

Article

Using Statistical Methods to Identify the Impact of Solid Fuel Boilers on Seasonal Changes in Air Pollution

Ewa Bakinowska ¹, Alicja Dota ^{1,*}, Rafał Urbaniak ², Bartosz Ciupek ³, Marcin Żurawski ²
and Marek Dębczyński ²

¹ Faculty of Control, Robotics and Electrical Engineering, Institute of Mathematics, Poznan University of Technology, 3a Piotrowo St., 61-138 Poznan, Poland; ewa.bakinowska@put.poznan.pl

² Faculty of Technology, University of Kalisz, 201-205 Poznańska St., 62-800 Kalisz, Poland; r.urbaniak@uniwersytetkaliszki.edu.pl (R.U.); m.zurawski@uniwersytetkaliszki.edu.pl (M.Ż.); m.debczynski@uniwersytetkaliszki.edu.pl (M.D.)

³ Faculty of Environmental Engineering and Energy, Institute of Thermal Energy, Poznan University of Technology, 3 Piotrowo St., 61-138 Poznan, Poland; bartosz.ciupek@put.poznan.pl

* Correspondence: alicja.dota@put.poznan.pl

Abstract

Air pollution with particulate matter (PM), recognized by the EU and WHO as a significant factor affecting human health, is subject to standards. Exceeding these standards on a daily or annual basis poses an increased health risk. This article presents an analysis of data from 2022 to 2024 from the administrative area of Pleszew (Poland), which, in 2023, ranked second in the country in terms of annual PM₁₀ concentration [$\mu\text{g}/\text{m}^3$]. The main cause of the poor air quality is identified as so-called “low emissions” resulting from residential heating using high-emission coal-fired boilers. The methods used in this analysis not only identified the main causes of pollutant emissions but also demonstrated the seasonal impact of these sources on air quality, both on an annual and daily basis. The analysis utilized statistical tools such as a mixed linear regression model and Tukey’s post hoc tests performed after analysis of variance (ANOVA). The obtained regression model of PM₁₀ concentration on the outside air temperature (defining the intensity of operation of heating devices) clearly indicates the predicted air pollution. Dividing the day into three time intervals proved to be an effective analytical tool enabling the identification of periods with the highest risk of high PM₁₀ concentrations. The highest average PM₁₀ concentration values were recorded in the autumn and winter months between 3:00 PM and 9:00 PM. The developed methods can serve as fundamental tools for local government authorities, guiding further energy policy directions for the study area to improve the identified situation. At the same time, daily and hourly air pollution analysis clearly confirmed the characteristics of inefficient heat sources, which will allow residents to protect their health by avoiding spending time outdoors during peak particulate matter concentration hours. Until the energy situation in the region changes, this will continue.

Keywords: air pollution forecasting; linear regression; urban air quality; sensor data modeling; energy-related environmental planning; heating boiler; emission



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1. Introduction

High concentrations of particulate matter in atmospheric air are among the main environmental factors negatively affecting human health. In particular, they contribute to the development of respiratory and cardiovascular diseases [1,2]. Therefore, the continuous

monitoring of particulate matter concentrations and identifying the factors leading to their increase are crucial [3]. Primary sources include both anthropogenic emissions, such as those from transport, the energy sector, and heating (particularly those resulting from the use of hand-fired grate boilers), and atmospheric factors that influence heating intensity.

The World Health Organization (WHO) [4–7] and the European Union (EU) [8] have drawn attention to the problem of air pollution. EU policy emphasizes the need to phase out fossil fuels to improve the environment and protect public health. Despite the ongoing geopolitical crisis, the EU maintains a strategic direction in climate and environmental policy [9]. Research indicates that atmospheric pollutant emissions in member states vary spatially depending on the level of industrialization, urbanization, and economic development and the environmental condition [10]. The relationship between meteorological conditions and particulate matter (PM) concentrations is also attracting increasing international interest [11–15]. At the same time, the literature emphasizes the role of non-atmospheric factors, which, however, are rarely subjected to detailed analysis.

The WHO air quality guidelines (for PM₁₀: annual recommended level 15 µg/m³, daily 45 µg/m³, with a maximum of three days per year exceeding this limit) are an important reference point for assessing population exposure and are widely analyzed in scientific studies [16,17]. However, scientists point out that the European regulations remain unadjusted to WHO recommendations and that public health institutions should participate more actively in the interpretation of environmental data. Additionally, attention is drawn to the need for research that takes into account the local context, as the WHO guidelines are based mainly on data from highly developed countries and focus on exposure to single pollutants [18].

The second decade of the 21st century has brought significant changes in energy policy and individual heating in Poland. Increased public awareness and stricter emission requirements for boilers, resulting from subsequent editions of the PN-EN 303-5 standard and the Ecodesign Directive (EU) 2015/1189, impose on manufacturers the obligation to reduce emissions and improve the energy efficiency of devices [19,20].

Despite these efforts, there are still regions in Poland where air quality improvement is slow. In a 2018 WHO report on the most polluted cities in Europe, Pleszew was ranked 14th [21]. These results prompted local authorities to take action, including inventorying heat sources and subsidizing their replacement [22]. However, due to changes in the law, municipalities have lost full control over the implementation of these goals.

Consequently, the study site was the urban–rural commune of Pleszew (Pleszew County, Greater Poland Voivodeship), with an area of 180.15 km² and a population of approximately 30,000 inhabitants [23]. Air quality monitoring was conducted in 2022–2024 to identify the impact of heating boilers on local pollution. Statistical analysis of the measurement data allowed for the clear identification of emission sources. This study also provides a new perspective on the temporal distribution of particulate matter concentrations and demonstrates strong correlations between emission levels, the lifestyle of residents, and the combustion technology used in hand-fired grate boilers [24,25].

The aim of this study was to identify the main sources of particulate matter emissions in the Pleszew commune and to determine the relationship between air temperature and PM₁₀ concentration, with particular emphasis on the role of hand-fired grate boilers. For this purpose, measurements were conducted using air quality sensors located throughout the commune between 2022 and 2024. Measurements were taken, among other things, of PM_{1.0}, PM_{2.5}, and PM₁₀ concentrations; relative humidity; atmospheric pressure; and air temperature at 10 min intervals. Because the relationships for PM_{1.0} and PM_{2.5} were analogous to those observed for PM₁₀, the detailed analysis focused on the latter parameter.

The study results demonstrated a significant relationship between temperature and particulate matter concentrations during the heating season. The temperature drop resulted in increased boiler operation, and the observed phenomena were additionally related to residents' lifestyles. Detailed statistical analysis of the data from 2022 to 2024, including linear regression models and analysis of variance (ANOVA), confirmed the key role of hand-fired grate boilers in shaping pollution levels. The developed PM₁₀–temperature regression model allowed for the prediction of local emission levels. Additionally, Tukey's post hoc tests were used to analyze the differences between average concentrations in three daily intervals. Graphical visualization was achieved using violin plots with boxplots.

2. Materials and Method

The primary goal of this research was to utilize statistical methods to identify the impact of solid fuel boilers on environmental pollution. A detailed description of the statistical tools used is presented directly in the computational section, which utilizes actual measurement data archived between 2022 and 2024 from the Pleszew administrative area (Poland). Section 2.1 presents detailed information on the location, methodology, and accuracy of environmental parameter measurements.

Based on environmental research conducted in Pleszew and knowledge of solid fuel combustion processes, the authors of the article made controversial assumptions that should not have been made given the emission standards contained in PN-EN 303-5:2012, which have been in force since 2012. In accordance with the cited standards, grate-fired boilers using top-firing techniques, which were characterized by high-emission combustion throughout their entire operating cycle, were withdrawn from production [26,27]. Since then, automatic pellet boilers, classified as a renewable energy source, and heat pumps have been gaining popularity. Unfortunately, to this day, grate-fired boilers with top-firing combustion throughout the entire bed are in use, and their combustion quality varies throughout the process. After firing, these boilers enter the clean-burning phase, which, when high-quality wood fuel is used, guarantees correct emission parameters. These boilers are approved for operation and distribution as wood gasification boilers, provided that the installation requirements requiring the user to install a heating medium buffer are met. In real-world conditions, they are subject to improper operation because they burn carbon-based fuels: hard coal, lignite, and pulverized coal. Most installations also lack buffer installation. This is an illegal practice, implemented due to a lack of environmental awareness and the energy poverty of residents, as reflected in high environmental pollution rates [28,29]. A detailed description of the construction and operation of the indicated boiler designs is presented in Section 2.2.

