defined under formal measurement standards. The results were aggregated for the entire city and for each district.

All input data are publicly available national datasets: concentrations from the State Environmental Monitoring network, emissions from the KOBiZE database, meteorological data from IMGW-PIB and building data from BDOT10k, which covers the whole territory of Poland in a uniform structure. The procedure can therefore be repeated without modification for any Polish city with an urban background monitoring station, or for individual districts, and for cities in other countries after substitution of the equivalent air-quality monitoring, emission-inventory and topographic databases. The only requirement specific to the building analysis is a storey-count or height attribute for individual buildings.

RESULTS AND DISCUSSION

Concentration trends

In 2024 the concentrations of all five pollutants were lower than in 2018 (Table 2). A comparison of two years alone does not, however, determine whether the change was monotonic throughout the period.

After Benjamini–Hochberg correction, significant monotonic decreases in concentration were found for BaP ($\rho = -1.00$; $p < 0.001$; pBH = 0.0020) and PM_{10} ($\rho = -0.96$; $p = 0.0028$; pBH = 0.0069). For the remaining pollutants no significant monotonic trend was detected (pBH ≥ 0.05) (Table 2, Fig. 1).

Table 2. Annual pollutant concentrations in Kraków in 2018 and 2024

Pollutant	Unit	2018	2024	Change 2018–2024 [%]
BaP	ng/m³	5.81	0.94	−83.8
C_6H_6	µg/m³	2.08	1.05	−49.4
NO_2	µg/m³	54.8	37.1	−32.4
PM_{10}	µg/m³	40.8	25.1	−38.4
$PM_{2.5}$	µg/m³	31.6	16.6	−47.4

Note: On the basis of data of the Chief Inspectorate of Environmental Protection (GIOŚ). BaP is given in ng/m³, the remaining pollutants in µg/m³; percentages were calculated from unrounded values.

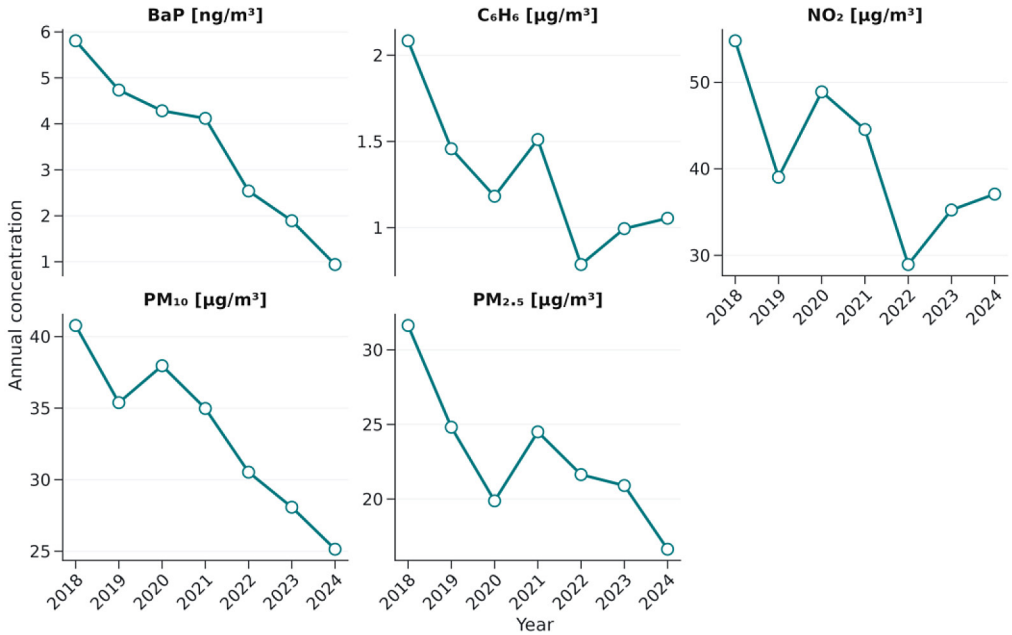


Fig. 1. Annual concentrations of five pollutants in Kraków from 2018 to 2024. Each panel contains seven annual values; the unit is stated in the panel heading. Source: based on data of the Chief Inspectorate of Environmental Protection (GIOŚ)

Emissions and concentrations

After Benjamini–Hochberg correction, significant positive emission–concentration relationships were found for BaP (ρ = 0.96; p = 0.0028; pBH = 0.0139) and PM_{10} (ρ = 0.93; p = 0.0067; pBH = 0.0169). Years with higher reported emissions therefore tended to be years with higher concentrations of these pollutants (Figs. 2 and 3).

