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Assessment of heating boiler replacement effectiveness in reducing PM10 and PM2.5 emissions: A case study of the Pszczyna Commune, Silesia, Poland

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Abstract: The Pszczyna commune in southern Poland has long faced poor air quality, especially during the heating season. This study assesses the effectiveness of a local policy to reduce PM10 and PM2.5 concentrations by replacing old solid-fuel boilers with low- or zero-emission systems. Using data on air quality from monitoring stations for the two years 2020 and 2023 as well as meteorological records, and administrative reports on the scale and scope of boiler replacements, the analysis applies statistical comparisons, meteorological normalization, and regression analysis to isolate commune policy effects from weather variability. Results show a significant reduction in PM levels, particularly in winter, with PM10 decreasing by over 30% and PM2.5 by up to about 40%. These findings confirm the effectiveness of targeted residential heating interventions and highlight how local actions, supported by regional and national funding, can yield measurable environmental and health benefits within a short period. Continued monitoring and public engagement are essential to sustaining air quality improvements.

Introduction

The 2008 CAFE Directive introduced unified air quality assessment standards across the EU (Directive CAFE 2008), leading to the establishment of Poland's State Environmental Monitoring system (PMŚ 2008), overseen by the Chief Inspectorate for Environmental Protection (GIOŚ). As part of this system, an air quality monitoring station was launched in Pszczyna in 2010.

Data from Pszczyna station, reported to the European Environment Agency (EEA), revealed that air quality in many Polish cities, especially in the south, was among the poorest in Europe. In 2016, the WHO identified 33 of the 50 most polluted European cities as being in Poland, with the highest $PM_{2.5}$ levels recorded in Żywiec and Pszczyna (WHO 2016). Later WHO reports confirmed persistently high $PM_{2.5}$ levels in other southern towns, including Kraków, Rybnik, and Nowy Sącz (WHO 2018, WHO 2022, IQAir 2024). Since the rankings include only cities with official EEA-reported data, they reflect a critical air quality situation in Poland.

In Poland, the main source of particulate matter is household heating using low-efficiency boilers that do not meet emission standards, often fueled with low-quality coal (GIOŚ 2022). Additional sources include industrial and energy-sector emissions, transport, and pollution from spoil heaps and mining pits (POP 2020, POP 2023). Pollution levels are further aggravated by poor dispersion conditions caused by windless periods, topography, and dense urban development. $PM_{2.5}$ exposure is linked to over 46,000 premature deaths annually in Poland (EEA 2020), and more than 4.14 million deaths globally (WMO 2023).

The Silesian Voivodeship is among the most polluted regions in Poland, as evidenced by numerous annual air quality assessment reports for Polish zones conducted by the Chief Inspectorate of Environmental Protection (GIOŚ). The primary problem is particulate matter and the PAHs it contains. All reports emphasize that low-level emissions, i.e., emissions from individual home and dwelling heating systems, are the main cause of this situation (Kobza et al. 2018, Cenowski 2019, Błaszczak et al. 2023, Janeczek and Jabłońska 2025).

The reasons cited include the widespread use of poor-quality fuels, the low efficiency of heating equipment, and unfavorable weather conditions. The latter limit urban ventilation due to the high frequency of light winds (< 2 $m \cdot s^{-1}$) and calm periods, as well as the occurrence of inversion conditions (Niedźwiedź et al 2021), which hinder the transport of pollutants into the upper atmosphere. It is also noted that the over-regional background plays a relatively large role in shaping particulate matter concentrations in the voivodeship, accounting for over 30% of the observed values (POP 2020, POP 2023). Additionally, the often dense and chaotic development of some areas of Silesian cities further impedes pollutant dispersion (Cenowski 2019).

Particulate matter from household heating significantly affects public health, contributing to respiratory (Fasola et al. 2020, Xing et al. 2016) and cardiovascular diseases (Wolf et al. 2021). Long-term exposure to $PM_{2.5}$ increases the risk of premature death (Mainka and Żak 2022). Ultrafine particles (<1 µm) are especially dangerous due to their ability to penetrate deeply into the lungs and bloodstream. Prolonged exposure may lead to heart and lung diseases, and even congenital defects (Brook et al. 2004, Guo et al. 2023, Gorini and Tonacci 2025). WHO guidelines recommend annual average concentrations below 5 $\mu g \cdot m^{-3}$ for $PM_{2.5}$ and 15 $\mu g \cdot m^{-3}$ for PM_{10} (WHO 2021), but these limits are frequently exceeded in Poland (PSA 2021). PM_{10} exposure shows delayed mortality effects, particularly among older adults and men, as well as people suffering from respiratory and circulatory diseases, children under 5 years of age, and pregnant women (Monn 2001, Schneider and Krzyzanowski 2004, Chen et al. 2016, Maciejewska 2020, Nazar and Niedoszytko 2022).

In 2016, local authorities and the community in Pszczyna initiated efforts to reduce particulate emissions by promoting cleaner heating practices and shifting social attitudes. The municipality joined the national "Clean Air" program, which provides funding for replacing heating systems, improving insulation and ventilation, and installing photovoltaics. Boiler inventories and regular inspections by the Municipal Guard help ensure compliance and discourage the burning of waste.

Pszczyna also collaborates with local initiatives such as "Don't Feed the Smog" and "Clean Pszczyna" to educate residents and promote environmentally friendly solutions. Eighteen particulate matter sensors have been installed across the municipality, and the NGO "Don't Feed the Smog" conducts educational campaigns (Pszczyński Alarm Smogowy 2019).

The results of these actions are visible. On February 17, 2025, when air pollution levels in much of southern Poland exceeded limits, Pszczyna remained below the thresholds. Data from municipal sensors, visualized via the Kanarek app (Kanarek 2016), confirmed that pollution levels in Pszczyna were lower than in neighboring municipalities (Figure S1 in Supplementary Material).

The aim of this study was to evaluate the impact of replacing outdated, low-efficiency residential heating systems with modern, higher-efficiency units using cleaner fuels or renewable energy on $PM_{2.5}$ and PM_{10} air pollution. Pszczyna was selected due to its status as one of the EU's most polluted cities until 2020. According to data of the Air Quality Department of Pszczyna City Hall, between 2020 and 2023, 44.21% of old heating systems, representing 74.66% of non-certified sources, were replaced. A noticeable reduction in particulate pollution was observed in 2023. This study seeks to determine whether the decline was caused by the replacement of heating systems or by other factors, such as rising temperatures during the heating season.

Materials and methods

Maps

Maps and GIS analyses were conducted using QGIS 3.30. A Digital Terrain Model (DTM) (GUGiK 2025) was prepared for hypsometric analysis, and terrain imaging and mosaicking were carried out in Surfer® 23 (Golden Software). Land use analysis was based on data from the Topographic Objects Database (BDOT 2011).

Data Sources

Air pollution data (PM_{10}, $PM_{2.5}$) were obtained from the State Environmental Monitoring system (PMŚ 2008) via the GIOŚ Air Quality Portal (GIOŚ 2015), as well as from local sensors in Pszczyna. These included 18 sensors managed through the Syngeos platform, six in the town and twelve in surrounding villages, recording data hourly (Syngeos 2025). Sensor locations are shown in Supplementary Figure S2.

Hourly meteorological data, including temperature and wind speed, were obtained from the Marek Dzida Specialist Horticultural Farm, where measurements are taken using PRIVA sensors. Additional daily meteorological parameters (air temperature, sunshine duration, and wind speed) were sourced from the climatological station of the Institute of Meteorology and Water Management, National Research Institute (IMGW-PIB) in Pszczyna (code: 249180010, location: 49°59'44.0"N 18°55'09.0"E).

Statistical Analysis

Particulate matter concentrations ($PM_{2.5}$ and PM_{10}) and meteorological parameters were analyzed in R (version 4.5.0; R Core Team). Since most variables did not follow a normal distribution (Anderson–Darling test), non-parametric methods were applied. Differences between years (2020 vs. 2023) and between months were assessed using the Mann–Whitney U test, with significant results ($p < 0.05$) indicated in the figures.

Associations between particulate matter and meteorological parameters were evaluated using Pearson's correlation coefficient after daily averaging. Multiple linear regression models were applied for the heating season (October-March) to assess the effects of air temperature, sunshine duration, and wind speed. Comparisons between Syngeos low-cost sensors and reference GIOŚ stations were performed using Spearman's correlation coefficient ρ.

Research Object

The study focused on the highly urbanized Pszczyna Commune, located in southern Poland's Silesian Voivodeship (Figure 1A), the country's most urbanized and densely populated region with 352 people/km^2 compared to the national average of 126 (WŚl 2024). The commune covers about 174 km^2 and has roughly 50,500 residents; while the city of Pszczyna itself has around 25,000 inhabitants within 22.5 km^2 (Figure 1B).

The city is predominantly composed of low, single-family houses (90%) (Figures 1C), and in 2020 its heating systems were largely low-efficiency (59.52%) (CEEB 2023).