2.1. Air Pollution Measurement Methodology

To reflect actual air quality conditions in a rural–urban area, the sensor was located in Pleszew in an area with a low concentration of residential development, devoid of tall buildings and industrial plants. The sensor's location partially borders agricultural land, which allowed for air circulation and eliminated the impact of road transport on air pollution readings. Figure 1 shows a site plan of the measurement station location.

The measurements were conducted from January 2022 to December 2024, in 10 min intervals. The purpose of these frequent measurements was to determine dynamic changes in environmental conditions and assess the impact of heating devices on changes in air quality.

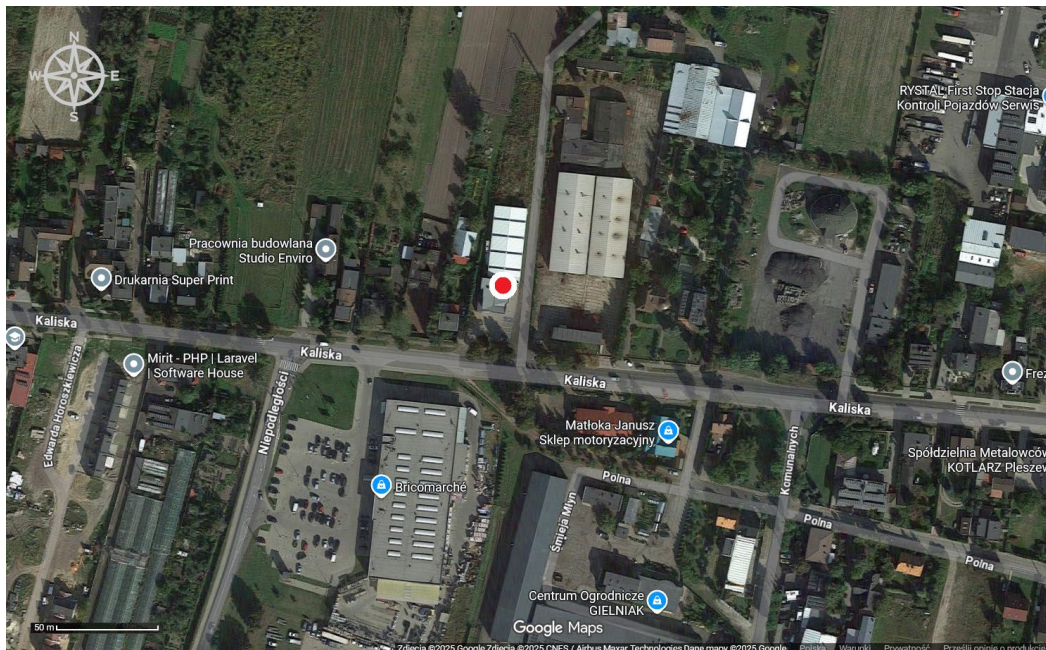


Figure 1. Location of the measuring station [source: Google Maps].

The measuring station recorded the following parameters:

- Humidity measurement: Measurement accuracy $\pm 3\%$ (in the absolute humidity range from 20% to 80%).
- Pressure measurement: Measurement accuracy $\pm 0.12\%$ (in the barometric pressure range from 700 kPa to 900 kPa).
- Temperature measurement accuracy:
 - $\pm 0.5\%$ (in the temperature range from 0 to 65 °C);
 - $\pm 1.25\%$ (in the temperature range from -20 to 0 °C);
 - $\pm 1.5\%$ (in the temperature range from -40 to -20 °C).
- Measurement of particulate matter PM_{10} , $PM_{2.5}$, $PM_{1.0}$: With an accuracy of 50% for 0.3 μm particles and 98% for $\geq 0.5 \mu m$ particles [30,31].

The PMS5003 sensor, a compact, inexpensive laser light scattering module, was used to measure particulate matter concentration. The particulate matter sensor is one of the measuring elements of an air quality analyzer named Air Sensor. It is a measuring device manufactured by the Polish company BRAGER from Pleszew, Poland. The PMS5003 uses a semiconductor laser diode and photodetector to estimate particle concentration through the phenomenon of light scattering, with particle size determined based on the intensity and angle of light scattering. The sensor can detect particles as small as 0.3 μm , with a 50% detection efficiency at this threshold. For particles 0.5 μm and larger, the detection efficiency exceeds 98%, which is sufficient for accurate estimation of the mass concentration of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} in ambient conditions [30].

Due to the need to reflect the actual values of environmental conditions, the station was subject to periodic (every 3 months) technical inspections.

2.2. Characteristics of Low-Power Boilers with Manual Fuel Loading

Hand-fired grate boilers are characterized by a simple design. They usually have a combustion chamber connected to the hopper and one or more combustion passages. Their efficiency reaches up to 87%, and the combustion time of a single fuel charge is up to 24 h [19,20]. In chamber boilers with manual fuel loading, the fuel is burned in the upper part of the fuel chamber, which is supplied with air. Flue gases are discharged to the heat

exchanger directly from the upper part of the fuel bed. A view of the boiler is shown in Figure 2.

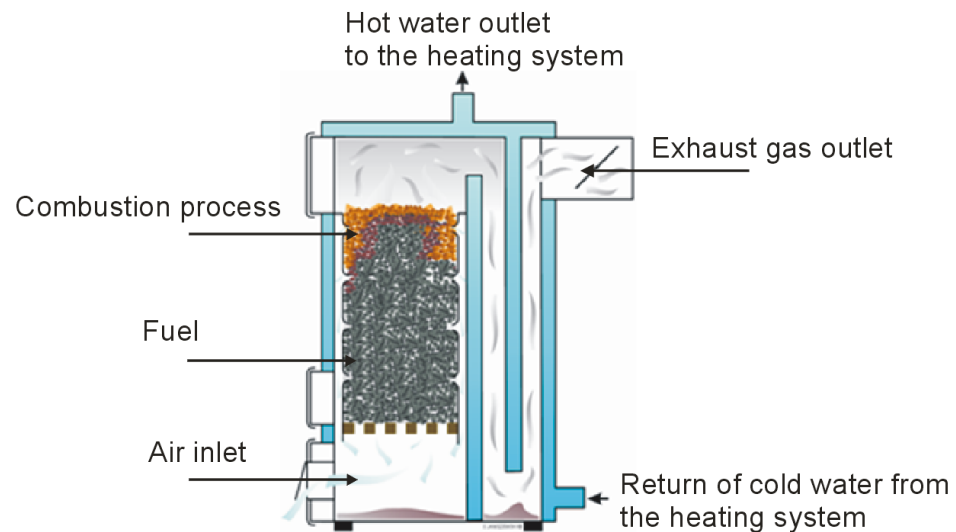


Figure 2. Hand-fired grate boiler [32].

The boilers of this type are often equipped with a forced-air fan that supplies air to the combustion chamber. The combustion process is regulated by a microprocessor system, which varies the fan speed depending on the set operating parameters. Thanks to these solutions, the concentrations of hydrocarbon compounds and carbon monoxide in the exhaust gases are many times lower than in bottom-fired boilers. Significantly higher combustion efficiency values are achieved, reaching up to 87%, and the boiler's output can be quickly adjusted to the current heat demand of the heated premises. Boilers fueled with pulverized coal are particularly popular. Modern boilers of this type are economically comparable to boilers with automatic feeders.

The use of top-firing techniques combined with microprocessor control systems has significantly improved thermal efficiency compared to boilers. This technique is not without its drawbacks. A single fuel loading prevents smooth boiler power regulation over a wider range due to the large combustion surface. Additionally, there are a number of operational problems associated with the need for daily boiler cleaning, fuel loading, and firing [28,29,32]. Research on solid fuel combustion in small-scale thermal power engineering focuses on both improving process efficiency and reducing pollutant emissions [33–37]. The importance of fuel feeding is described in [38–40], and the problem of pollutant emissions during co-combustion of different fuel types is described in [41,42].

From the point of view of the discussed issues related to the periodic increase in air pollution, two key factors should be distinguished:

- Periodic increases in thermal energy demand resulting from seasonal changes and seasonal drops in outdoor temperatures observed between October and April. This is a natural phenomenon occurring in the analyzed climate zone, requiring residents to utilize heating devices to ensure comfortable living conditions. During these periods, we recorded local increases in air pollution resulting from the operation of the heating devices presented.
- Daily changes in air pollution indicators resulting from the operating characteristics of boilers with manual fuel loading. Technical data regarding the operation of these devices indicate that the boilers have a burn time of up to 24 h; unfortunately, in real conditions, the burn time is limited to a range of 6 to 12 h, depending on the outside temperature and the amount of fuel loaded [43,44].