Reported BaP emissions declined over most of the period, with a slight increase in the final year; the overall direction of change corresponds to the systematic decrease in the concentration of this pollutant.

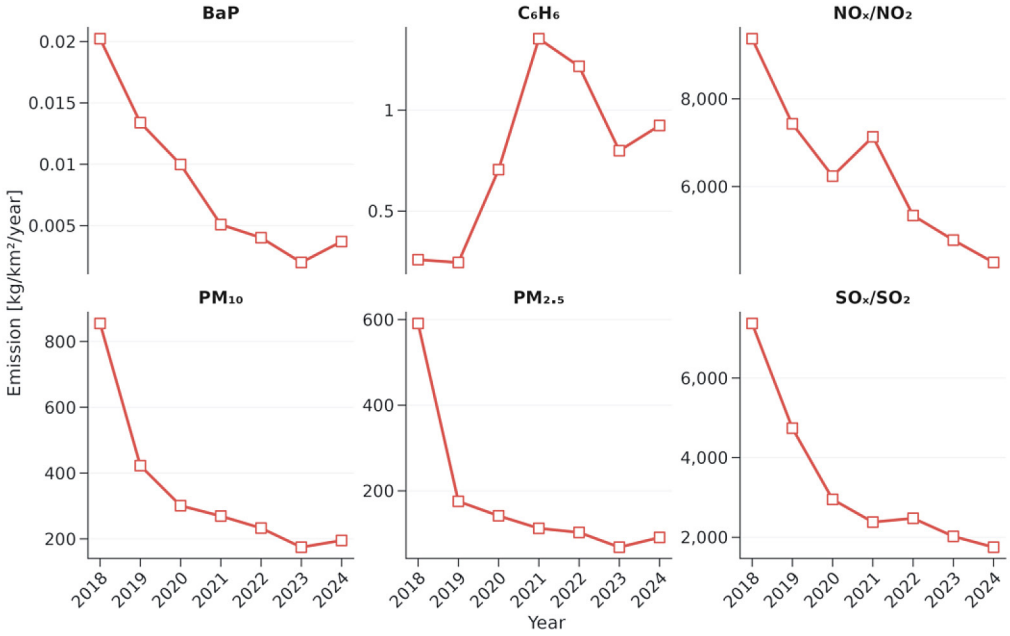


Fig. 2. Annual emissions reported to KOBiZE in Kraków from 2018 to 2024, expressed per km² of city area. Six emission categories are shown. No corresponding concentration series was available for SO_x/SO_2. Source: own elaboration based on data of the National Centre for Emissions Management (KOBiZE)