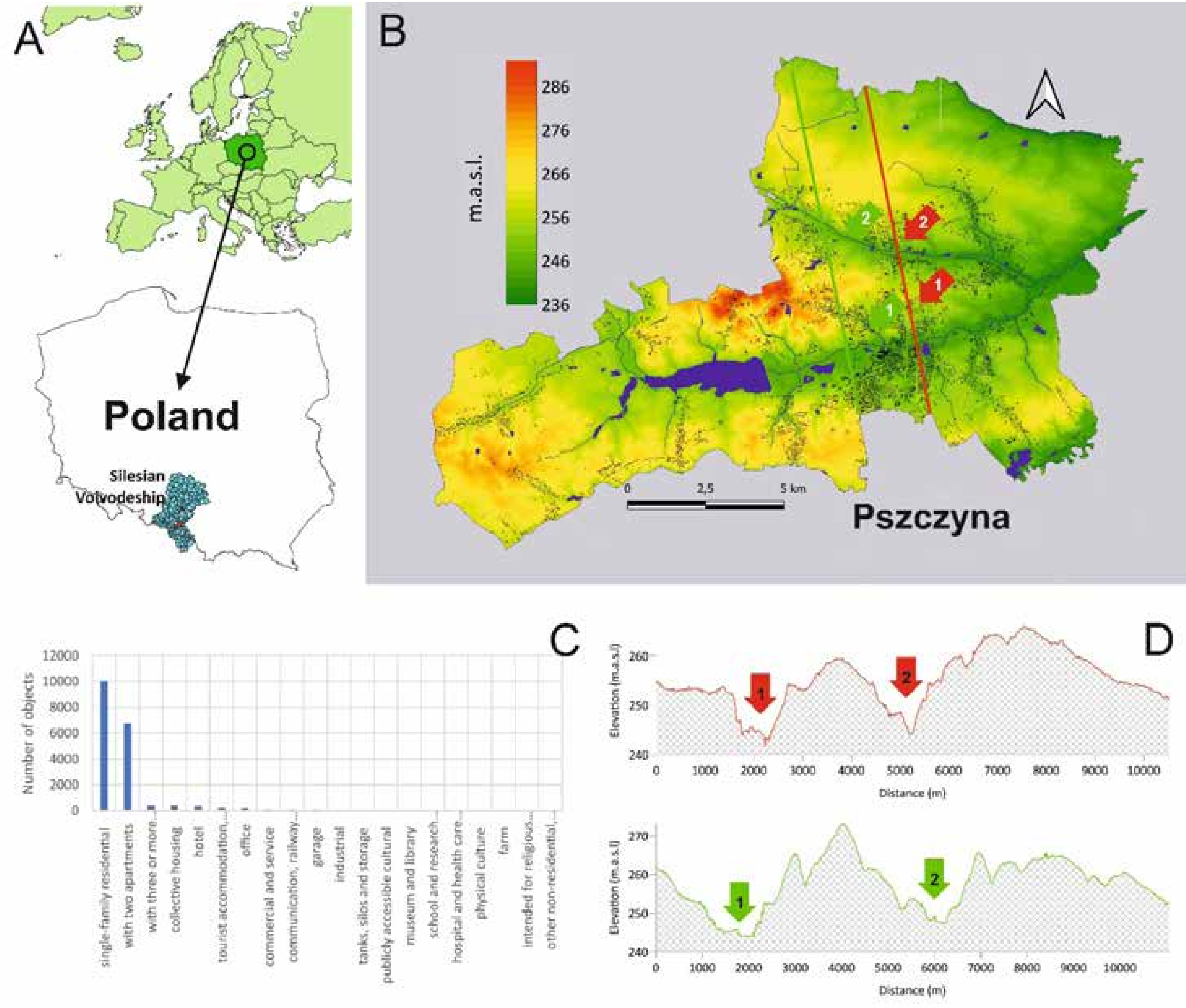

Figure 1 Location and analysis of the building structure and hypsometric analysis of the area of the Pszczyna Commune. A - Location of the Pszczyna Commune and Pszczyna City; B - Hypsometry of the commune with the distribution of buildings based on BDOT and the digital terrain model (DTM); C - building structure based on the number of buildings in the commune in individual classes, based on BDOT 2024; D - height profiles in accordance with the designated routes based on DTM. Red arrow indicates the location of the old town.
Maps were created in QGIS 3.40 based on the data obtained from Database of Topographic Objects (BDOT) and Digital Terrain Model (DTM) 2025 and OpenStreetMap 2025 as the map base. Hypsography and cross-sections were prepared in Surfer 22.0. based on DTM.

Hypsometric analysis shows that Pszczyna's central area, situated in the Pszczynka River valley, is prone to air stagnation and particulate accumulation, especially during temperature inversions, which limits ventilation (Figures 1B, 1D). Elevation profiles indicate that the valley floor is surrounded by higher terrain to both the east and west, creating a natural basin-like form that restricts air circulation. These topographic conditions favor the persistence of cold air masses and hinder pollutant dispersion, potentially intensifying episodes of poor air quality in the central part of the town.

During the winter 2021 in the Pszczyna area, manned balloon flights were used to measure PM_{10}, $PM_{2.5}$, and PM_1 concentrations at temperatures of 0 - 3°C and wind speeds of approximately 2 $m \cdot s^{-1}$ (Smołka-Danielowska et al. 2021). The results showed that particulate concentrations decreased with altitude; $PM_{2.5}$ and PM_1 levels equalized at around 100 m, while PM_{10} concentrations gradually declined up to 700 m, where they converged toward the levels of respirable dust fractions ($PM_{2.5}$ and PM_1). Pollutant accumulation in the boundary layer, typical of winter smog, was exacerbated by unfavorable meteorological conditions. The measured PM_{10} and $PM_{2.5}$ originated primarily from low-stack emissions, with sources below 40 m in height.

Results of the analyses

Analysis of the air pollution history in Pszczyna

Particulate matter concentrations were analyzed using data from the PM_{10} station PL0528A in Pszczyna and the nearby

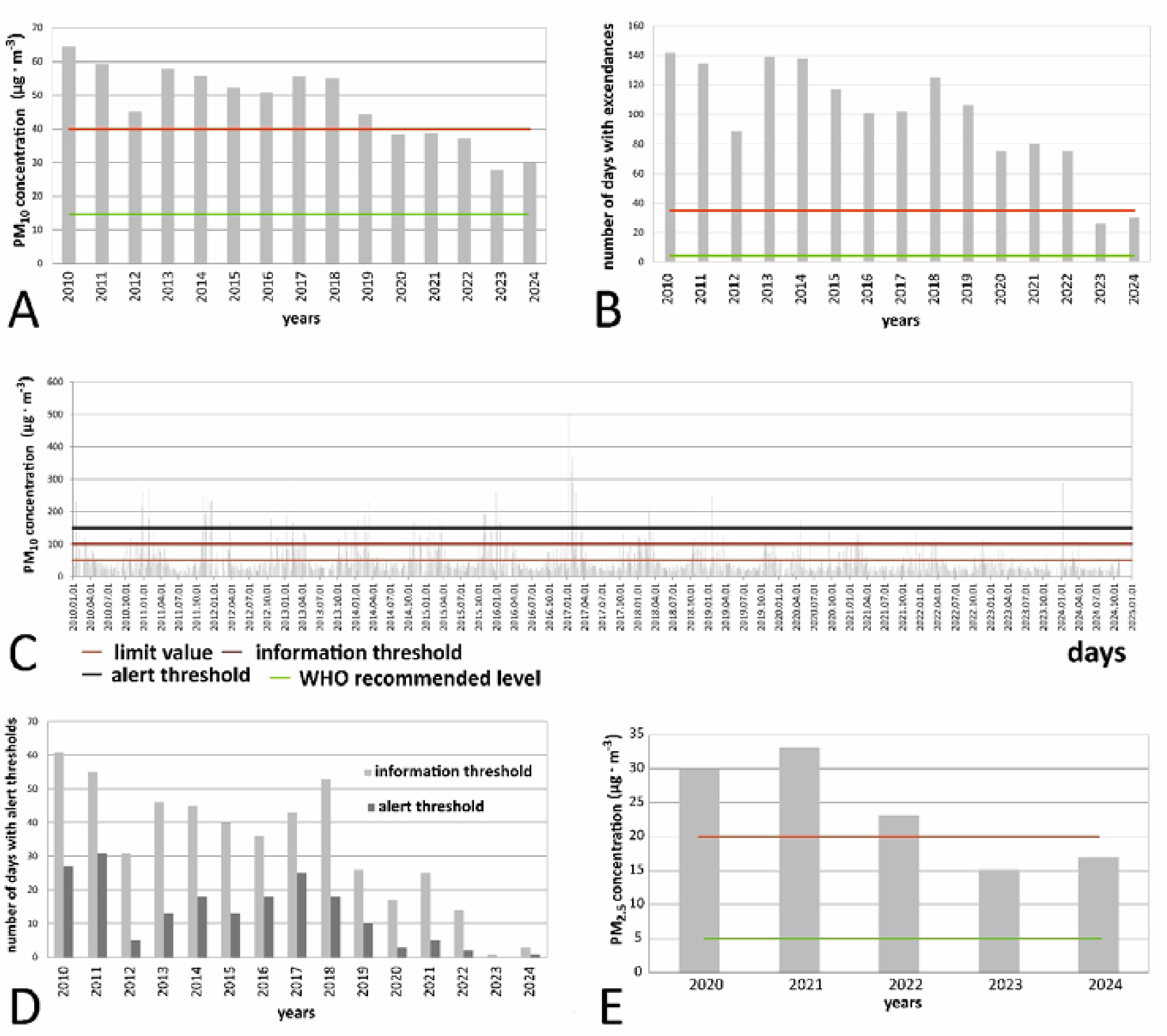

Figure 2. Variability of dust concentrations.
A - Average annual PM_{10} concentrations in the years 2010-2024 on monitoring station at Pszczyna; B - Frequency of 24-hour PM_{10} concentration exceedance in the years 2010-2024 on monitoring station at Pszczyna; C - 24-hour PM_{10} concentrations in the years 2010-2024 on monitoring station at Pszczyna; D - Frequency of information and alert thresholds exceedance in the years 2010-2024 on monitoring station at Pszczyna; E - Average annual $PM_{2.5}$ concentrations in the years 2020-2024 on monitoring station at Goczałkowice-Zdrój.
Source: own study based on data from State Environmental Monitoring (PMŚ).

$PM_{2.5}$ station PL0742A in Goczałkowice-Zdrój (about 4.5 km south of Pszczyna), both part of the State Environmental Monitoring (PMŚ) network (PMŚ 2008). PM_{10} data cover 2010-2024, $PM_{2.5}$ data 2020-2024.

Annual average PM_{10} concentrations (Figure 2A) exceeded the 40 $\mu g \cdot m^{-3}$ standard until 2019, ranging from 64.42 $\mu g \cdot m^{-3}$ (2010) to 44.29 $\mu g \cdot m^{-3}$ (2019). In 2020, for the first time, averages fell below this limit and have since remained between 27.90 and 38.80 $\mu g \cdot m^{-3}$, though still above the WHO recommended 15 $\mu g \cdot m^{-3}$ (WHO 2021).

Analysis of 24-hour PM_{10} levels, based on manual 24-hour measurements (Figure 2C), showed frequent exceedances of Poland's alert threshold of 150 $\mu g \cdot m^{-3}$ before 2020, with some days surpassing 300-400 $\mu g \cdot m^{-3}$ and a maximum of 503.50 $\mu g \cdot m^{-3}$ recorded on January 9, 2017. Since 2021, very high daily concentrations exceeding the information or alert threshold have markedly decreased. Importantly, concentrations also decreased during warmer months.

The frequency of exceeding the 24-hour PM_{10} limit at the Pszczyna station (Figure 2B) shows that the European standard of a maximum 35 exceedance days per year was met only in the last two analyzed years. In 2010-2022, exceedances ranged from 75 to 142 days annually, exposing residents to high PM_{10} levels for 2.5 to nearly 5 months each year. Exposure is even longer when considering the stricter WHO-recommended limit of 45 $\mu g \cdot m^{-3}$.

Table 1. Basic descriptive statistics of PM_{10} and $PM_{2.5}$ concentrations [μg·m^{-3}] in the respective years.

	N	Mean	Median	Min	Max	Q_1	Q_3	SD	V_x	A stat	p value
2020											
$PM_{2.5}$	5857	18.59	11.29	0.01	451.63	4.92	24.47	24.69	132.79	466	<0.001
PM_{10}	5857	30.08	17.90	0.02	752.71	7.44	39.45	40.56	134.81	296	<0.001
2023											
$PM_{2.5}$	6295	11.67	7.55	0.19	91.68	4.16	14.67	11.72	100.46	400	<0.001
PM_{10}	6294	20.05	13.30	0.34	146.26	7.35	25.47	19.46	97.06	293	<0.001

Notation: N - sample size, Q_1 - first quartile, Q_3 - third quartile, SD - standard deviation, V_x - coefficient of variation. Anderson–Darling test results: A stat - test statistic, p value - probability values of the Anderson–Darling test assessing data normality. Values below 0.05 indicate a deviation from the normal distribution.

Similarly, the number of days exceeding Polish thresholds, the information level (100 μg·m^{-3}) and alert level (150 μg·m^{-3}), varied between 1 and 61 days, and 0 to 31 days per year, respectively (Figure 2D). The lowest exceedance counts occurred in the last three years, with 14, 1, and 3 days above the information level, and 2, 0, and 1 days above the alert level per year. It should be stressed that before 2019 the information and alert thresholds were set at much higher values (200 and 300 μg·m^{-3}, respectively), but for consistency this work refers to present thresholds. The change of these values was a consequence of a study described in Adamkiewicz et al. (2021 a).