These boilers require a complete combustion cycle each time, which is characterized by variable pollutant emissions depending on the phase of the process. During operation, five basic stages of the combustion process are completed:

1. **Fuel loading.** Due to the residents' lifestyles, this phase typically begins in the afternoon after returning from work. It can be assumed that most residents work a single shift and return home between 3 and 5 PM. During this period, both the boiler and the heating system are completely cooled (the water temperature in the boiler is approximately 20 °C). The boiler should be cleaned of ash and any remaining burnt fuel. A new batch of fuel, ranging from a few to a dozen kilograms, is then loaded. In addition to the fuel, a "kindling" in the form of pieces of wood or other materials is also placed in the boiler to ensure a quick flame with a combustion temperature sufficient to ignite the primary fuel (coal, fine coal, wood).
2. **Ignition phase.** This is the combustion phase that produces the highest levels of pollutants. This phase lasts from one to several hours. During this phase, flammable materials ignite, with combustion temperatures sufficient to ignite the main fuel bed. The combustion process involves both the combustion of solid carbon and the combustion of volatile combustible components released from the fuel as a result of degassing, which is one of the combustion phases. During this phase, the combustion chamber is at a low temperature, preventing rapid degassing of combustible components. This combustion phase produces high emissions of carbon monoxide and soot, which are not combusted due to the low temperature of this process.
3. **The boiler operating parameters stabilization phase.** After the ignition period, the combustion process gradually stabilizes. This phase lasts approximately 1 h. During this time, the water in the boiler and heating system reaches a temperature of 50 to 70 °C, which guarantees an increase in the temperature in the combustion chamber. In this phase of the combustion process, pollutant emissions gradually decrease, but the observed level of emitted pollutants still exceeds the emission standards for class 3 and 4 boilers according to PN-EN 303-5:2012.
4. **The stable combustion phase.** This is the longest phase of the combustion process, lasting from 6 to 7 hours. During this period, the boiler operates stably. The building's energy performance, in the form of poor thermal insulation, guarantees stable heat collection, enabling a uniform combustion process. Pollutant emissions are reduced.
5. **The bed burnout phase.** This is the final phase of the combustion process. The fuel is completely burned, and the boiler water temperature gradually drops. During this phase, we observe low pollutant emissions and high oxygen concentration in the exhaust gases resulting from the absence of combustible substances. This phase lasts approximately one hour.

Detailed knowledge of the energy processes characteristic of each of the mentioned phases and knowledge of the residents' lifestyles and employment patterns allowed us to determine the suggested time intervals adopted in the further course of the research.

3. Results

The WHO-recommended PM₁₀ concentration standards are quite restrictive and should be considered the globally accepted standard. However, due to Poland's membership in the EU, all analyses in this chapter were conducted in relation to the less stringent EU standard.

This chapter is devoted to the analysis of PM₁₀ particulate matter concentrations in the administrative area of Pleszew in the years 2022–2024.

Section 3.1 presents the monthly averages of PM₁₀ values, along with graphs and a discussion on the observations. Particular attention is paid to the analysis of seasonality,

in the autumn–winter months (heating season) and in the spring–summer months, to demonstrate the relationship between PM_{10} concentrations and the heating season.

In Section 3.2, a preliminary analysis of the detailed data, i.e., hourly PM_{10} values for the selected days during the heating period, is conducted. To facilitate interpretation, three day types are introduced:

- Standard combustion process (SCP)—Weekdays, when most residents return home in the afternoon.
- Weekend (WEEKEND)—Days off from work, characterized by a different lifestyle of the residents.
- Constant heat reception (CHR)—Days with forced, continuous boiler operation cycle with manual fuel loading. The heating system does not cool down because the low outside temperature remains at a similar level throughout the day.

In order to examine the change in air pollution levels on a daily basis, the day was divided into three time intervals, which were used in further analysis:

- Int0: Hours in the interval between [3.00 PM and 9.00 PM];
- Int1: Hours in the interval between [9.00 PM and 9.00 AM];
- Int2: Hours in the interval between [9.00 AM and 3.00 PM].

In Section 3.3, the correlation coefficients between PM_{10} values and temperature are determined separately for each month, and a mixed linear regression model is presented. An extension of this analysis, as well as a presentation of the simple regression models describing the PM_{10} –temperature relationship for each month and each year separately, is included in Section 3.4. Furthermore, mixed linear regression models were estimated, which enabled the forecasting of monthly PM_{10} values in the future based on data from the years 2022–2024.

In Section 3.5, a detailed analysis of hourly PM_{10} measurements is performed for the selected days indicated earlier in Section 3.2. Appropriate statistical tests are applied based on which specific conclusions were drawn.

3.1. Air Pollution Recording Results for the Pleszew Administrative Area (Poland) over the Years 2022–2024

The World Health Organization (WHO) recommendations regarding permissible concentrations of PM_{10} particulate matter are more restrictive than the current EU standards. According to WHO, the recommended levels are as follows [4–7]:

- Average annual limit: $15 \mu\text{g}/\text{m}^3$ (previously $20 \mu\text{g}/\text{m}^3$);
- Daily limit: $45 \mu\text{g}/\text{m}^3$ (previously $50 \mu\text{g}/\text{m}^3$).

The EU regulations [8] recommend the following for PM_{10} (particulate matter with a diameter of up to $10 \mu\text{m}$):

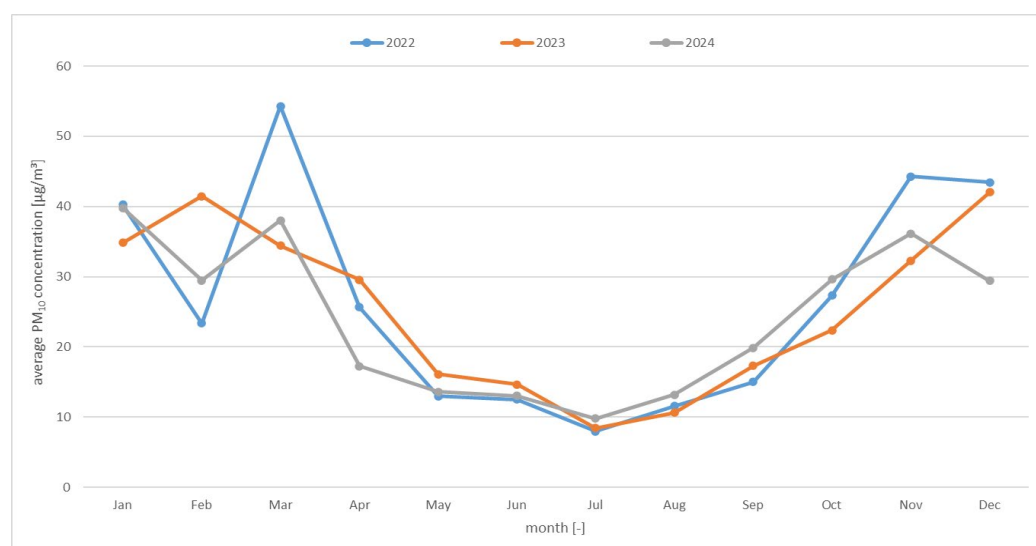
- Annual limit: $40 \mu\text{g}/\text{m}^3$;
- Daily limit: $50 \mu\text{g}/\text{m}^3$.

According to the EU regulations, the daily norm can be exceeded a maximum of 35 times a year.

Air pollution in the Pleszew area was analyzed in relation to the EU standards. The average PM_{10} concentration levels for 2022–2024 in individual months are presented in Table 1 and Figure 3.

Table 1. Average monthly PM₁₀ concentration levels in µg/m³ for the administrative area of Pleszew (Poland).

Month	2022	2023	2024
January	40.24	34.84	39.81
February	23.34	41.48	29.46
March	54.30	34.44	38.02
April	25.64	29.58	17.23
May	12.98	16.12	13.62
June	12.51	14.65	13.05
July	7.97	8.44	9.80
August	11.59	10.61	13.21
September	15.01	17.31	19.88
October	27.31	22.39	29.61
November	44.29	32.26	36.16
December	43.47	42.02	29.41
Annual average:	26.61	25.23	24.09

**Figure 3.** Average monthly PM₁₀ concentrations in 2022–2024.

Both the tabular data and the corresponding graph allow for the determination of the typical concentration levels that can be expected in individual months. The analysis of the annual values indicates that, despite meeting the requirements of the very liberal EU standards, the average annual concentrations significantly exceed the World Health Organization's (WHO) recommended limit value of 15 µg/m³. The data in Table 1 (Figure 3), while important, are general in nature and do not allow for a full understanding of air pollution dynamics. Therefore, a more detailed analysis of the daily particulate matter concentration values is necessary.