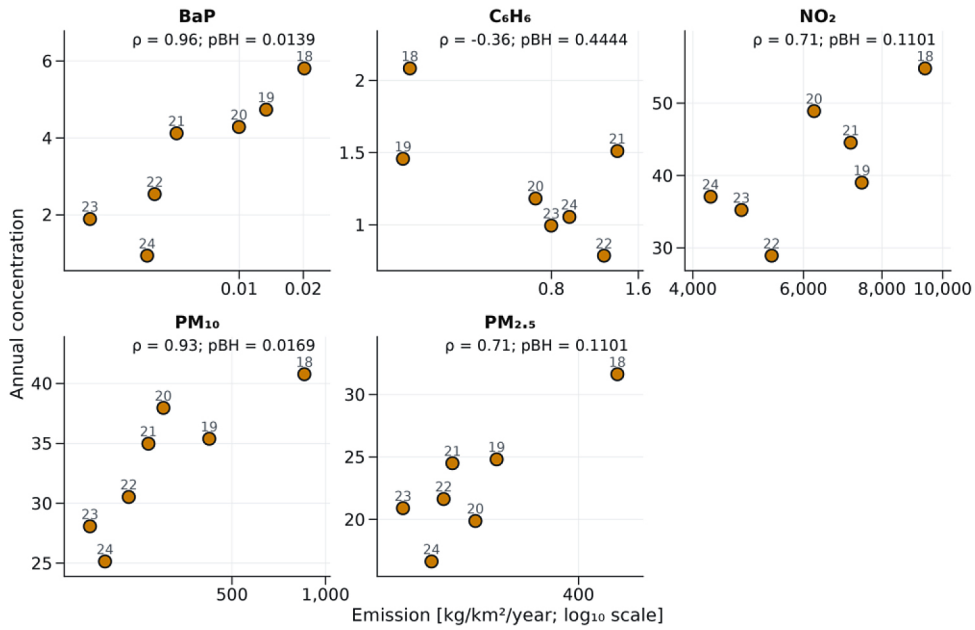


Fig. 3. Association between emissions reported to KOBiZE and annual concentration in Kraków. Point labels give the last two digits of the year. The coefficient ρ is the Spearman rank correlation across seven years. P values were adjusted by the Benjamini–Hochberg method across five pollutants; the figure reports pBH. The correlations were not adjusted for temporal trend. Source: based on GIOŚ and KOBiZE data

Meteorological conditions

None of the 15 meteorology–concentration tests was significant after Benjamini–Hochberg correction. The largest absolute correlation was recorded for the wind speed–NO_2 pair ($\rho = -0.87$; $p = 0.0571$; $pBH = 0.5714$) (Figs. 4–6).

Air temperature and precipitation totals varied markedly between years, whereas the mean annual wind speed remained within a narrow range. Wind speed was highest in winter and decreased towards the summer months, with the greatest between-year variability in the winter season.

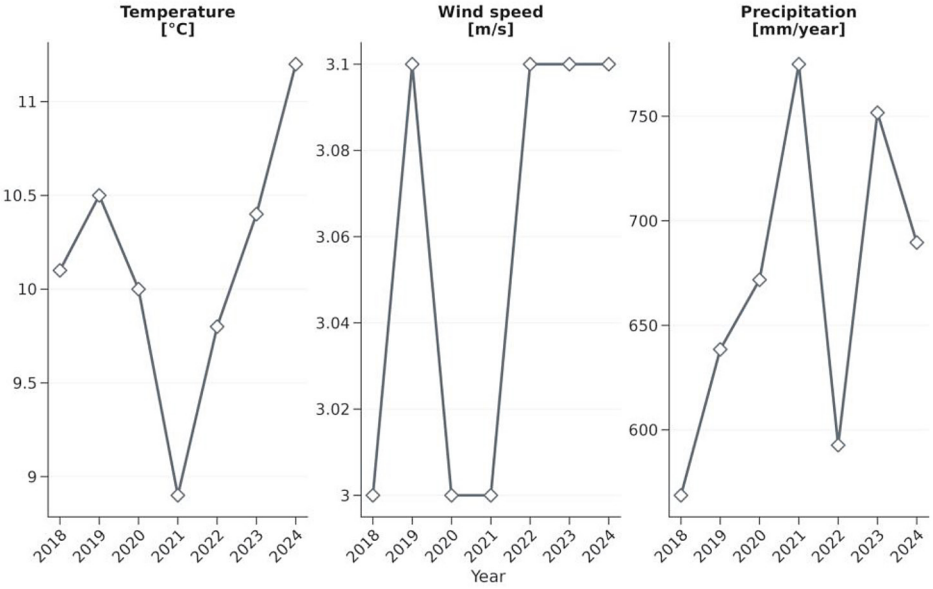


Fig. 4. Annual temperature, wind speed, and precipitation values used in the analysis for Kraków, 2018–2024. Source: based on data of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB)