Since PMŚ does not measure $PM_{2.5}$ directly in Pszczyna, data from the nearby Goczałkowice-Zdrój station were used (Figure 2E). $PM_{2.5}$ measurements there have been available since 2020. Only in 2023 and 2024 annual average $PM_{2.5}$ concentrations fell below the standard limit, at 15.10 and 16.94 μg·m^{-3}, respectively. However, these values remain far above the WHO-recommended level of 5 μg·m^{-3}. The highest annual concentration was recorded in 2021 and it amounted to 33.00 μg·m^{-3}.

Since 2010, alongside PM_{10} measurements, Pszczyna has monitored PM_{10} composition, including heavy metals (lead, arsenic, cadmium, nickel) and benzo(a)pyrene, a marker for PAHs, as part of the PMŚ. While heavy metal limits have never been exceeded, benzo(a)pyrene levels have annually surpassed permissible values by several to more than ten times.

Before 2020, poor air quality caused by household solid-fuel combustion occurred broadly in southern Poland. To address this, emission reduction measures were implemented to reduce low-stack emissions. Residents were encouraged to replace outdated heating systems with more efficient alternatives using cleaner fuels or renewable energy.

One of the first subsidy programs for replacing home heating sources was the KAWKA program, launched in 2013 by the National Fund for Environmental Protection and Water Management (NFOŚiGW) (NFOŚiGW 2010) in cooperation with regional funds (KAWKA 2013). In 2017, the Silesian Voivodeship adopted the Anti-Smog Resolution, banning lignite and low-quality fuels and setting a timeline for replacing old heating systems with those meeting PN-EN 303-5:2012 and EU Ecodesign standards (Anti-Smog Resolution 2017, PN-EN 2012, Directive Ecodesign 2009). In 2018, the Minister of Energy introduced solid-fuel quality standards (ME Regulation 2018).

At the same time, in 2017 - 2018, the Low-Stack Emission Reduction Program (PONE) (PONE 2017) was introduced in the Pszczyna municipality, with annual calls for applications from residents. This program provided funding for the replacement of heating sources.

Currently, the "Clean Air" program, launched in September 2018, supports the replacement of old solid-fuel stoves and boilers with compliant devices, as well as funding insulation, window and door replacement, renewable energy installations, and mechanical ventilation with heat recovery (Clean Air 2018).

Analysis of Particulate Matter in the Years 2020 and 2023

In 2023, the average annual concentration of PM_{10} in Pszczyna decreased by one-third compared to 2020. A similar decrease in concentration was also observed for $PM_{2.5}$ (Table 1).

In 2023, the average PM_{10} concentration in the Pszczyna municipality decreased by 33.34% compared to 2020, while the average $PM_{2.5}$ concentration decreased by 37.22% over the same period.

The Mann-Whitney U test was used to compare $PM_{2.5}$ and PM_{10} concentrations between the two years due to the non-normal distribution of the data (see Table 1). For $PM_{2.5}$, the test yielded W = 497276, p-value < 0,001 and for PM_{10}, W = 69982, p-value < 0,001. In both cases, the differences were statistically significant, indicating a marked decrease in particulate matter levels in 2023 compared to 2020.

Analysis of monthly PM_{10} and $PM_{2.5}$ concentrations (Figure 3A, 3B, 3C) shows a significant decrease in levels across all months in 2023 compared to 2020, except for February, where no reduction was observed. In both years, particulate levels were substantially lower in summer than in winter, but in 2023 the seasonal differences were smaller than in 2020.

The daily distributions of particulate matter concentrations (Figure 3D) show that in 2020 there were greater differences in concentration levels between midday and evening/night hours. In contrast, in 2023, the daily distributions of particulate

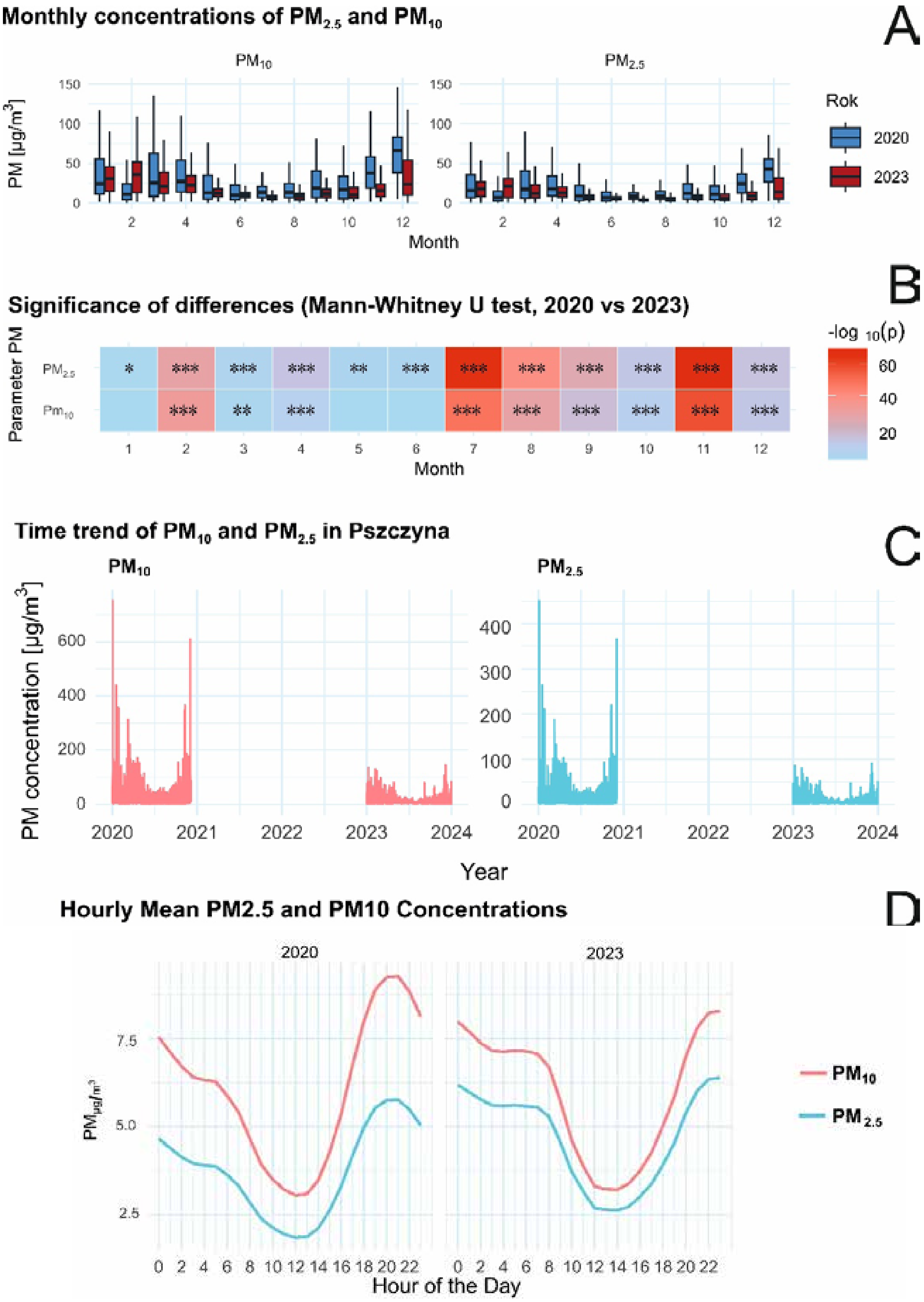

Figure 3. Analysis of $PM_{2.5}$ and PM_{10} concentrations in Pszczyna.
A - Boxplots showing monthly medians of $PM_{2.5}$ and PM_{10} concentrations; B - Heatmap presenting the significance of differences between concentration levels in the analyzed years (Mann–Whitney U test; significance levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$); C - Distributions of $PM_{2.5}$ and PM_{10} concentrations in both years; D - Daily distribution. Average $PM_{2.5}$ and PM_{10} concentrations by hour across all days, showing typical daily patterns.

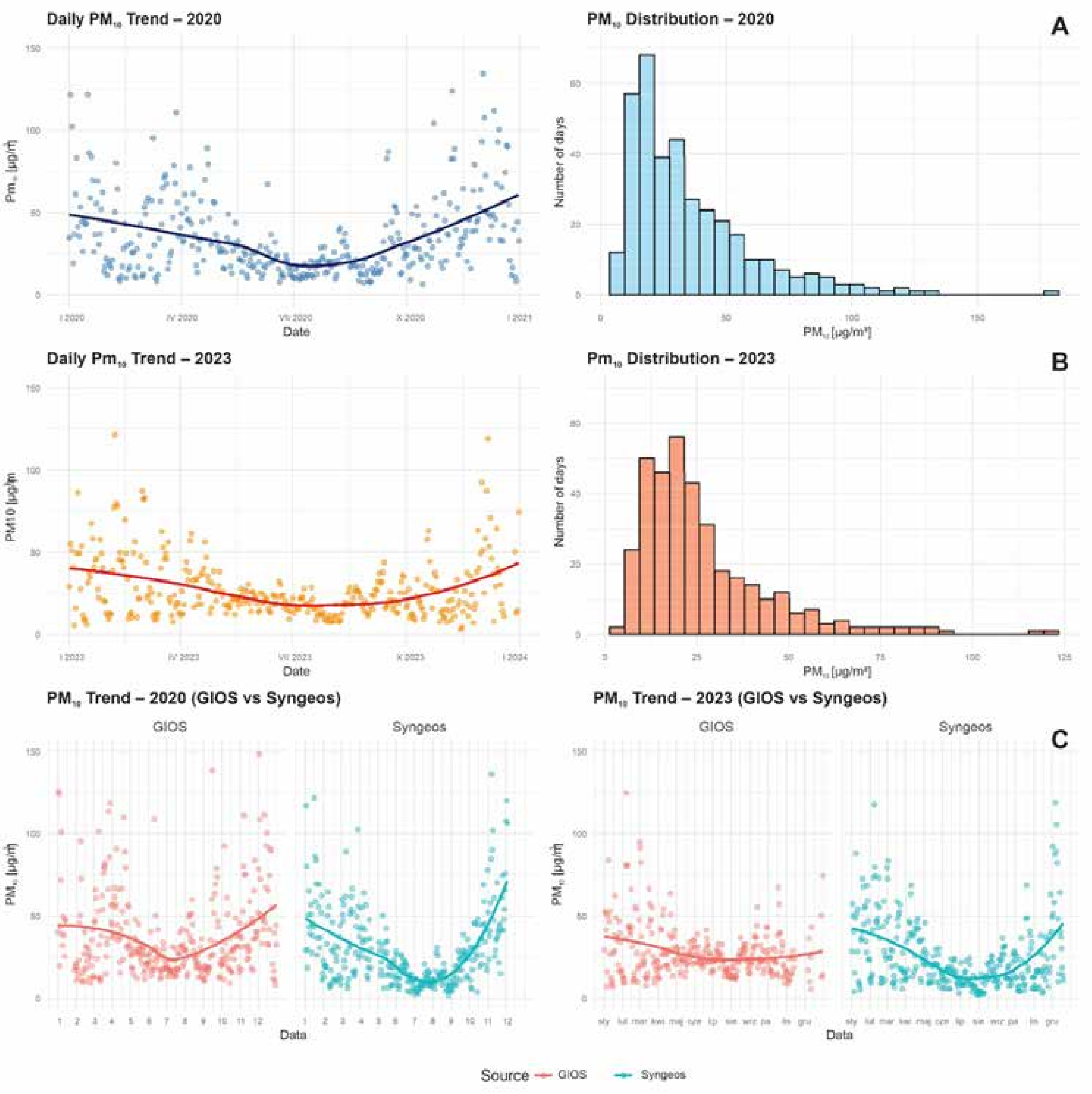

Figure 4. Daily distributions of PM_{10} dust concentrations (µg·m⁻³) in both analyzed years, based on measurement data averaged from PMŚ monitoring station (GIOŚ) and 18 Syngeos sensors placed in the commune.

matter concentrations became more uniform ("flattened") compared to 2020.