The annual PM₁₀ concentration patterns in 2022–2024 show a similar pattern. Seasonality is clearly visible—the highest average values were recorded in the winter months, while the lowest were recorded in the summer. This relationship indicates a significant influence of atmospheric conditions, particularly air temperature. Low temperatures favor the more intensive use of individual heat sources, including boilers with manual fuel loading, which may be the main source of the increased particulate matter concentrations during the heating season. These assumptions are confirmed by the observed relationships between average monthly temperature and average monthly PM₁₀ concentration presented in Figures 4–6.

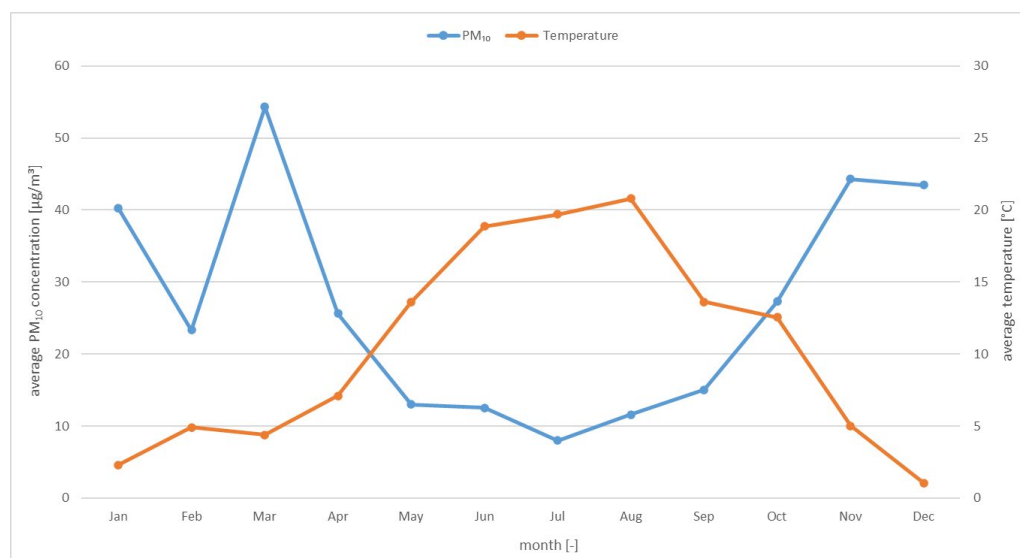


Figure 4. Average monthly PM₁₀ concentrations and temperatures in 2022.

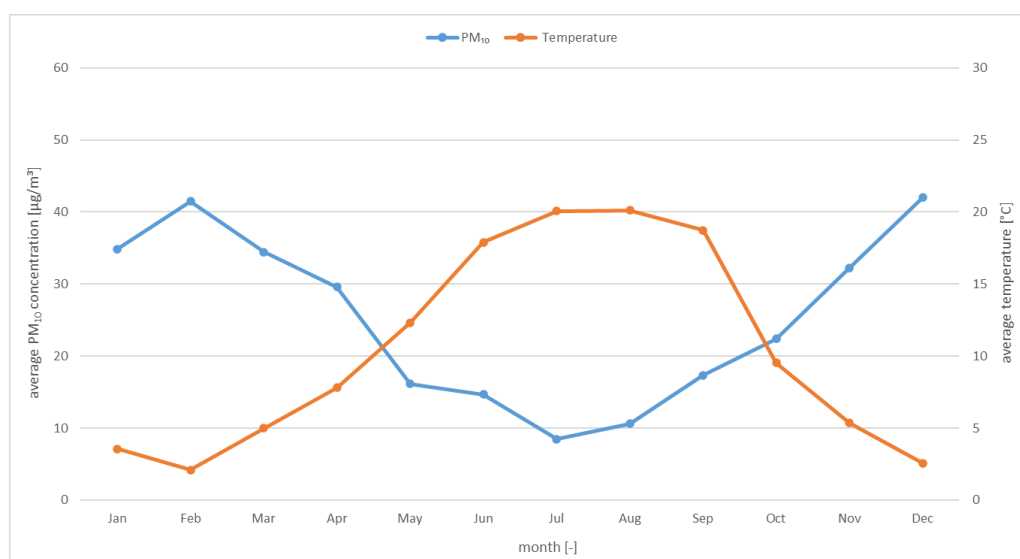


Figure 5. Average monthly PM₁₀ concentrations and temperatures in 2023.

The graphs indicate that the lowest PM₁₀ concentrations occur in months characterized by higher air temperatures, while the highest values are observed in months with lower temperatures. Detailed calculations regarding the correlation between these values are presented in Section 3.3.

The demand for thermal energy, particularly during the autumn and winter months, is driving the increased use of boilers. In turn, boiler operation intensity is closely related to the air temperature outside the heated building. Hence, the study of the influence of the intensity of use of hand-fired grate boilers on the level of particulate matter pollution comes down, with some simplification, to the study of the influence of temperature on the concentration of particulate matter in the air.

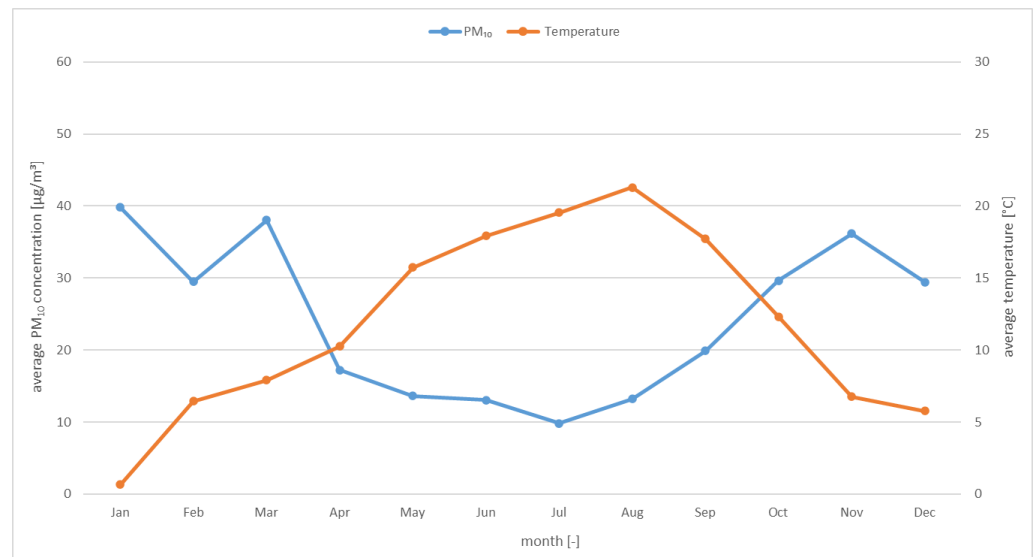


Figure 6. Average monthly PM₁₀ concentrations and temperatures in 2024.

Based on the data obtained during the three-year research period, statistical analyses were carried out taking into account two main aspects:

- The impact of air temperature outside heated buildings (relative to boiler use intensity) on PM₁₀ levels. We answer the question of how PM₁₀ values change depending on the temperature. Based on the years 2022–2024, we created a prediction model for each month that allowed us to predict the level of PM₁₀ pollution in the future depending on the temperature.
- For randomly selected days, we analyzed how PM₁₀ concentrations changed over the course of a single 24 h period depending on the time of day. This is, of course, closely related to the stages of the combustion process, i.e., the operation of hand-fired grate boilers. This confirmed the thesis that hand-fired grate boilers are the main cause of increased air pollution on a daily and hourly basis.

First, however, similarly to this chapter, the graphs of the daily distribution of PM₁₀ values for the selected days of the heating period are analyzed.

3.2. Daily Distribution of Air Pollution for the Administrative Area of Pleszew (Poland) over the Years 2022–2024

From the entire recorded time period, several characteristic days were selected, which are presented in the graphs below. The first four graphs illustrate the typical combustion process during spring and autumn, i.e., during periods of moderate temperatures.

Figure 7 shows the hourly average temperatures and PM₁₀ concentrations on 15 November 2022. This was a standard combustion process (SCP) day—Tuesday. The graph shows a significant increase in particulate matter concentration in the afternoon, approximately from 3:00 PM to 6:00 PM, which corresponds to Interval 0 (Int0). At 5:00 PM, the particulate matter concentrations reach their maximum value. The PM₁₀ concentrations remain above the EU-recommended standard for almost the entire 24 h period.