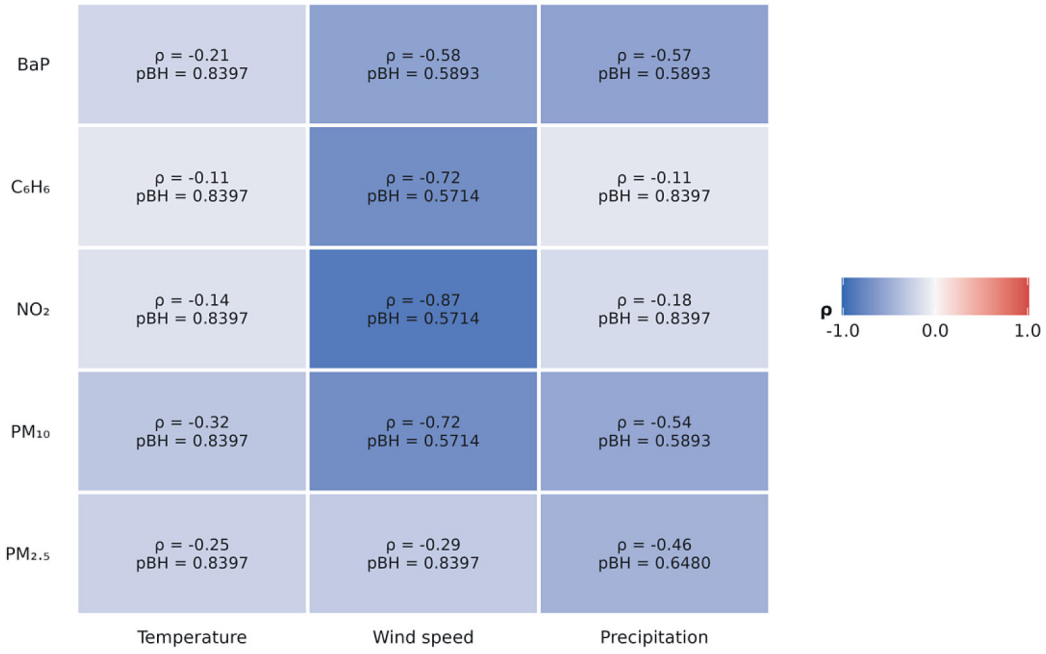


Fig. 5. Spearman rank correlations between three meteorological variables and concentrations of five pollutants in Kraków. Each correlation is based on seven annual observations. P values were adjusted jointly across 15 tests; cells report pBH