Previous analyses were based on readings from Syngeos sensors, which provide high-resolution data suitable for detailed hourly assessments. However, these low-cost sensors are often criticized for their limited accuracy in measuring coarse particulate matter (e.g., PM_{10}), particularly at the upper end of the PM_{10} range. Therefore, comparative analyses were performed using data from GIOŚ sensors. In these comparisons, only daily average PM_{10} concentrations were considered, as such data are the only ones available in the GIOŚ databases. The comparison of measurements from both sensor types is presented in Figure 4, which shows the daily distributions of PM_{10} and $PM_{2.5}$ concentrations.

The analyses revealed a strong correlation between daily PM_{10} measurements from the two types of sensors (Spearman's correlation coefficient, $\rho = 0.79$). On average, GIOŚ sensors reported PM_{10} concentrations 3.60 $\mu g \cdot m^{-3}$ higher than Syngeos sensors. In 2023, according to GIOŚ data, 9.90% of days exceeded 50 $\mu g \cdot m^{-3}$, whereas Syngeos sensors recorded 7.72% of such days. Similarly, in 2020, 19.60% of days exceeded this threshold according to GIOŚ measurements, compared

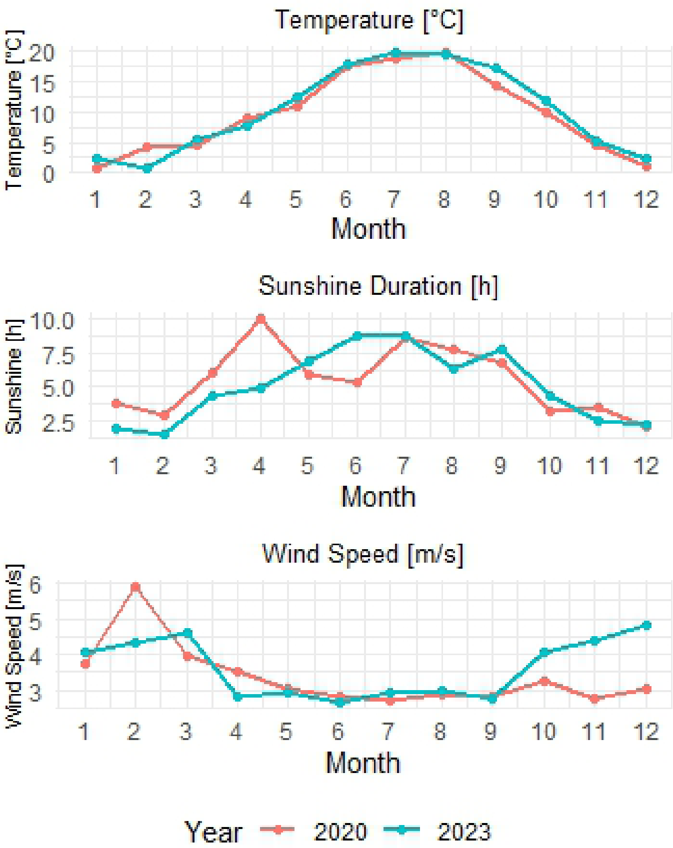

Figure 5. Monthly distributions of temperature, sunshine duration and wind speed in the years 2020 and 2023 in the analyzed area.

to 14.13% based on Syngeos data. Despite the differences between the two sensor types, the results indicate that air quality in Pszczyna improved in 2023.

Analysis of Climatic Conditions

The climatic conditions in both analyzed years were very similar (Figure 5).

In 2023, the average daily temperature in Pszczyna (10.32°C) was slightly higher than in 2020 (9.71°C), with both years showing a similar range of extremes, from winter minima (−7.5°C in 2023 and −5.9°C in 2020) to summer maxima (25.0°C and 24.1°C, respectively). Sunshine duration was slightly lower in 2023 (5.12 h) compared to 2020 (5.51 h), while wind speed was marginally higher in 2023 (3.60 $m \cdot s^{-1}$) than in 2020 (3.36 $m \cdot s^{-1}$). Both parameters exhibited considerable day-to-day variability, reflecting irregular weather patterns. Overall, 2023 was characterized by slightly warmer and windier conditions, whereas sunshine remained moderately stable and comparable to 2020.

The daily distributions of particulate matter concentrations in 2023 (Figure 4) remained relatively constant, which differed markedly from the daily distribution patterns observed in 2020. For this reason, PM concentration levels in February were compared for both years to identify the factors that most strongly influenced suspended particulate matter levels. The choice of February was intentional, as it was the only month in 2023 in which significantly higher PM concentration levels were recorded compared to 2020 (Figure 5). However, it should be noted that in February 2023, average air temperatures and sunshine duration were both significantly lower than in February 2020. Additionally, wind speeds were substantially higher in February 2020, which may have contributed to better air quality.

Daily particulate matter concentrations were lower on warmer and windier days (see Figure S3 in the Supplementary Materials). To assess the impact of the "Clean Air" program in Pszczyna, PM levels were compared during the heating seasons, i.e., in the months of January–March and October–December, in both analyzed years.

The Mann-Whitney U test revealed significant differences in $PM_{2.5}$ and PM_{10} concentrations between 2020 and 2023 ($PM_{2.5}$: Z = 4.79 $p < 0.001$; PM_{10}: Z = 4.62, $p < 0.001$). In 2023, particulate matter levels were lower than in 2020 ($PM_{2.5}$: 16.02 vs. 24.71 µg m^{-3}; PM_{10}: 27.32 vs. 39.91 µg m^{-3}; values are means), indicating an improvement in air quality.

During the 2023 heating season, compared to 2020, the average air temperature was higher (4.73°C vs. 4.20°C), and wind speed was slightly greater (4.37 $m \cdot s^{-1}$ vs. 3.75 $m \cdot s^{-1}$). In contrast, sunshine duration was lower (2.83 h vs. 3.61 h) (Table 2). $PM_{2.5}$ and PM_{10} concentrations were markedly lower, indicating an improvement in air quality.

Table 2. Selected descriptive statistics for selected climate parameters for measurements during the heating seasons.

	N	Mean	Median	Min	Max	Q1	Q3	SD	Vx
2020									
temperature [oC]	183	4.20	3.60	-5.90	17.10	0.90	7.10	4.32	103.05
sunshine duration [h]	183	3.61	2.70	0.00	11.40	0.10	6.60	3.43	95.09
wind speed [m•s-1]	183	3.75	3.10	1.00	11.30	2.30	4.80	2.01	53.67
2023									
temperature [oC]	182	4.73	4.50	-7.50	17.90	0.70	8.40	5.46	115.32
sunshine duration [h]	182	2.83	1.45	0.00	11.20	0.00	5.20	3.23	114.25
wind speed [m•s-1]	182	4.37	4.00	0.50	10.50	2.60	5.90	2.06	47.23

Notation: N - sample size, Q_1 - first quartile, Q_3 - third quartile, SD - standard deviation, V_x - coefficient of variation. Sunshine duration equal to 0.00 indicates the absence of direct sunlight during the measurement period.

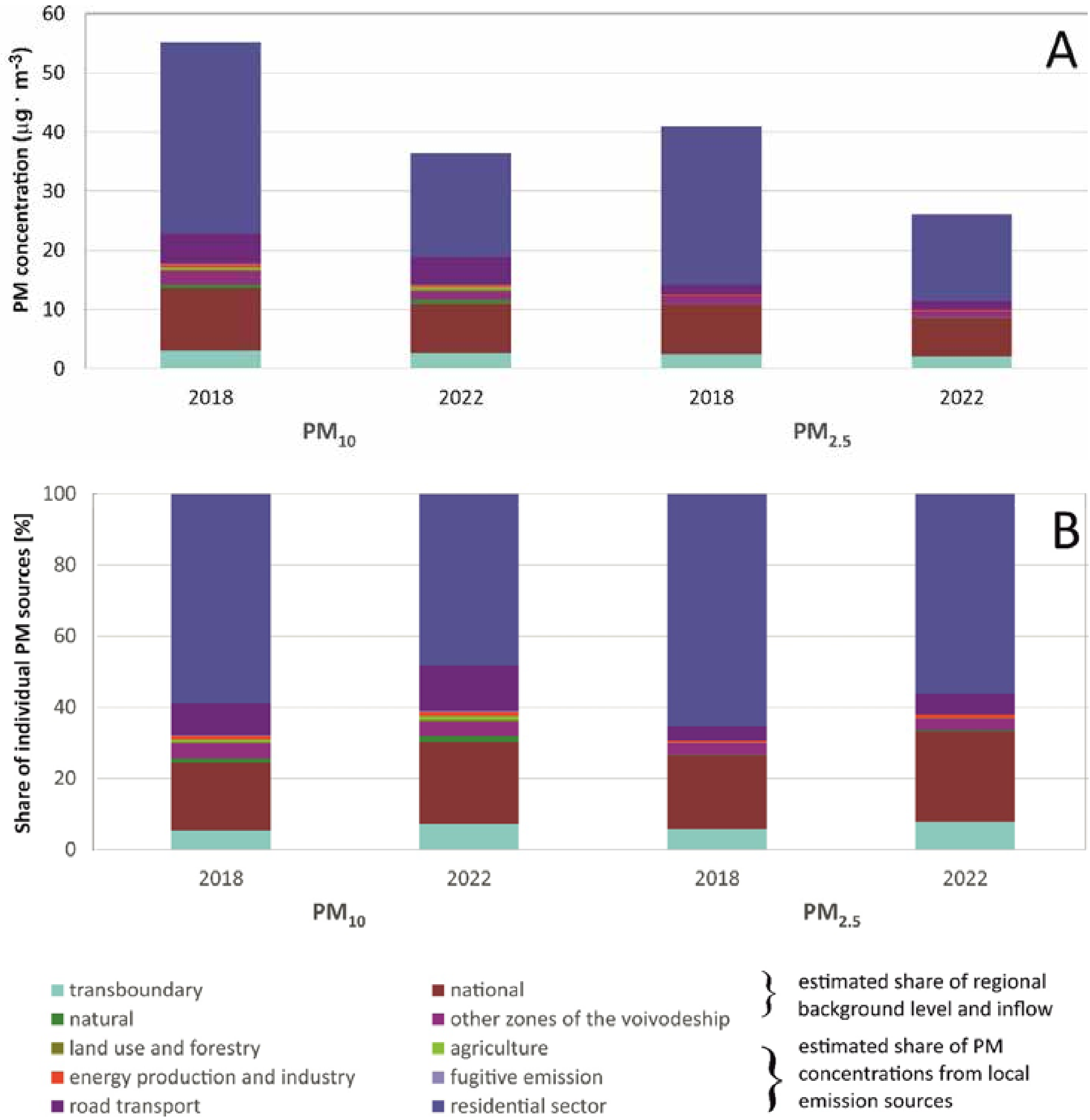

Figure 6. A - Impact of inflow and individual local emission sources on PM_{10} and $PM_{2.5}$ concentrations in Pszczyna in 2018 and 2022; B - Share of inflow and individual local emission sources in PM_{10} and $PM_{2.5}$ concentration levels in Pszczyna in 2018 and 2022. Source: own study based on modelled data (POP 2020, POP 2023).