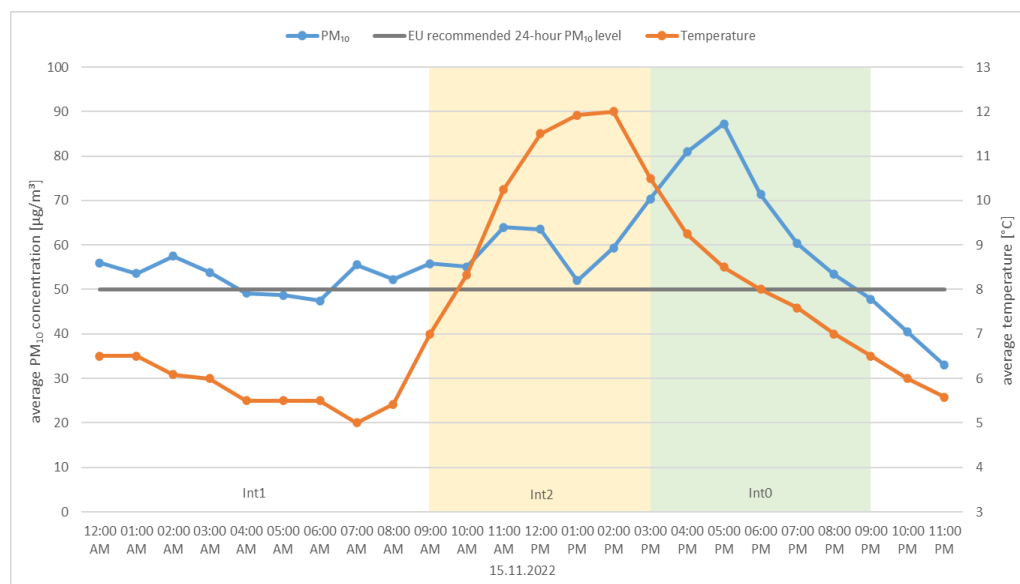


Figure 7. Average hourly PM_{10} concentrations and temperatures on 15 November 2022.

Figure 8 shows the hourly average temperatures and PM_{10} concentrations on 15 March 2023. This was a standard combustion process (SCP) day—Wednesday. The graph again shows a significant increase in particulate matter concentration in the afternoon, this time from approximately 5:00 PM to 9:00 PM, which also corresponds to Interval 0 (Int0). Starting around 6:00 PM, the PM_{10} concentrations exceed the EU-recommended daily standard, and at 7:00 PM, the particulate matter concentrations reach their maximum value.

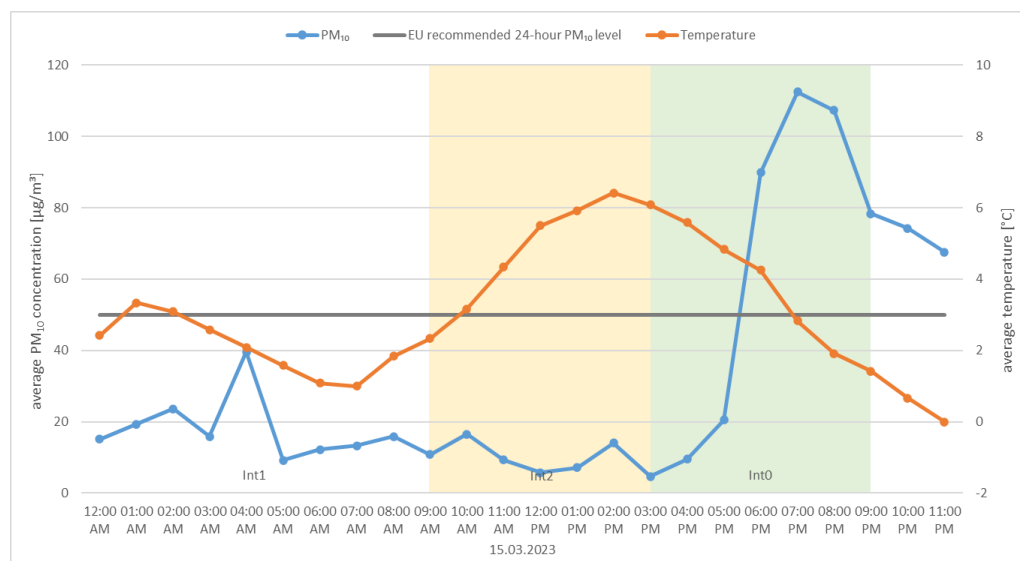


Figure 8. Average hourly PM_{10} concentrations and temperatures on 15 March 2023.

Figure 9 shows the hourly average temperatures and PM_{10} concentrations on 23 October 2023. This was a standard combustion process (SCP) day—Monday. The graph again shows a significant increase in particulate matter concentration in the afternoon, starting at approximately 5:00 PM, during Interval 0 (Int0). Particulate matter concentrations remain high in the evenings, reaching a local maximum at 6:00 PM, at which time they exceed the EU-recommended daily standard.

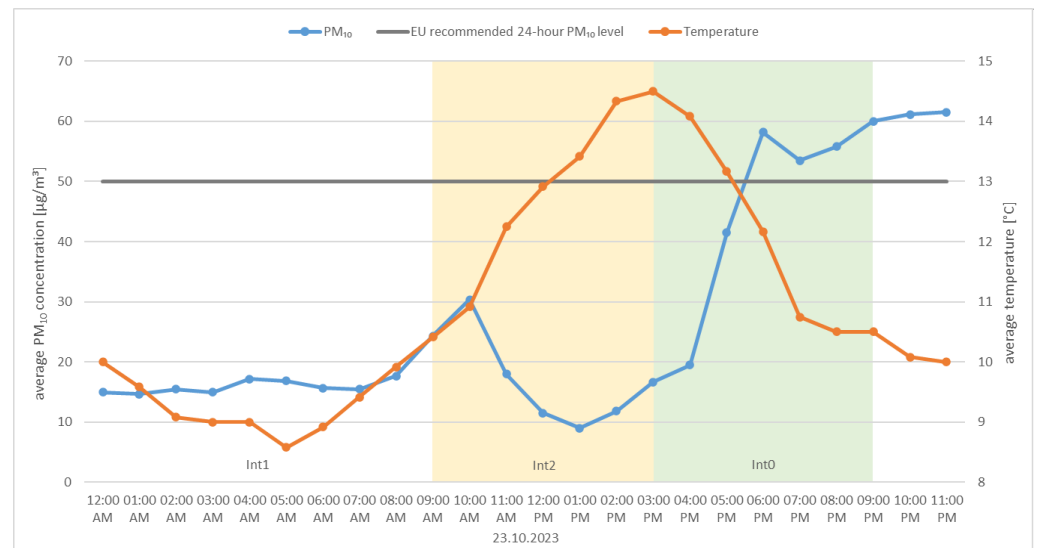


Figure 9. Average hourly PM_{10} concentrations and temperatures on 23 October 2023.

Figure 10 shows the hourly average temperatures and PM_{10} concentrations on 14 April 2024. This was a standard combustion process (SCP) day—Monday. The graph below shows an increase in particulate matter concentration, with a maximum at around 7:00 PM, also during Interval 0 (Int0). During this time interval, the PM_{10} concentrations temporarily exceeded the EU-recommended daily standard.

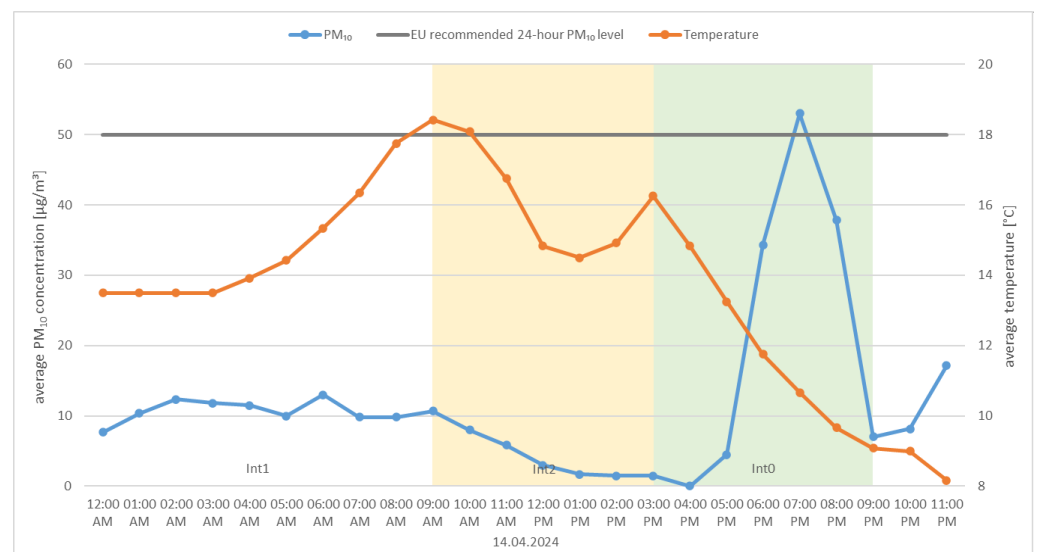


Figure 10. Average hourly PM_{10} concentrations and temperatures on 14 April 2024.