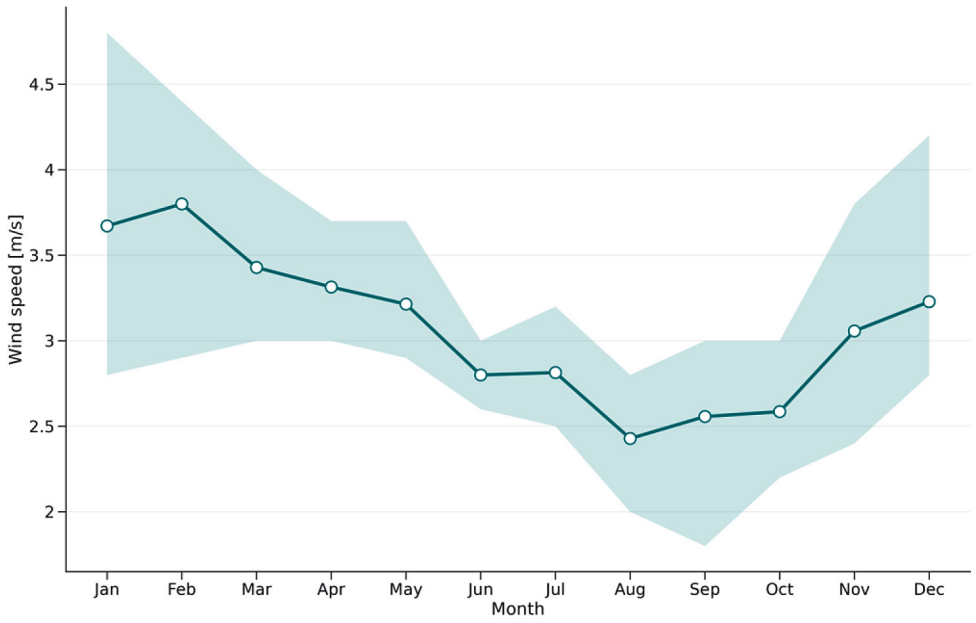


Fig. 6. Monthly wind-speed pattern in Kraków. The line gives the seven-year mean for each month; the band gives the minimum and maximum across those years for that month. Source: own elaboration

Building structure and intensity

The picture of Kraków's building stock differs markedly depending on the aggregation method applied. Low-rise buildings account for 88.45% of all buildings and 72.16% of the total building footprint area. When the number of storeys is taken into account, however, their share of the pseudo-usable floor area decreases to 43.68%. At the same time, the share of medium-rise buildings increases from 10.39% of the total number of buildings to 43.51% of the pseudo-usable floor area. High-rise buildings account for 12.75%, whereas very high-rise buildings represent only 0.06% of the city's pseudo-usable floor area. The shares of the four height classes are summarised in Table 3.

These results indicate that low-rise and medium-rise buildings account for nearly identical shares of the estimated total floor area in Kraków. A simple comparison based on the number of buildings strongly emphasises low-rise development and does not adequately reflect the importance of multi-storey residential complexes.

The largest total pseudo-usable floor area was recorded in Dębniki, which accounts for 9.62% of the citywide value. It is followed by Prądnik Biały (9.45%), Podgórze (9.16%), Stare Miasto (8.56%) and Nowa Huta (7.04%). The high values recorded in these districts result from both the spatial extent of development and the number of storeys.

The largest combined shares of classes W and WW in the internal building structure were recorded in Bieńczyce (37.62%), Mistrzejowice (35.93%) and Prądnik Czerwony (31.78%), which indicates that high-rise development is concentrated primarily in districts containing large residential estates. In contrast, the largest shares of medium-rise buildings occur in Stare Miasto (66.94%) and Krowodrza (60.02%). Buildings classified as WW occur only in Grzegórzki and Krowodrza, and their significance at the citywide scale remains marginal.

Normalising the results by district area changes the spatial pattern of building intensity. The highest pseudo-usable floor area per hectare was recorded in Stare Miasto (10,019 m^2/ha), followed by Grzegórzki (6,663 m^2/ha), Krowodrza (6,601 m^2/ha), Prądnik Czerwony (5,389 m^2/ha) and Bieńczyce (4,680 m^2/ha). The value for Stare Miasto corresponds to a simplified floor area ratio of approximately 1.00, meaning that on average approximately 1 m^2 of pseudo-usable floor area corresponds to every 1 m^2 of district area. The lowest values were recorded in Nowa Huta (701 m^2/ha), Wzgórza Krzesławickie (714 m^2/ha), Zwierzyniec (908 m^2/ha) and Swoszowice (975 m^2/ha). These results reveal a clear contrast between the compact urban fabric of the central districts and the spatially extensive peripheral districts. The spatial distribution of the indicator is shown in Figure 7, and the detailed results for individual districts in Table 4.

Table 3. Shares of building height classes in the pseudo-usable floor area of Kraków

City	N [%]	SW [%]	W [%]	WW [%]
Kraków	43.68	43.51	12.75	0.06

Note: On the basis of BDOT10k data. N – low-rise, SW – medium-rise, W – high-rise, WW – very high-rise buildings