The results indicate that meteorological conditions in Pszczyna played a key role in shaping $PM_{2.5}$ and PM_{10} concentrations in both 2020 and 2023. Pearson correlation coefficients (Table S1) revealed significant negative relationships between PM levels and air temperature as well as wind speed. Temperature had the strongest effect in both years, with correlations of approximately −0.35 in 2020 and −0.59 in 2023, indicating higher PM concentrations during colder periods. Wind speed consistently contributed to pollutant dispersion, with correlations of around −0.23 in 2020 and −0.26 in 2023. Sunshine duration showed a weaker influence, slightly increasing PM levels in 2020 and reducing them in 2023.

Multiple regression models (Table S2) were used to estimate $PM_{2.5}$ and PM_{10} concentrations in Pszczyna for the years 2020 and 2023. The $PM_{2.5}$ model explained 31–57% of concentration variability, depending on the year, with an accuracy of approximately ±18 µg m^{-3}. Air temperature and wind speed were the most significant predictors, consistently indicating that lower temperatures and weaker winds increased $PM_{2.5}$ levels, while sunshine duration had a smaller effect.

The PM_{10} model accounted for 32–58% of variability, with an accuracy of ±27 μg m^{-3}, and similarly highlighted the dominant role of temperature and wind speed in controlling concentrations. Overall, colder and calmer conditions favored the accumulation of particulate matter, whereas sunshine contributed only moderately to daily variability.

Of course, the presented models do not fully explain PM_{10} and $PM_{2.5}$ concentration levels, indicating that additional factors influence their variability. Nevertheless, the concentration levels observed in 2020 and 2023 suggest that the replacement of heating sources has significantly improved air quality in Pszczyna. It is worth noting that a strong positive correlation was observed between the cumulative number of replaced boilers in 2020–2023 and the annual average PM_{10} concentration (ρ = 0.80), although the result is not statistically significant due to the small number of measurements.

Table 3. Replacing of boilers in Pszczyna in the years 2020-2023.

Year	Number of boilers replaced	Total thermal power of old boilers [kW]
2020	188	2 790.00
2021	837	14 093.00
2022	446	7 015.50
2023	309	11 185.80
Total	1 780	35 084.30

Source of data: Air Quality Department of Pszczyna City Hall

Discussion

Poor air quality in Pszczyna is primarily caused by emissions from low-height (under 10 m) emitters of household heating systems burning solid fuels, which directly affect the air inhaled by residents. Efforts to encourage boiler replacements have led to significant reductions in particulate emissions and ambient PM concentrations, as confirmed by both monitoring and modeling data.

The existing modeling data available for the PMŚ station location in Pszczyna come from the two most recent *Air Protection Programs for the Silesian Voivodeship* (POP 2020, POP 2023). Model simulations were performed for the years 2018 and 2022. The results show that between 2018 and 2022, annual average PM_{10} concentrations dropped from 55.02 to 36.51 μg·m^{-3} (Figure 6). In 2018, the residential sector contributed 32.50 μg·m^{-3} (59%) of total PM_{10}, falling to 17.70 μg·m^{-3} (48%) by 2022. Similarly, $PM_{2.5}$ concentrations fell from 41.00 to 26.00 μg·m^{-3}, with residential contributions decreasing from 26.80 μg·m^{-3} (65%) to 14.70 μg·m^{-3} (56%) over the same period.

In Pszczyna, a city severely affected by smog, local authorities actively participate in the national "Clean Air" program, offering subsidies for heating system replacement and building insulation. The city established an Air Quality Department to assist residents with grant applications, coordinate anti-smog initiatives, and monitor outcomes.

According to data from Air Quality Department of City Hall, between 2020 and 2023, 1,780 boilers with a total heating capacity exceeding 35 MW were replaced (Table 3). All of the replaced boilers were of at most class 3 and were substituted with new boilers of the same capacity. The current structure of heat sources in Pszczyna is presented in Table 4 (CEEB 2023).

To meet the requirements of the Anti-Smog Resolution in Pszczyna, 1,472 additional boilers (i.e. all boilers below Class 5 existing after 2023) must be replaced by the end of 2027. This means that the current rate of replacement of these devices, an average of approximately 445 boilers per year between 2000 and 2023, should increase to approximately 490 boilers per year.

Analysis of air quality trends in Pszczyna indicates a gradual decrease in PM_{10} concentrations over 2020–2023, largely influenced by meteorological conditions. While weather factors, particularly during the heating season, account for a significant portion of the reduction in particulate matter concentrations, they do not explain the entire observed decrease. Therefore, other factors, primarily driven by residents' actions, must have contributed to the improvement in air quality in Pszczyna. Measures, such as replacing old boilers and discontinuing the use of low-quality solid fuels in households, contributed to the reduction of emissions from low-stack sources, leading to a decrease in airborne concentrations. However, further research based on more extensive data is required to definitively confirm this conclusion.

Similar large-scale research was presented in the European Clean Air Centre report (Adamkiewicz et all. 2021 B). Using an advanced statistical model, the study quantified the contribution of weather conditions versus human actions to air quality improvements. Results for 11 Polish cities from 2010-2019 indicate that human activity contributed to the level of PM_{10} concentrations. The most substantial reductions in PM_{10} concentration, resulting from measures undertaken to reduce the amount of emissions (after eliminating the impact of meteorological factors), were observed for two stations in Kraków: 22.90 μg·m^{-3} and 22.60 μg·m^{-3}, corresponding to 78% and 70% of the total PM_{10} reduction, respectively. In Katowice, a city located in Silesia, human activities independent of weather conditions were responsible for approximately half of the decrease in PM_{10} concentrations.

The observed decrease in PM concentrations in Pszczyna between 2020 and 2023, a reduction of 33.30% for PM_{10} and 37.20% for $PM_{2.5}$, indicates that the implemented anti-smog measures (e.g., boiler replacement, emission reduction programs) had a tangible effect. If this trend continues at a similar pace and no significant increases in emissions occur, average annual PM_{10} levels could approach about 12 μg·m^{-3} by 2030, meeting the requirements of the Ambient Air Quality Directive (Directive AAQD 2024). However, this projection should be interpreted cautiously, as it does not account for potential variations in emissions or extreme weather events.

This conclusion is supported by other studies conducted for Poland. In 2024, air quality concentrations predicted for 2030 were modeled using the EMEP4PL chemical transport model (Adamkiewicz et all. 2024), based on the EMEP MSC-W European Monitoring and Evaluation Program, Meteorological Synthesis Center-West. As demonstrated by the conducted modelling, Poland has the potential to meet the AAQD thresholds proposed by the European Commission by

2030. Achieving this target will require the replacement of 2.70 million outdated boilers, i.e., approximately 6,000 boilers per week, a pace currently being approached in Poland. The report emphasizes that meeting this goal also requires the continued implementation of anti-smog resolutions, coal and biomass quality standards, emission standards for low-power combustion devices, and the further development of the Clean Air Program and other subsidy initiatives, including for multi-family housing.

Climate change leads to additional complexity. Warmer winters reduce heating demand and emissions, but more frequent calm winds and winter temperature inversions hinder pollutant dispersion, causing local accumulation of particulate matter.

Conclusions

The example of Pszczyna shows that, despite adverse meteorological conditions, particularly during the autumn-winter period (e.g., weak winds, temperature inversions, lack of precipitation, and a lowering of the mixing layer height), which promote smog formation, air quality improvement is possible.

Thanks to the replacement of 1,780 boilers over the past four years, air quality in Pszczyna has already improved significantly. Estimates indicate that with a slight increase in the rate of boiler replacement (from 445 to 490 boilers per year), the municipality could meet the requirements of the Anti-Smog Resolution by January 1, 2028. This, in turn, would result in a reduction of particulate matter emissions sufficient to maintain the current pace of air quality improvement.

The ongoing decrease in particulate matter concentrations also suggests that Pszczyna could meet the new air quality standards introduced by the Ambient Air Quality Directive by 2030. However, this projection should be interpreted cautiously, as it does not account for potential variations in emissions or extreme weather events.

Given the unfavorable geographical conditions of cities situated in river valleys, spatial development plans should incorporate requirements for the use of zero- or low-emission heating systems in buildings. Implementing such measures, however, necessitates financial compensation mechanisms for users, due to the higher costs associated with the construction and operation of these systems.

Programs that provide residents with funding to replace old heating sources with new, low-emission boilers are particularly effective, as they directly reduce emissions from household heating. However, these initiatives should be accompanied by educational campaigns that raise awareness of health and environmental impacts, encouraging residents to take an active role in improving their living conditions and reducing health risks. Local authorities also play a critical role by assisting residents in accessing financial resources, guiding them through grant applications, identifying suitable programs, and advising on selecting the most suitable new heating source based on technical requirements.

The analyses presented here focus on the initial observable effects resulting from heating system replacement. The long-term effectiveness of the measures implemented in the city's heating infrastructure should be subject to continuous monitoring.

Table 4. The structure of heat sources in Pszczyna in 2020.

Heat source	Number [pcs]	Share of heating systems
Gas boiler	14 000	50.61%
Solid fuel boiler of which: Boilers below Class 3 or no information available Class 3 boilers Class 4 boilers Class 5 boilers Ecodesign	4 866 1720 664 868 1510 104	17.59%
Residential space heater	3 490	12.62%
Electric heating	3 410	12.33%
Heat pump	1 100	3.98%
Solar collectors	289	1.04%
System heat	277	1.00%
Photovoltaics	190	0.69%
Oil boiler	39	0.14%
Total	27 661	100.00%

Source of data: CEEB

References

Adamkiewicz, Ł., Maciejewska, K., Skotak, K., Krzyzanowski, M., Badyda, A., Juda-Rezler, K. & Dąbrowiecki, P. (2021 a). Health-Based Approach to Determine Alert and Information Thresholds for Particulate Matter Air Pollution. *Sustainability*, 13, 3, p. 1345. DOI: 10.3390/su13031345

Adamkiewicz, Ł., Mucha, D. & Cygan, M. (2021 b), People or weather. What improves air quality? Analyses with the application of the model normalizing concentration of air pollutants with the application of meteorological data. Pilot study. European Clean Air Centre, Warsaw (https://cleanaircentre.eu/wp-content/uploads/2025/08/People-or-weather_what-improves-air-quality_ECAC.pdf (10.10.2025)).

Adamkiewicz, Ł., Maciejewska K. & Mucha, D. (2024), Poland's journey to clean air and AAQD compliance by 2030. Summary of the results. European Clean Air Centre, Warsaw (https://cleanaircentre.eu/wp-content/uploads/2025/08/ECAC_POLANDS_JOURNEY_TO_CLEAN_AIR_en-1.pdf (10.10.2025))

Anti-Smog Resolution (2017). Silesian Voivodeship, 2017. Resolution No. V/36/1/2017 of the Silesian Voivodeship Assembly of 7 April 2017 on the introduction of restrictions on the operation of installations burning fuels in the Silesian Voivodeship, Official Journal of the Silesian Voivodeship of 2017, item 2624 (in Polish), (https://dzienniki.slask.eu/WDU_S/2017/2624/akt.pdf (15.04.2025)).

BDOT (2011). Topographic Objects Database (BDOT10k), Open Data (in Polish), (https://dane.gov.pl/en/dataset/2030 (15.04.2025)).