All four graphs above (Figures 7–10) show a significant increase in PM_{10} concentration in the afternoon, starting around 5:00 PM. This is due to the fact that most residents finish work between 3:00 PM and 5:00 PM and, upon arriving at their homes, begin the process of firing the boiler. This process, performed on a cold heating system, is inefficient and generates a large amount of particulate matter. After the boiler is lit and the system is warmed up—usually after 7:00 PM—particulate matter emissions decrease significantly, even though the falling outside temperature increases the boiler's thermal output.

The next two graphs show the relationship between temperature and particulate matter concentration for weekend days, i.e., days off from work.

Figure 11 shows the hourly average temperatures and PM_{10} concentrations on 19 November 2022. This was a non-working day (WEEKEND)—Saturday. The graph below

shows an increase in particulate matter concentration starting at approximately 6:00 AM, with a maximum around 8:00 AM, this time during Interval 1 (Int1), temporarily exceeding the EU-recommended limit value.

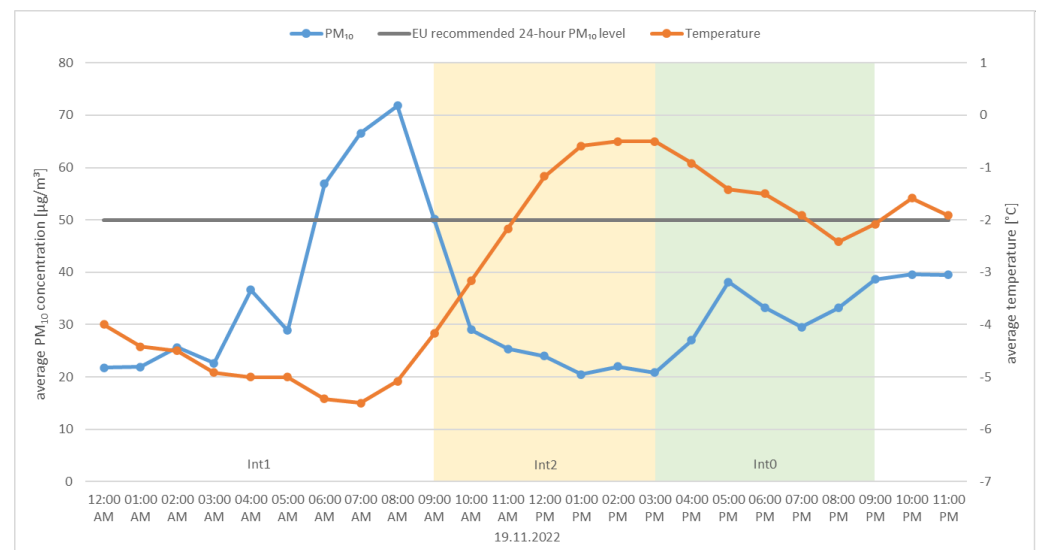


Figure 11. Average hourly PM₁₀ concentrations and temperatures on 19 November 2022.

Figure 12 shows the hourly average temperatures and PM₁₀ concentrations on 10 February 2024. This was a non-working day (WEEKEND)—Saturday. The graph below shows a morning increase in particulate matter concentration, with a local maximum at 9:00 AM, on the border of Interval 2 (Int2). For most of the day, pollution remains above the EU-recommended standard.

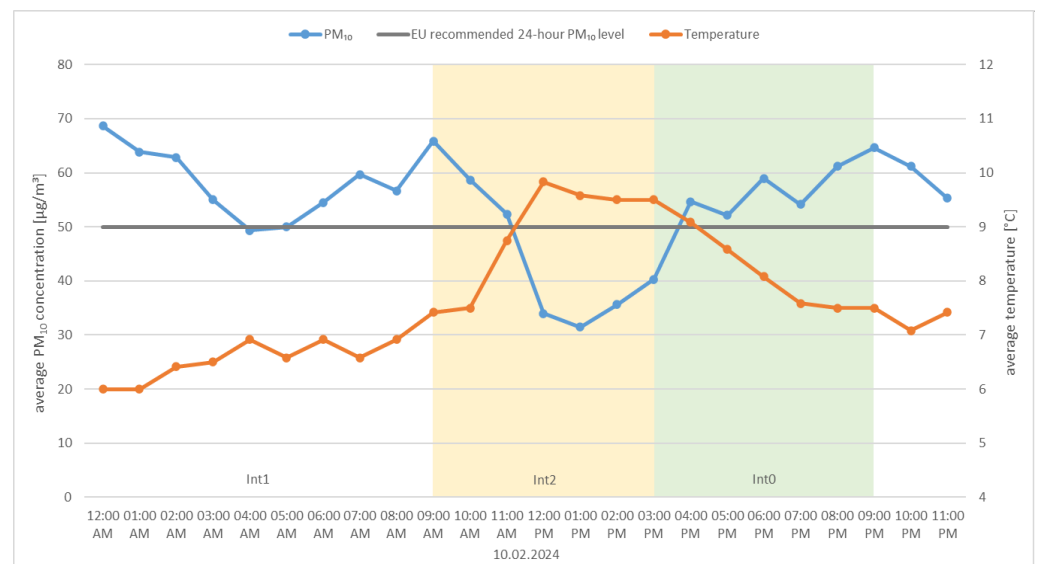


Figure 12. Average hourly PM₁₀ concentrations and temperatures on 10 February 2024.

In the above two graphs (Figures 11 and 12), the highest particulate matter emissions occur in the morning, in contrast to weekdays, where the highest emissions occur in the afternoon. This is most likely due to the fact that, on non-working days, residents begin firing up their boilers shortly after waking up.

The last graph shows the relationship between temperature and particulate matter concentration during a day with a low outside temperature that remained at a similar level throughout the day.

Figure 13 shows the hourly average temperatures and PM₁₀ concentrations on 12 November 2024. This was a constant heat reception (CHR) day—Tuesday. In the graph below, the PM₁₀ concentration levels remain similar throughout the day and are above the EU-recommended standard most of the time. Due to the relatively low and constant temperatures, in this case, heating systems operate around the clock, so there is no single common moment when boilers are fired up, as was the case on the days shown in Figures 7–10 (even though it is also a weekday).

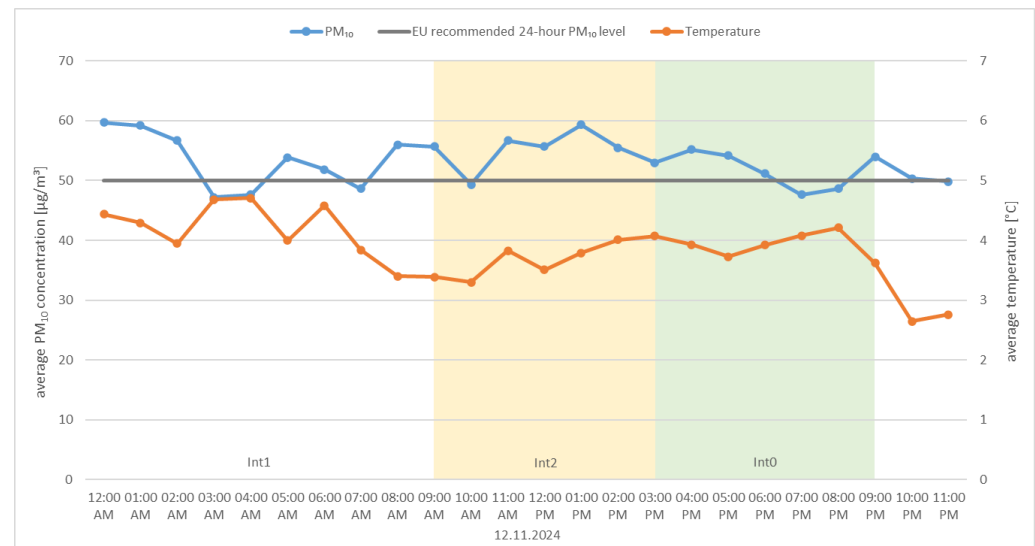


Figure 13. Average hourly PM₁₀ concentrations and temperatures on 12 November 2024.