Table 4. Building structure and intensity by district in Kraków

District	Area [ha]	Pseudo-usable floor area [m²/ha]	N [%]	SW [%]	W [%]	WW [%]	Dominant class
Bieńczyce	369.45	4,679.76	19.81	42.56	37.62	0.00	SW
Bieżanów-Prokocim	1,845.12	2,273.44	46.72	38.80	14.48	0.00	N
Bronowice	954.71	2,527.44	45.89	37.02	17.09	0.00	N
Czyżyny	1,224.16	2,748.21	35.18	42.82	22.00	0.00	SW
Dębniki	4,612.80	1,357.77	48.11	46.08	5.81	0.00	N
Grzegórzki	583.79	6,663.29	28.71	49.11	21.44	0.74	SW
Krowodrza	561.18	6,601.41	22.66	60.02	17.10	0.23	SW
Łagiewniki-Borek Fałęcki	540.81	2,627.52	61.53	24.82	13.65	0.00	N
Mistrzejowice	558.31	4,221.68	21.08	42.99	35.93	0.00	SW
Nowa Huta	6,533.28	701.42	68.63	30.12	1.25	0.00	N
Podgórze	2,563.52	2,325.69	47.71	49.47	2.82	0.00	SW
Podgórze Duchackie	952.80	3,372.66	34.47	42.25	23.28	0.00	SW
Prądnik Biały	2,338.87	2,629.66	37.61	48.86	13.53	0.00	SW
Prądnik Czerwony	642.98	5,388.73	25.44	42.78	31.78	0.00	SW
Stare Miasto	556.05	10,018.80	31.78	66.94	1.28	0.00	SW
Swoszowice	2,557.22	974.59	85.00	15.00	0.00	0.00	N
Wzgórza Krzesławickie	2,378.69	713.90	79.18	18.74	2.07	0.00	N
Zwierzyniec	2,869.31	908.40	75.47	24.39	0.15	0.00	N

Note: On the basis of BDOT10k data. N – low-rise, SW – medium-rise, W – high-rise, WW – very high-rise buildings

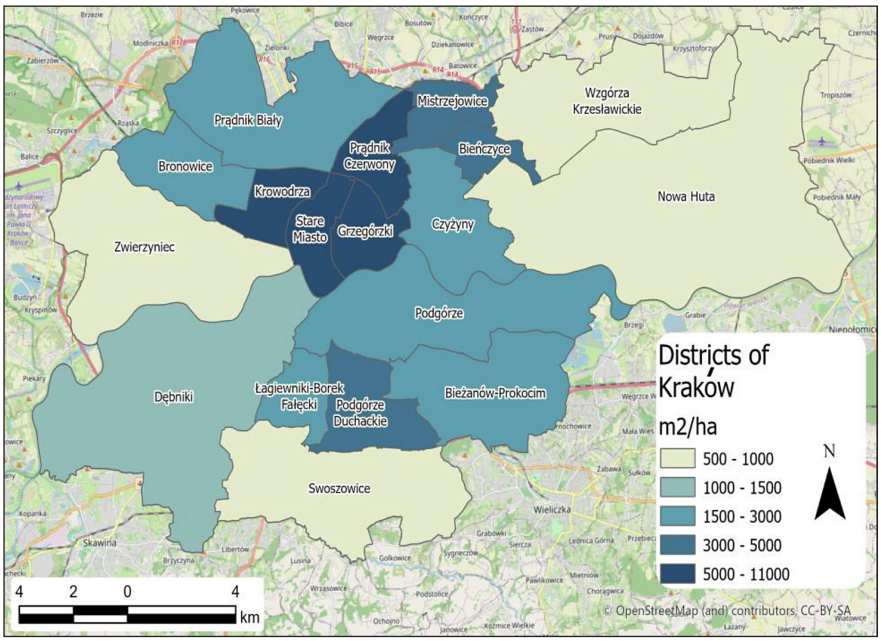


Fig. 7. Spatial differentiation of the pseudo-usable floor area of buildings per 1 ha of the district area in Kraków. The indicator was calculated as the quotient of the sum of the building footprint area multiplied by the number of storeys and the area of the district. Source: based on BDOT10k; map base: OpenStreetMap

Taken together, the two strands of the results describe the same city at two different spatial and temporal resolutions, and the present data do not allow them to be joined into a single statistical model. The concentration, emission and meteorological series are annual values representative of the city as a whole, whereas the building-structure indicators describe a single cross-section aggregated by district; there is no common unit at which the two could be matched. What can be stated is that the building-structure data describe a single point in time and therefore cannot account for the temporal change observed in the concentration series. The relevance of building structure is more plausibly expressed in the spatial distribution of exposure within the city – between the compact fabric of Stare Miasto, where building intensity reaches 10,019 m^2/ha, and the peripheral districts, where it is lower by more than an order of magnitude – than in the year-to-year variation of the citywide mean. Testing that proposition would require building-morphology indicators computed for the immediate surroundings of individual monitoring stations, which lies beyond the scope of the present study.