Błaszczak, B., Mathews, B., Słaby, K. & Klejnowski, K. (2023) Distribution of EC and OC temperature fractions in different research materials, *Archives of Environmental Protection* 49, 2, pp. 95-103. DOI: 10.24425/aep.2023.145901

Brook, R.D., Franklin, B., Cascio, W., Hong, Y., Howard, G., Lipsett, M., Luepker, R., Mittleman, M., Samet, J., Smith, S.C. Jr. & Tager, I. (2004) Air Pollution and Cardiovascular Disease: A Statement for Healthcare Professionals From the Expert Panel on Population and Prevention Science of the American Heart Association, *Circulation* 109, 21. DOI: 10.1161/01.CIR.0000128587.30041.C8

CEEB (2023). Central Register of Building Emissions (CEEB), Chief Office of Building Control (GUNB). Data obtained from Air Quality Department of Pszczyna City Hall

Cenowski, M. (2019) Air pollutions, in: *Urban-industrial areas facing climate change based on the example of cities in the central part of the Górnośląsko-Zagłębiowska Metropolis*, Gorgoń J. (Ed.) (in Polish). Work & Studies, Zabrze, pp. 54-68.

Chen, X., Zhang, L.W., Huang, J.J., Song, F.J, Zhang, L.P., Qian, Z.M., Trevathan, E., Mao, H.J., Han, B., Vaughn, M., Chen, K.X., Liu, Y.M., Chen, J., Zhao, B.X., Jiang, G.H., Gu, Q., Bai, Z.P., Dong, G.H. & Tang, N.J. (2016) Long-term exposure to urban air pollution and lung cancer mortality: A 12-year cohort study in Northern China, *Science of The Total Environment* 571, pp. 855-861. DOI: 10.1016/j.scitotenv.2016.07.064

Clean Air (2018). New Clean Air program - thermal modernization and replacement of heat sources (in Polish), (https://czystepowietrze.gov.pl/ (15.04.2025)).

Directive AAQD (2024). Directive EU 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast), OJ L, 2024/2881, 20.11.2024, (https://eur-lex.europa.eu/eli/dir/2024/2881/oj (25.04.2025)).

Directive CAFE (2008). Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, OJ L 152, 11.6.2008, p. 1–44, (https://eur-lex.europa.eu/eli/dir/2008/50/oj/eng (15.04.2025)).

Directive Ecodesign (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast), OJ L 285, 31.10.2009, p. 10–35, (https://eur-lex.europa.eu/eli/dir/2009/125/oj/eng (25.04.2025)).

DTM (2025). Digital Terrain Model (DTM) – Open Data (in Polish), (https://dane.gov.pl/pl/dataset/2027,numeryczny-model-terenu-nmt (15.04.2025)).

EEA (2020). European Environment Agency, 2020. Air quality in Europe - 2020 report, (file:///C:/Users/str.e/Downloads/Air%20quality%20in%20Europe%20-%202020%20report-2.pdf (15.04.2025)).

EPA (2025). United States Environmental Protection Agency, 2025. Health and Environmental Effects of Particulate Matter (PM), (https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm (15.04.2025)).

Fasola, S., Maio, S., Baldacci, S., La Grutta, S., Ferrante, G., Forastiere, F., Stafoggia, M., Gariazzo, C. & Viegi, G., (2020) Effects of particulate matter on the incidence of respiratory diseases in the pisan longitudinal study, *International Journal of Environmental Research and Public Health* 17, 7, p. 2540. DOI: 10.3390/ijerph17072540

GIOŚ (2015). Chief Inspectorate for Environmental Protection (GIOŚ). Estimation of air quality - Up-to-date measurement data, (https://https://powietrze.gios.gov.pl/pjp/current?lang=en&woj=/ (15.04.2025)).

GIOŚ (2022). Chief Inspectorate for Environmental Protection (GIOŚ), 2022. Assessment of air pollution at regional background monitoring stations in Poland in 2021 in terms of PM_{10} and $PM_{2.5}$ dust composition and heavy metals and PAHs deposition (in Polish), (https://powietrze.gios.gov.pl/depoz/en/publikacje/assessment-of-air-pollution-at-regional-background-monitoring-stations-in-poland-in-2021-in-terms-of-pm10-and-pm2-5-dust-composition-and-heavy-metals-and-pahs-deposition/ (25.04.2025)).

Gorini, F. & Tonacci, A. (2025) Ambient Air Pollution and Congenital Heart Disease: Updated Evidence and Future Challenges. *Antioxidants* 14, 48, pp.33. DOI: 10.3390/antiox14010048

GUGiK (2025). Head Office of Geodesy and Cartography (GUGiK), 2025. National Geoportal (in Polish), (https://www.geoportal.gov.pl/pl/aplikacje/geoportal-krajowy/ (15.04.2025)).

Guo, J., Chai, G., Song, X., Hui, X., Li, Z., Feng, X. & Yang, K. (2023) Long-term exposure to particulate matter on cardiovascular and respiratory diseases in low- and middle-income countries: A systematic review and meta-analysis. *Frontiers in Public Health* 11:1134341. DOI 10.3389/fpubh.2023.1134341

IQAir (2024). IQAir, 2024. 2024 IQAir World Air Quality Report, (https://www.iqair.com/newsroom/waqr-2024-pr?srsltid=AfmBOorkzgfhJig59I5p67gjsC15mGyr313EaIYpGsaWQmCqY8QeP-8A (25.04.2025)).

Janeczek, J. & Jabłońska M. (2025) Evolution of Air Quality in the Upper Silesian Agglomeration, in: *Silesia Superior: Narratives on Upper Silesia – The Multitude of Perspectives*, Dampc-Jarosz, R., Kowalczyk, A. & Sadzikowska, L. (Eds.). V&R Unipress, pp. 249-268.

Kanarek (2016). [Android and iOS]. Kanarek app (in Polish), (https://play.google.com/store/apps/details?id=pl.tajchert.canary&hl=pl (15.04.2025)).

KAWKA (2013). Voivodeship Fund for Environmental Protection and Water Management in Katowice, 2013. Call for applications under the "KAWKA" Program (in Polish), (https://stara.wfosigw.katowice.pl/aktualnosci-archiwum/9-aktualnosci/803-nabor-wnioskow-w-ramach-programu-kawka.html (15.04.2025)).

Kobza, J., Geremek, M. & Dul, L. (2018) Characteristics of air quality and sources affecting high levels of PM_{10} and $PM_{2.5}$ in Poland, Upper Silesia urban area. *Environmental Monitoring and Assessment* 190, 515. DOI: 10.1007/s10661-018-6797-x

Maciejewska, K. (2020). Short-term impact of $PM_{2.5}$, PM_{10}, and PMc on mortality and morbidity in the agglomeration of Warsaw, Poland. *Air Quality, Atmosphere & Health* 13, pp. 659-672. DOI: 10.1007/s11869-020-00831-9

Mainka, A. & Żak, M. (2022) Synergistic or Antagonistic Health Effects of Long- and Short-Term Exposure to Ambient NO_2 and $PM_{2.5}$: A Review. *International Journal of Environmental Research and Public Health* 19, 14079. DOI: 10.3390/ijerph192114079

ME Regulation (2018). Regulation of the Minister of Energy of 27 September 2018 on quality requirements for solid fuels, (Polish) Journal of Laws 2018, item 1890. (in Polish), (https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180001890 (15.04.2025)).

Monn, C. (2001). Exposure assessment of air pollutants: a review on spatial heterogeneity and indoor/outdoor/personal exposure to suspended particulate matter, nitrogen, dioxide and ozone. Atmospheric Environment 35, pp.1-32. DOI: 10.1016/S1352-2310(00)00330-7

Nazar, W. & Niedoszytko, M. (2022). Air Pollution in Poland: A 2022 Narrative Review with Focus on Respiratory Diseases. *International Journal of Environmental Research and Public Health* 19, 2, p. 895. DOI: 10.3390/ijerph19020895

NFOŚiGW (2010). National Found for Environmental Protection and Water Management (NFOŚiGW). Programs and Projects (in Polish), (https://www.gov.pl/web/nfosigw/ (25.04.2025)).

Niedźwiedź, T., Łupikasza, E. B., Małarzewski, Ł. & Budzik, T. (2021) Surface-based nocturnal air temperature inversions in southern Poland and their influence on PM_{10} and $PM_{2.5}$ concentrations in Upper Silesia. *Theoretical and Applied Climatology* 146, pp. 897–919. DOI: 10.1007/s00704-021-03752-4

OSM (2025). OpenStreetMap Contributors, 2025. Open Database License., (https://www.openstreetmap.org/#map=11/49.9806/18.8278 (15.04.2025)).

PMŚ (2008). Chief Inspectorate for Environmental Protection. State Environmental Monitoring (PMŚ) (in Polish), (https://www.gov.pl/web/gios/panstwowy-monitoring-srodowiska (15.04.2025)).

PN-EN (2012). PN-EN 303-5: 2012, Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW - Terminology, requirements, testing and marking. (in Polish).

PONE (2017). Low-stock Emission, 2017. PONE Pszczyna - Applications·(in Polish), (https://www.niskaemisja.pl/aktualnosci/97/ (25.04.2025)).

POP (2020). Silesian Voivodeship, 2020. Resolution No. VI/21/12/2020 of the Silesian Voivodeship Assembly of 22 June 2020 on the adoption of the "Air Protection Program for the Silesian Voivodeship", Official Journal of the Silesian Voivodeship of 2020, item 5070 (in Polish), (https://dzienniki.slask.eu/WDU_S/2020/5070/akt.pdf (15.04.2025)).

POP (2023). Silesian Voivodeship, 2023. Resolution No. VI/62/8/2023 of the Silesian Regional Assembly of 20 November 2023 on the adoption of the update of the "Air Protection Program for the Silesian Voivodeship" adopted by Resolution No. VI/21/12/2020 of the Silesian Regional Assembly of 22 June 2020, Official Journal of the Silesian Voivodeship of 2023, item 8625, (in Polish), (https://dzienniki.slask.eu/WDU_S/2023/8625/akt.pdf (15.04.2025)).

PSA (2021). Polish Smog Alert, 2021. Air in Poland, (https://www.polishsmogalert.org/air-in-poland/ (15.04.2025)).

Pszczyński Alarm Smogowy (2019). Pszczyna Smog Alert. Don't Feed the Smog (in Polish), (http://niedokarmiajsmoga.pl/ (15.04.2025)).

Schneider, J. & Krzyzanowski, M. (2004). Health aspects of air pollution summary of main findings of the WHO project "Systematic review of health aspects of air pollution in Europe". Newsletter No. 33, June 2004, WHO Collaborating Centre for Air Quality Management and Air Pollution Control, Berlin. (https://www.researchgate.net/publication/237457854_Health_aspects_of_air_pollution_summary_of_main_findings_of_the_WHO_project_systematic_review_of_health_aspects_of_air_pollution_in_Europe (05.10.2025))

Smołka-Danielowska, D., Jabłońska, M. & Godziek, S. (2021). The influence of hard coal combustion in individual household furnaces on the atmosphere quality in Pszczyna (Poland). *Minerals* 11, 11, p. 1155. DOI: 10.3390/min11111155

Syngeos (2025). Syngeos. Global Innovative Solution, 2025. Monitoring and measuring air quality - smog sensor (in Polish), (https://syngeos.pl/ (15.04.2025)).

WHO (2016). World Health Organization, 2016. Air quality database 2016, (https://www.who.int/data/gho/data/themes/air-pollution/who-air-quality-database/2016 (15.04.2025)).