3.3. Linear Regression Model

One of the statistics of bivariate data is the Pearson linear correlation coefficient from the sample, which is denoted as r and defined by the following formula:

$$r = \frac{s_{xy}}{s_x \cdot s_y} \quad (1)$$

where

- s_{xy} is the sample covariance: $s_{xy} = \frac{1}{n-1} (\sum_{i=1}^n x_i \cdot y_i - n \cdot \bar{x} \cdot \bar{y})$;
- s_x is the sample standard deviation for the variable X, $s_x = \sqrt{\frac{1}{n-1} (\sum_{i=1}^n x_i^2 - n \cdot \bar{x}^2)}$;
- s_y is the sample standard deviation for the variable Y, $s_y = \sqrt{\frac{1}{n-1} (\sum_{i=1}^n y_i^2 - n \cdot \bar{y}^2)}$.

The absolute value of the correlation coefficient informs about the strength of the linear relationship between the examined features X and Y:

- 0—No linear relationship;
- 0–0.2—Very weak linear relationship;
- 0.2–0.4—Weak linear relationship;
- 0.4–0.6—Moderate linear relationship;
- 0.6–0.8—Strong linear relationship;
- 0.8–1—Very strong linear relationship.

Based on the data from 2022–2024 regarding air pollution with PM₁₀, the correlation coefficient (dependence) of PM₁₀ concentration on air temperature and, consequently, on the intensity of boiler use was determined for each month.

Table 2 presents the values of the correlation coefficients from Sample (1) determined from three years of measurements in total.

Table 2. Correlation coefficients (effect of temperature on PM₁₀). Data from 2022–2024.

Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>r</i>	−0.54	−0.34	−0.21	0.01	0.07	0.37	0.58	0.72	0.17	−0.05	−0.45	−0.62

Designation:

- Jan—Data from January 2022, January 2023, and January 2024 taken together;
- Feb—Data from February 2022, February 2023, and February 2024 taken together;
- ...
- Dec—Data from December 2022, December 2023, and December 2024 taken together.

A moderate positive relationship between temperature and PM₁₀ can be observed in July and a strong positive relationship in August. This means that as temperature increases, PM₁₀ pollution increases moderately/strongly.

The opposite relationship can be observed for the autumn and winter months: November, December, and January. The negative relationship means that as temperatures decrease, PM₁₀ pollution increases. This relationship is moderately negative for November and January and strongly negative for December.

Although the correlation coefficient allows for the description of the direction and strength of the relationship, it does not allow for the prediction of the value of the dependent variable Y for a given value of the independent variable X.

Such prediction is possible using, for example, a linear regression model, the advantage of which is a clear interpretation of parameters.

To include the random effect of year in the model, a regression model is used for statistical analysis, which, in scalar form, can be presented as follows [45,46]:

$$y_{ij} = \beta_0 + \beta_1 x_{ij} + \gamma_j + \varepsilon_{ij} \quad (2)$$

where

- y_{ij} is the observed individual i -th value in the j -th year (random variable, dependent);
- β_0 is the intercept of the linear regression (fixed parameter);
- β_1 is the linear regression coefficient (fixed parameter);
- x_{ij} is the i -th value of the independent variable (covariate) in the j -th year;
- γ_j is the random effect of the j -th year;
- ε_{ij} is the random error of the i -th observation in the j -th year.

It is assumed that the random variables from the model have the following parameters:

- $E(y_{ij}) = \beta_0 + \beta_1 x_{ij}, \text{Var}(y_{ij}) = \sigma^2;$
- $E(\gamma_j) = 0, \text{Var}(\gamma_j) = \sigma_j^2;$
- $E(\varepsilon_{ij}) = 0, \text{Var}(\varepsilon_{ij}) = \sigma^2.$

Here, $E(\cdot)$ denotes the expected value of the random variable, and $\text{Var}(\cdot)$ denotes the variance of the random variable.

3.4. Regression Analysis of PM₁₀ Concentration on Temperature

Knowledge about particulate matter air pollution allows us to take action to minimize the negative impact on health and the environment. It allows us to understand the causes and effects of pollution and take steps to improve air quality. Monitoring pollution throughout the year and at different times of the day allows us to make informed decisions, for example, regarding outdoor physical activity, especially during periods of increased particulate matter concentration.

Hence, detailed studies of the influence of the atmospheric environment, in particular air temperature (in relation to the operation of top-loaded boilers), on the level of particulate matter pollution in different months of the year seem justified.

Research conducted for the years 2022–2024 allowed us to determine a simple linear regression model for PM₁₀ levels as a function of temperature. Such a model could be created for each month of a given year separately. The simple linear regression model would then have the following form [46]:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \quad (3)$$

where

- y_i is the observed individual i -th value (random, dependent variable);
- β_0 is the intercept of linear regression (fixed parameter);
- β_1 is the linear regression coefficient (fixed parameter);
- x_i is the i -th value of the independent variable (covariate);
- ε_i is the random error of the i -th observation.

It is assumed that the random variables from the model have the following parameters:

- $E(y_i) = \beta_0 + \beta_1 x_i, \text{Var}(y_i) = \sigma^2$;
- $E(\varepsilon_i) = 0, \text{Var}(\varepsilon_i) = \sigma^2$.

Here, $E(\cdot)$, as before, denotes the expected value of the random variable, and $\text{Var}(\cdot)$ denotes the variance of the random variable. Model (3) is quite “poor” because it does not include the year effect.

Based on Model (3), the PM₁₀ level, i.e., y , can be determined depending on temperature x . For example, for December in 2022, 2023, and 2024, the graphs of the simple regression lines (3) are presented in Figure 14.

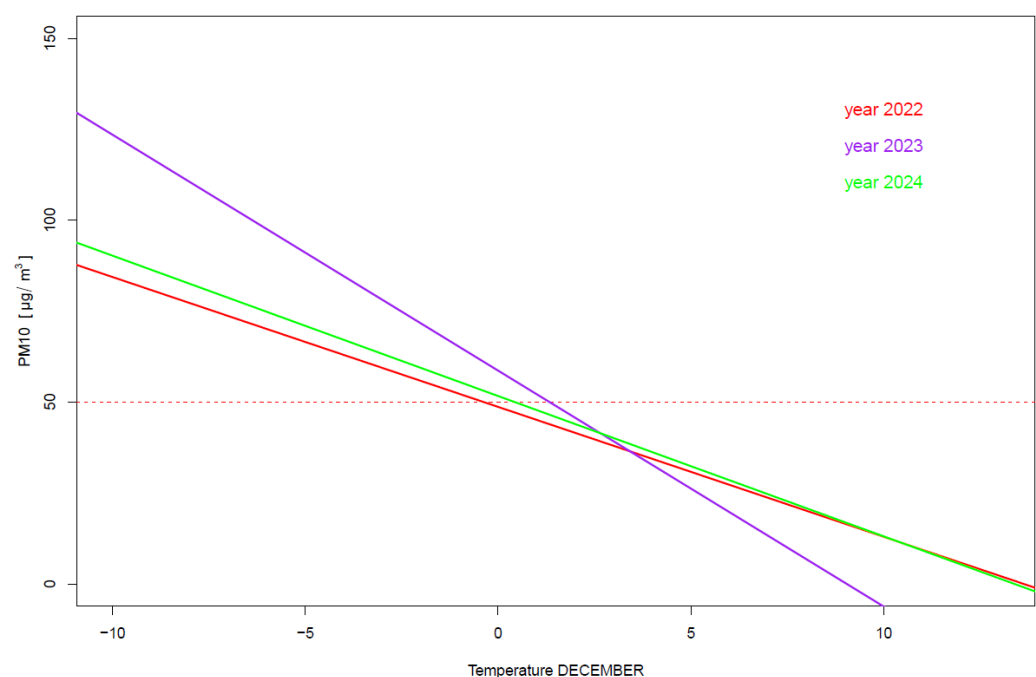


Figure 14. Linear regression: Dependence of PM₁₀ level on temperature in December in 2022–2024. The horizontal red dashed line marks the daily standard PM₁₀ = 50 µg/m³ permitted by EU regulations.

According to Formula (3), regression lines were estimated for the three years under consideration. We can read the level of PM₁₀ pollution; for example, in December 2022, at a temperature of 0 °C (red line), it was slightly higher at the same temperature in 2024 (green

line) and the highest in 2023. Of course, we can see differences between the years, although the trend is maintained in all three years. Additionally, the daily standard of $50 \mu\text{g}/\text{m}^3$ permitted by the EU regulations is marked with a horizontal dashed line.

The graphs showing these relationships are interesting from a statistical perspective. It can be analyzed how PM_{10} levels have changed in previous years depending on outdoor air temperature and, consequently, boiler operation intensity.