Interpretation and comparison with other studies

The results obtained for Kraków are consistent with the findings of studies which indicate that the decline in benzo(a)pyrene and particulate matter concentrations in Polish cities has been driven primarily by the replacement of solid-fuel heating appliances [12, 22]. In Kraków this process coincided with an administrative measure of exceptional scope: the anti-smog resolution for the city, which has prohibited the combustion of coal and wood since 1 September 2019 [35]. The empirical result is the magnitude of the BaP decrease (−83.8% between 2018 and 2024) and its perfectly monotonic character ($\rho = -1.00$). Attributing that decrease to the resolution is an interpretation, not a finding of this study: it is consistent with the operation of a systematic, long-term intervention rather than with year-to-year variability of weather, but a series of seven annual means cannot separate the effect of the ban from other processes acting in the same direction, such as the replacement of heating appliances that preceded it.

The significant positive emission–concentration relationships obtained for BaP and PM_{10} should be interpreted with caution. The KOBiZE data cover sources reported by entities using the environment, whereas the dominant source of BaP in Polish cities is municipal and residential combustion [22]. The correlation observed here therefore cannot be read as a direct causal contribution of the reported sources. A plausible explanation, which the present data do not test, is the parallel course of two processes that were subject to the same regulatory and economic pressures during the analysed period. Neither of these correlations was corrected for the trend over time, so part of the observed association may result from the fact that both series decreased throughout the period.

The absence of significant meteorology–concentration relationships contrasts with the well-documented role of thermal inversions and calm conditions in the accumulation of pollutants in the Kraków area [29, 30]. This apparent inconsistency results from the temporal resolution of the analysis: annual means average out precisely those episodes – periods of several days with strong inversion and calm – during which the influence of meteorology on concentrations is greatest. With seven annual observations, the statistical power of the analysis is also low, and the correction for multiple testing across 15 pairs further raises the detection threshold. The strongest correlation obtained, between wind speed and NO_2 ($\rho = -0.87$), has the direction expected on physical grounds, but with pBH = 0.5714 it cannot be regarded as evidence.

The height structure of development in Kraków, described by the pseudo-usable floor area indicator, is characterised by an almost identical share of low-rise (43.68%) and medium-rise (43.51%) buildings. A comparison based on the number of buildings alone would suggest a decisive predominance of low-rise development (88.45%), which illustrates why the choice of aggregation method determines the picture of the city obtained. This is the empirical content of the building analysis. Its relevance to ventilation is a hypothesis rather than a result: the obstruction that buildings present to airflow depends on their volume and height, not on their number, so the pseudo-usable floor area approximates the relevant quantity more closely than a building count does; this is a physical argument, not a finding of this study, since no ventilation or dispersion variable was measured. The concentration of high-rise development in the large housing estates of Bieńczyce, Mistrzejowice and Prądnik Czerwony, and of medium-rise development in the compact fabric of Stare Miasto and

Krowodrza, indicates that two morphologically distinct types of area may attain similar values of the aggregate indicator – a distinction that is lost at the city scale and whose significance for local dispersion conditions would have to be tested with morphology indicators computed around individual monitoring stations.