WHO (2018). World Health Organization, 2018. World health statistics 2018: monitoring health for the SDGs. Sustainable development goals. (https://www.who.int/publications/i/item/9789241565585300 (15.04.2025)).

WHO (2021). World Health Organization, 2021. WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide, (https://https://www.who.int/publications/i/item/9789240034228 (15.04.2025)).

WHO (2022). World Health Organization, 2022. Air quality database 2022, (https://www.who.int/data/gho/data/themes/air-pollution/who-air-quality-database/2022 (15.04.2025)).

WMO (2023). World Meteorological Organisation e-Library, 2023. WMO Air Quality and Climate Bulletin, No. 3 – September 2023, (https:// https://library.wmo.int/records/item/62090-no-3-september-2023?offset=35/ (15.04.2025)).

Wolf, K., Hoffmann, B., Andersen, Z.J., Atkinson, R.W., Bauwelinck, M., Bellander, T., Brandt, J., Brunekreef, B., Cesaroni, G., Chen, J., de Faire, U., de Hoogh, K., Fecht, D., Forastiere, F., Gulliver, J., Hertel, O., Hvidtfeldt, U.A., Janssen, N.A.H., Jørgensen, J.T., Katsouyanni, K., Ketzel, M., Klompmaker, J.O., Lager, A., Liu, S., MacDonald, C.J., Magnusson, P.K.E., Mehta, A.J., Nagel, G., Oftedal, B., Pedersen, N.L., Pershagen, G., Raaschou-Nielsen, O., Renzi, M., Rizzuto, D., Rodopoulou, S., Samoli, E., van der Schouw, Y.T., Schramm, S., Schwarze, P., Sigsgaard, T., Sørensen, M., Stafoggia, M., Strak, M., Tjønneland, A., Verschuren, W.M.M., Vienneau, D., Weinmayr, G., Hoek, G., Peters & A., Ljungman, P.L.S. (2021). Long-term exposure to low-level ambient air pollution and incidence of stroke and coronary heart disease: a pooled analysis of six European cohorts within the ELAPSE project. *The Lancet Planetary Health* 5, 9, pp. e620–e632. DOI: 10.1016/S2542-5196(21)00195-9

WŚl (2024). Public Information Bulletin of the Silesian Voivodeship, 2024. Report on the State of the Voivodeship for 2023 (in Polish), (https://bip.slaskie.pl/wojewodztwo/raporty-o-stanie-wojewodztwa/raport-o-stanie-wojewodztwa-za-2023-rok.html (25.04.2025)).

Xing, Y.F., Xu, Y.H., Shi, M.H. & Lian, Y.X. (2016). The impact of $PM_{2.5}$ on the human respiratory system. *Journal of Thoracic Disease* 8,1,pp. E69-74. DOI: 10.3978/j.issn.2072-1439.2016.01.19

Ocena skuteczności wymiany kotłów grzewczych pod kątem redukcji emisji pyłów PM10 i PM2,5 na przykładzie gminy Pszczyna (województwo śląskie, Polska)

Streszczenie: Gmina Pszczyna zlokalizowana w południowej Polsce od dawna zmaga się z niską jakością powietrza, szczególnie w sezonie grzewczym. Niniejsze badania oceniają skuteczność lokalnej polityki redukcji stężeń pyłów PM10 i PM2,5 poprzez wymianę starych kotłów na paliwo stałe na systemy niskoemisyjne lub zeroemisyjne. Wykorzystując dane ze stacji monitorujących jakość powietrza (2020 i 2023), dane meteorologiczne oraz raporty administracyjne dotyczące skali i zakresu wymiany kotłów, analiza wykorzystuje porównania statystyczne, normalizację danych meteorologicznych oraz analizę regresji, aby oddzielić skutki polityki od zmienności pogody. Wyniki wskazują na znaczną redukcję poziomów pyłu zawieszonego, szczególnie zimą, przy czym poziom PM10 spada o ponad 30%, a PM2,5 nawet o 40% w rozpatrywanych latach. Potwierdza to skuteczność interwencji ukierunkowanych na wymianę ogrzewania budynków mieszkalnych i podkreśla, jak lokalne działania, wspierane finansowaniem regionalnym i krajowym, mogą przynieść wymierne korzyści dla środowiska i zdrowia w krótkim okresie. Ciągły monitoring i zaangażowanie społeczne są niezbędne dla utrzymania poprawy jakości powietrza.

Supplementary Material

Table S1. Correlation matrix determining the impact of climatic conditions on particulate matter concentrations. Red color indicates statistically significant results ($p < 0.05$).

	Temperature (°C)	sunshine duration [h]	wind speed [m•s^{-1}]
2020			
$PM_{2.5}$	-0.35	0.19	-0.23
PM_{10}	-0.35	0.19	-0.23
2023			
$PM_{2.5}$	-0.59	-0.25	-0.26
PM_{10}	-0.59	-0.25	-0.26
All results			
$PM_{2.5}$	-0.46	-0.02	-0.26
PM_{10}	-0.47	-0.02	-0.26

Table S2. Multiple regression for particulate matter concentration levels based on weather conditions.

	$PM_{2.5}$					PM_{10}				
	b	SE	t(358)	p	R^2	b	SE	t(358)	p	R^2
	All results [F(3.696)=107.68; p<0.0001]					**All results** [F(3.696)=111.96; p<0.0001]				
Intercept	32.16	1.50	21.44	<0.001	0.31	53.22	2.40	22.20	<0.001	0.32
temperature [°C]	-1.27	0.08	-16.80	<0.001		-2.07	0.12	-17.10	<0.001	
sunshine duration [h]	0.82	0.12	6.63	<0.001		1.29	0.20	6.50	<0.001	
wind speed [m•s^{-1}]	-2.44	0.30	-8.24	<0.001		-4.02	0.47	-8.50	<0.001	
	2020 [F(3.334)=39.72; p<0.0001]					**2020** [F(3.334)=39.82; p<0.0001]				
Intercept	34.86	2.90	12.02	<0.001	0.26	56.52	4.65	12.17	<0.001	026
temperature [°C]	-1.42	0.14	-10.20	<0.001		-2.27	0.22	-10.22	<0.001	
sunshine duration [h]	1.19	0.22	5.48	0.93		1.87	0.35	5.40	<0.001	
wind speed [m•s^{-1}]	-2.51	0.58	-4.35	<0.001		-4.07	0.92	-4.41	<0.001	
	2023 [F(3.358)=158.40; p<0.0001]					**2023** [F(3.358)=161.92; p.0.0001]				
Intercept	29.26	1.05	27.82	<0.001	0.57	49.49	1.74	28.50	<0.001	0.58
temperature [°C]	-1.02	0.06	-17.95	<0.001		-1.70	0.09	-18.10	<0.001	
sunshine duration [h]	0.22	0.10	2.23	<0.001		0.35	0.16	2.20	<0.001	
wind speed [m•s^{-1}]	-2.32	0.21	-11.25	<0.001		-3.89	0.34	-11.43	<0.001	

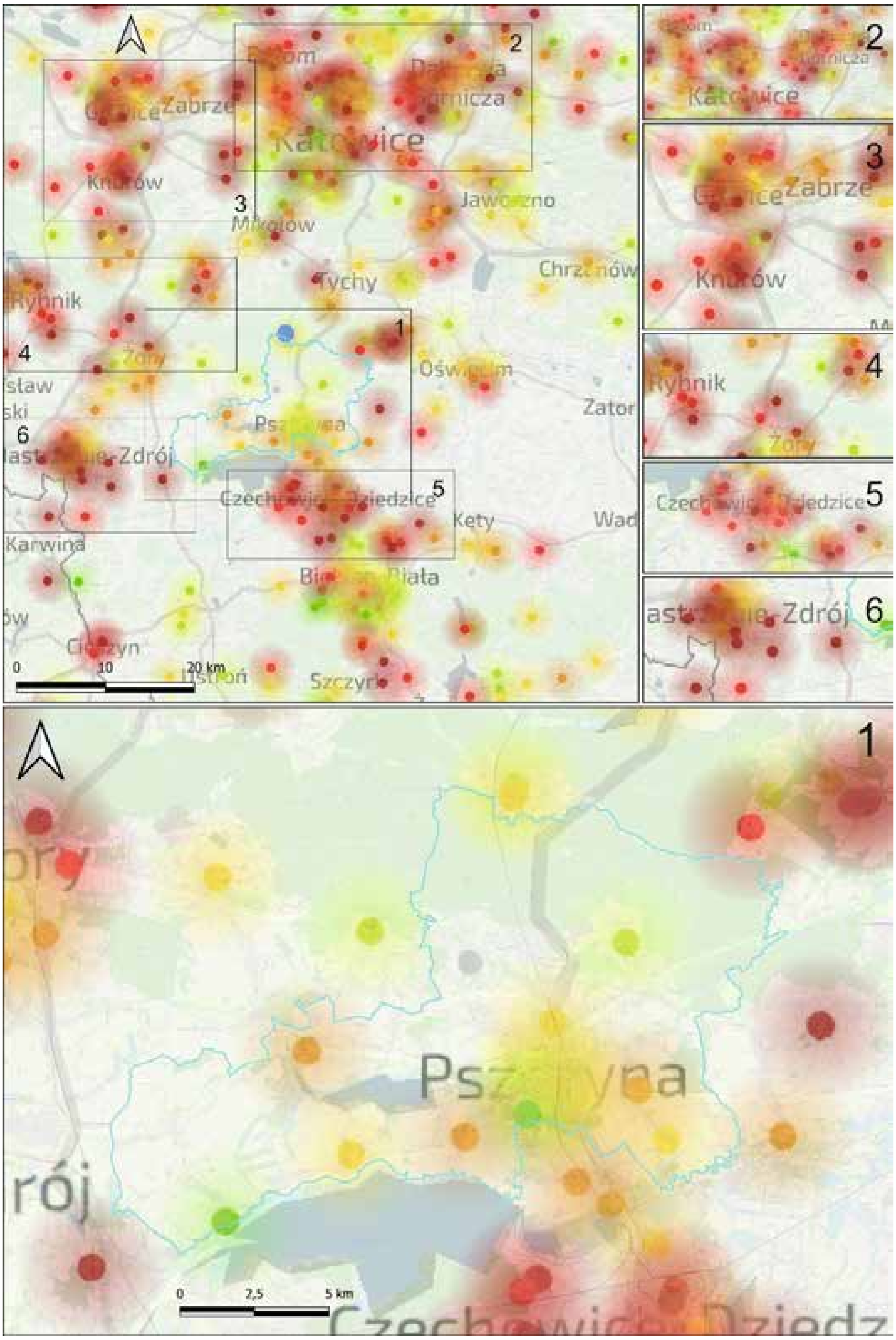

Figure S1. Image of PM_{10} and $PM_{2.5}$ dust air pollution in Silesia (Pszczyna region) in the Kanarek application (Kanarek 2016) on February 17, 2025. Screenshots taken between 8:00 and 8:15 am.