The practical significance of the changes recorded here becomes clearer when the 2024 values are compared with the standards laid down in the revised Ambient Air Quality Directive, which entered into force in December 2024 and must be met by 2030 [36]. Of the five pollutants analysed, two met the applicable levels in 2024: C_6H_6, at 1.05 µg/m^3, remained well below the limit value of 5 µg/m^3, and BaP, at 0.94 ng/m^3, fell just below its target value of 1.0 ng/m^3. The remaining three exceeded the limit values that will apply from 2030: the annual mean NO_2 concentration by approximately 86% (37.1 against 20 µg/m^3), PM_{10} by about 26% (25.1 against 20 µg/m^3) and $PM_{2.5}$ by roughly 66% (16.6 against 10 µg/m^3). Even the pronounced downward trend documented in this study would therefore have to be sustained, and in the case of nitrogen dioxide substantially accelerated, for Kraków to comply within the statutory horizon.

This observation shifts the emphasis of the policy problem. The measures adopted in the period – the replacement of heating appliances and the anti-smog resolution – acted on the municipal and residential combustion sector, which is the dominant source of both pollutants in Polish cities [12, 22]. The replacement of heating sources on the scale required calls for substantial investment; the technical and economic assessment of such investments against the criteria of the EU taxonomy for environmentally sustainable activities is discussed by Ciuła et al. [37]. Nitrogen dioxide, in contrast, originates predominantly from road transport [4], a sector on which those measures had no direct effect; this is consistent with the renewed increase in NO_2 concentrations recorded after 2022 and with the absence of a significant monotonic trend for this pollutant. Studies of urban form and air quality indicate that transport-related concentrations respond less to source substitution than to changes in the spatial organisation of traffic and to ventilation conditions [16, 17]; whether this applies to Kraków could not be evaluated with the present data, which is why the morphology of development is treated here as a candidate explanatory variable for station-level analyses rather than as a factor whose effect has been demonstrated.

Limitations

The analysis is based on seven annual values for the city as a whole. This limits both the precision of the results and the possibility of separating the influence of time from that of weather. The KOBiZE data cover sources reported by entities using the environment rather than total urban emissions, and municipal and residential combustion – the dominant source of BaP in Polish cities [22] – is therefore represented only indirectly. The building-structure indicators were aggregated at the level of 18 districts, whereas the concentrations are point measurements at monitoring stations aggregated to the scale of the whole city; the results therefore describe the co-occurrence of urban form and air quality at the city scale and do not permit conclusions about the immediate surroundings of individual stations. Consequently, the results describe changes within the analysed period but do not allow their causes to be established. No ventilation or dispersion variable was measured; statements relating building structure to ventilation conditions are therefore hypotheses drawn from the literature, not results of this study.

CONCLUSIONS

1. Between 2018 and 2024 the mean annual concentrations of all five air pollutants analysed in Kraków decreased; the largest declines were recorded for benzo(a)pyrene (−83.8%) and benzene (−49.4%).
2. Statistically significant monotonic downward trends were found for BaP and PM_{10}. For the same pollutants, significant positive relationships were obtained between reported emissions and concentrations, which is consistent with emission reduction having contributed to the improvement in air quality, although the nature of the data does not permit causal inference.
3. With seven annual observations, none of the 15 meteorology–concentration relationships was significant after correction for multiple testing. This does not indicate the absence of a meteorological influence, but reflects the limited statistical power of the analysis and the averaging of episodic conditions in annual means.

4. The height structure of development in Kraków is characterised by an almost identical share of low-rise (43.68%) and medium-rise (43.51%) buildings in the pseudo-usable floor area, whereas a comparison based on the number of buildings would indicate a decisive predominance of low-rise development (88.45%). The choice of aggregation method therefore determines the picture of urban structure obtained; indicators based on the number of buildings alone should not be used as a proxy for the volume of development, and the use of either indicator as a proxy for ventilation conditions would require validation against dispersion data that were not part of this study.
5. Building intensity in Kraków, expressed as the pseudo-usable floor area per hectare, varies by more than an order of magnitude between the compact central districts (Stare Miasto: 10,019 m^2/ha) and the spatially extensive peripheral districts (Nowa Huta: 701 m^2/ha). Air quality in the city is therefore measured in markedly different local development contexts; whether these differences translate into differences in concentrations could not be tested with the present data and requires morphology indicators computed around individual monitoring stations.

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