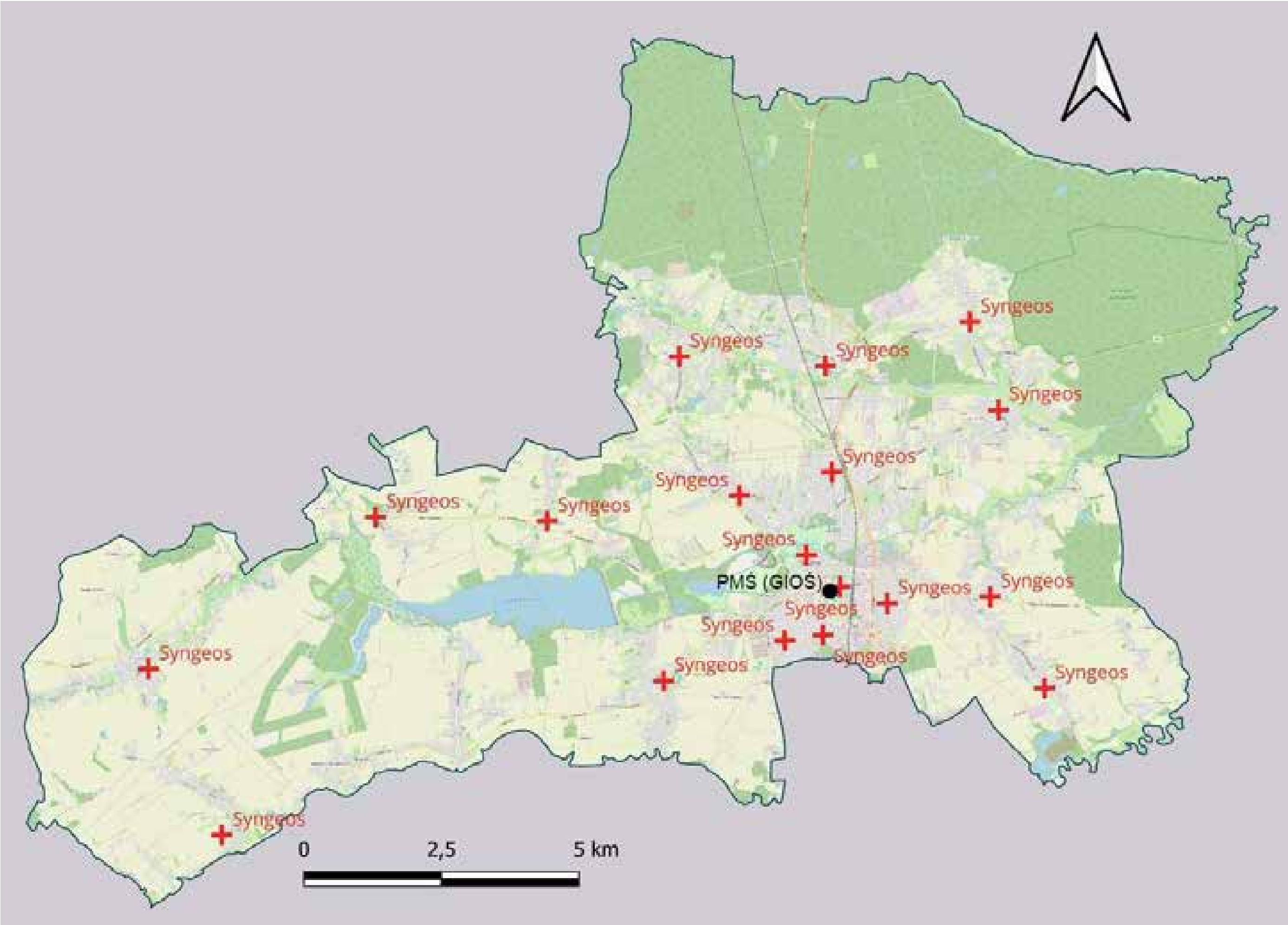

Figure S2. Distribution of air pollution sensors in the municipality of Pszczyna.

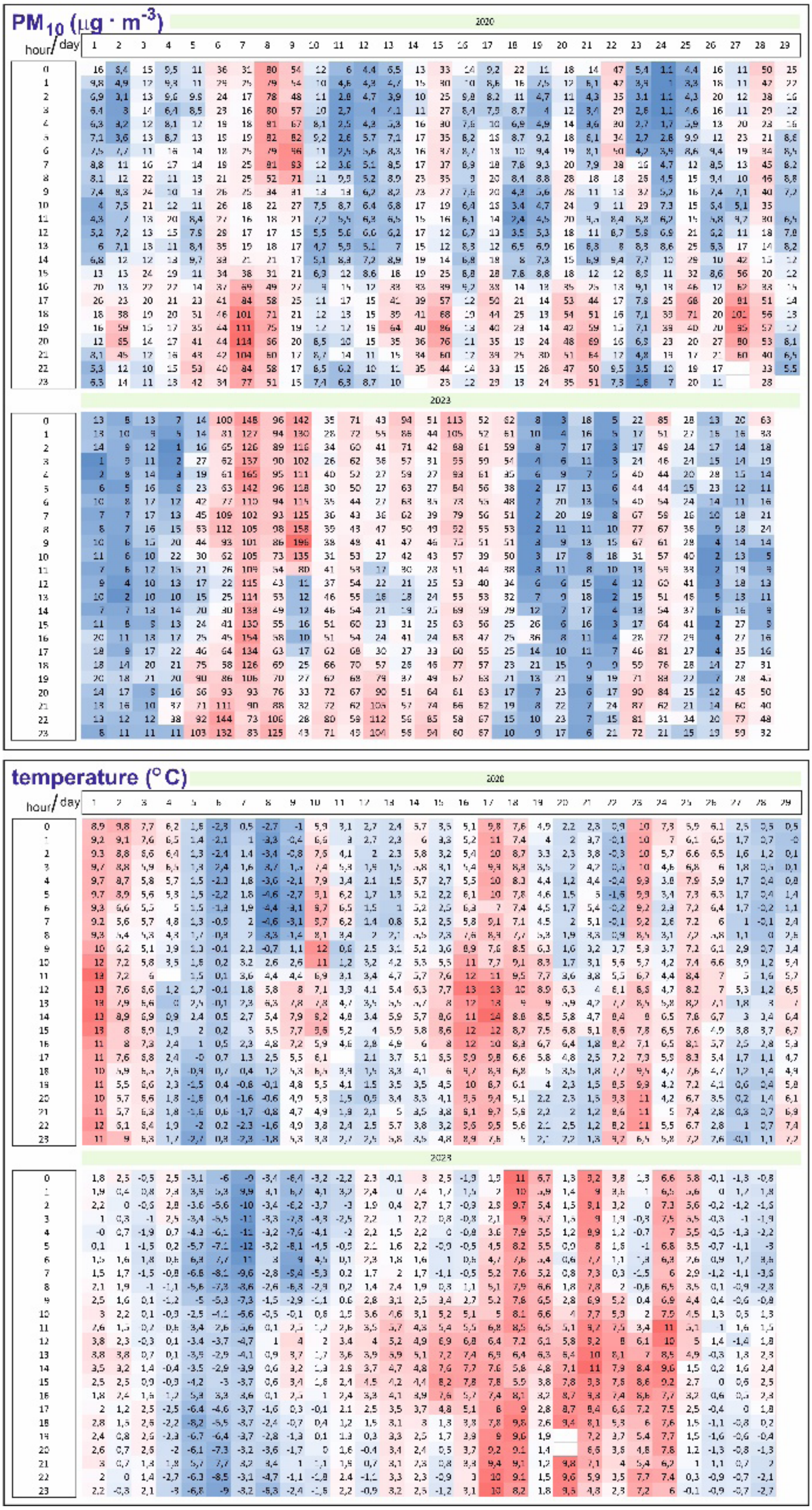

Figure S3. Daily variation of particulate matter concentrations and atmospheric conditions in February in 2020 and 2023. Matrices generated in Excel based on measurement data averaged from PMŚ monitoring stations and 18 Syngeos sensors placed in the commune.

Blue shows the lowest values, red the highest.

(PMŚ 2008, Syngeos 2025, For wind speed: data from PRIVA sensors form the Specialist Horticultural Farm Marek Dzida).

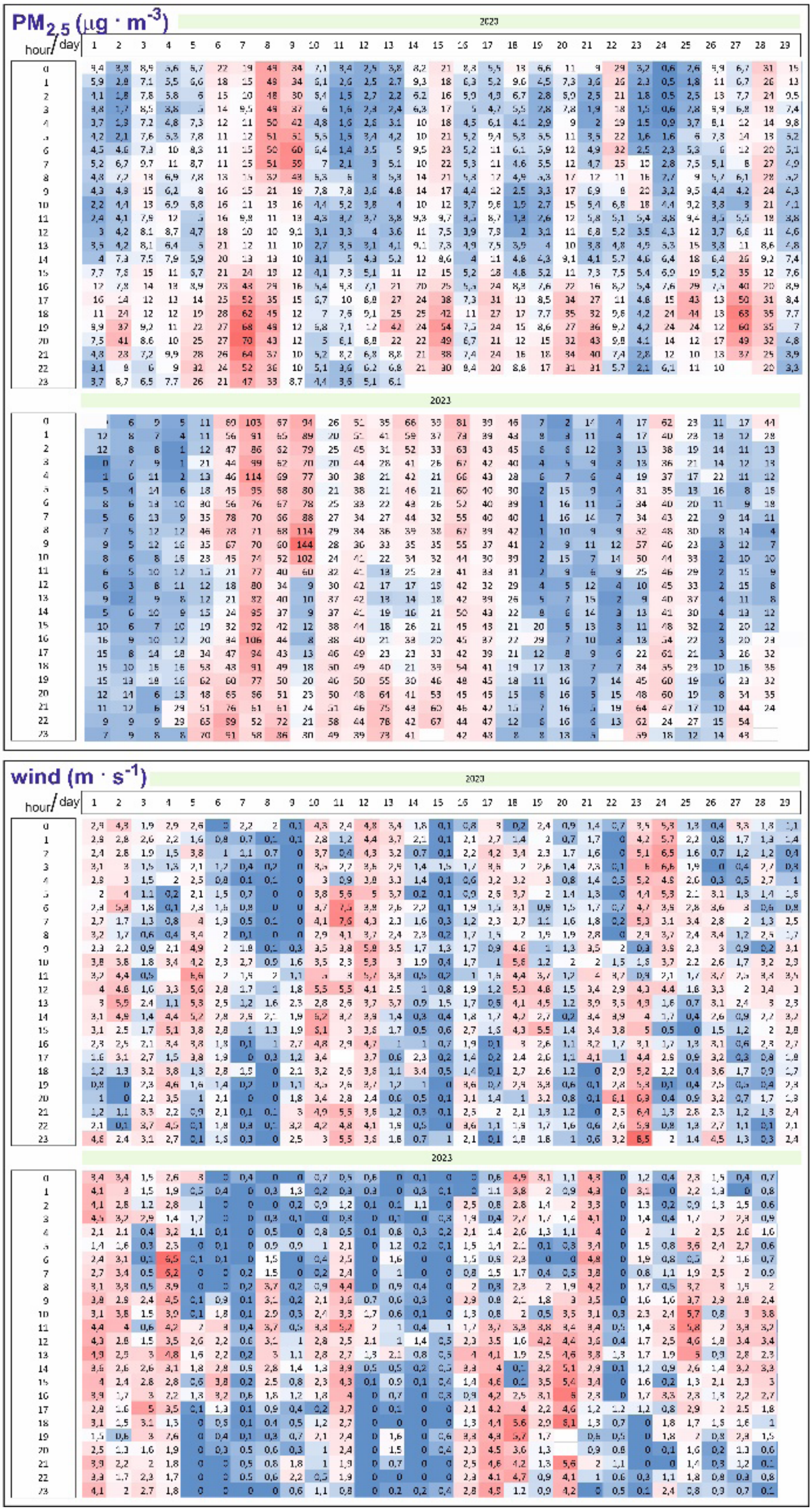

Figure S3.