However, a more meaningful approach than determining the relationship for a given month of a given year is to make predictions (forecasts) for the future based on previous years. Model (2), which takes into account the year effect, provides this capability.

Based on the observed PM_{10} concentration values in the 2022–2024 study years, the regression models presented in Figures 15 and 16 were estimated separately for each month according to Formula (2).

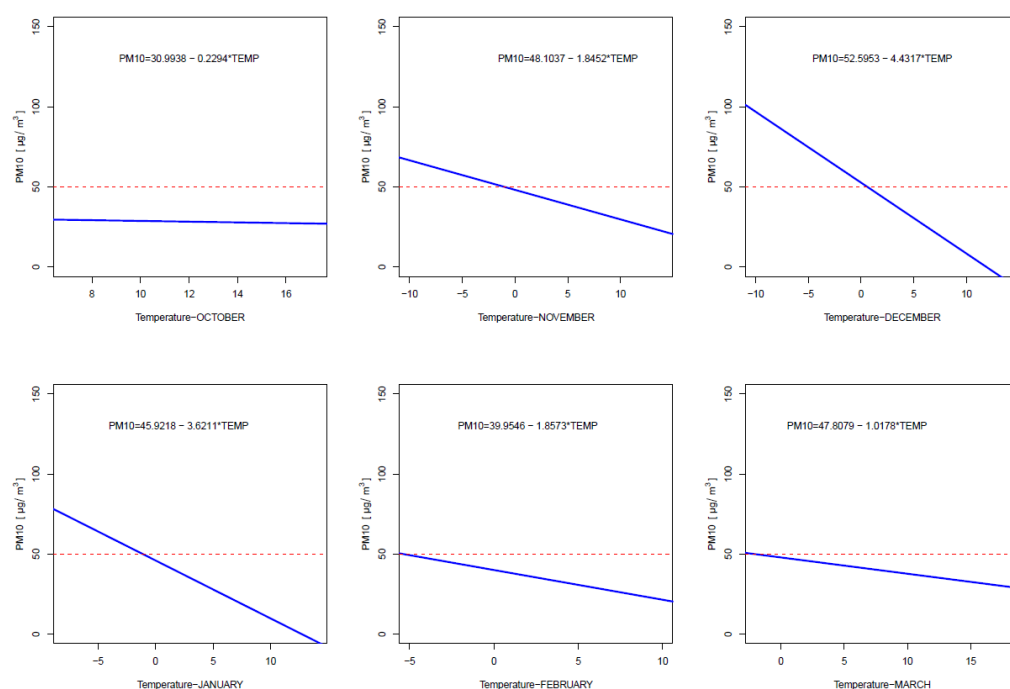


Figure 15. Regression Models (2) of the PM_{10} level on temperature, estimated based on data from 2022–2024, taking into account the effect of year: October, November, December, January, February, and March. The horizontal red dashed line marks the daily standard $\text{PM}_{10} = 50 \mu\text{g}/\text{m}^3$ permitted by EU regulations. The asterisk (*) represents the multiplication symbol.

For example, the model for December (Figure 15) presents a linear regression (PM_{10} values as a function of temperature), which enables the prediction of future PM_{10} particulate matter pollution for a given temperature in December from the following equation:

$$\text{PM}_{10} = 52.5953 - 4.4317 * \text{TEMP} \quad (4)$$

An example forecast for five selected temperatures in December is presented in Table 3.

The above estimates were based on three years of research. Each graph also includes a horizontal dashed line (the daily limit of $50 \mu\text{g}/\text{m}^3$ permitted by EU regulations). Note that, in December, even at 0°C , we can expect air pollution in Pleszew to exceed $50 \mu\text{g}/\text{m}^3$. The lower the temperature, the higher the pollution, according to Model (4).

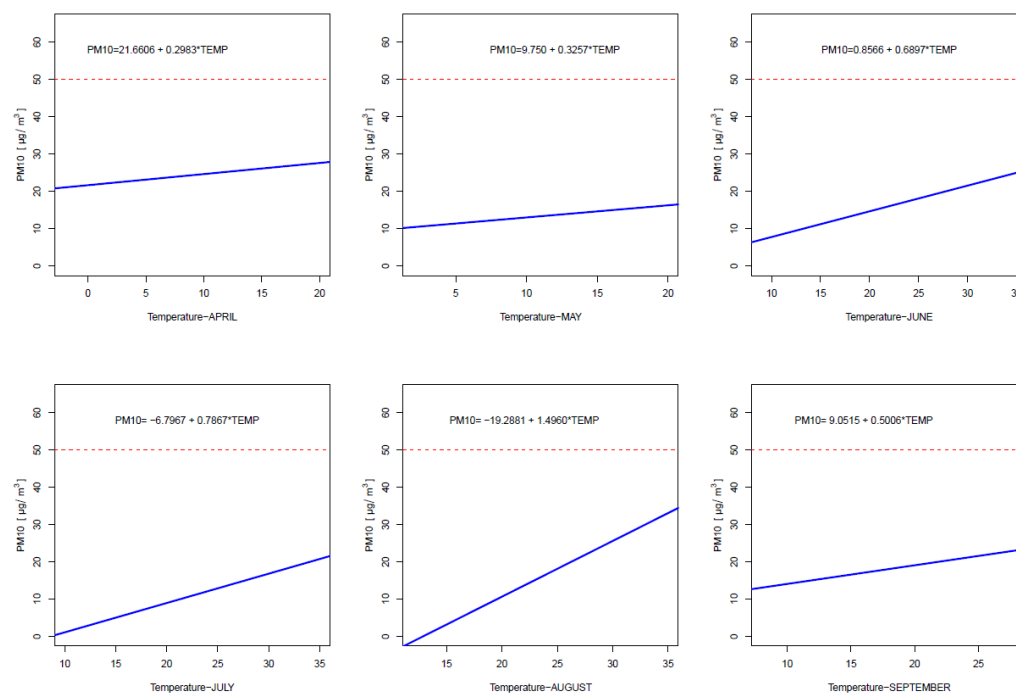


Figure 16. Regression Models (3) of PM_{10} levels on temperature, estimated based on data from 2022–2024, taking into account the year effect. Months are April, May, June, July, August, and September. The horizontal red dashed line marks the daily standard $PM_{10} = 50 \mu\text{g}/\text{m}^3$ permitted by EU regulations. The asterisk (*) represents the multiplication symbol.

Table 3. Predicted PM_{10} concentration values for five selected temperatures.

December	
Temperature [°C]	PM_{10} [$\mu\text{g}/\text{m}^3$]
−10	96.9123
−5	74.7538
0	52.5953
5	30.4368
10	8.2783

The graphs in Figure 15 are consistent with the information in Table 2. The largest negative relationship between PM_{10} and temperature can be observed for November, December, and January. The straight lines (blue) are the most sloped, and in each of these three months, the relationship is statistically highly significant. Furthermore, for the negative temperatures typical of these three months, the predicted PM_{10} values exceed $50 \mu\text{g}/\text{m}^3$. In the remaining three months (Figure 15), although the relationship is also negative, slightly lower PM_{10} pollution can be expected.

Based on the models estimated for the months of April to September (Figure 16), we can expect a positive relationship between PM_{10} and temperature. This means that as the temperature increases, PM_{10} increases. Although the relationship is quite strong in July and August, we can expect PM_{10} concentrations to be significantly below the permissible limit of $50 \mu\text{g}/\text{m}^3$.

3.5. Daily and Hourly Air Pollution Analysis

To determine whether boilers with manual fuel loading are a major cause of increased air pollution on a daily and hourly basis, a detailed analysis of randomly selected days was conducted. To obtain reliable results, the analysis included days/24 h periods from different years and seasons, taking into account the varying heat consumption of Pleszew residents.

The analysis was carried out

- (1) on 15 November 2022 and two days preceding and two days following (five consecutive days randomly selected from the 2022 heating period);
- (2) on three randomly selected days from the 2023 heating period (a spring day, an autumn day, and a winter day);
- (3) on randomly selected days (from three years), taking into account the combustion process and heat reception.

It was analyzed how the concentrations of PM₁₀ change during one day depending on the time of day, which is closely related to the stages of the combustion process, i.e., the operation of the hand-fired grate boilers.

The first analysis was performed for the five consecutive days in November 2022: from 13 November to 17 November. Average PM₁₀ value levels were plotted for individual days (adopted time intervals).

In the graph (Figure 17), it can be seen that for almost all days, the average PM₁₀ values were the highest during Interval 0, i.e., between 3:00 PM and 9:00 PM. The exception was 16 November.

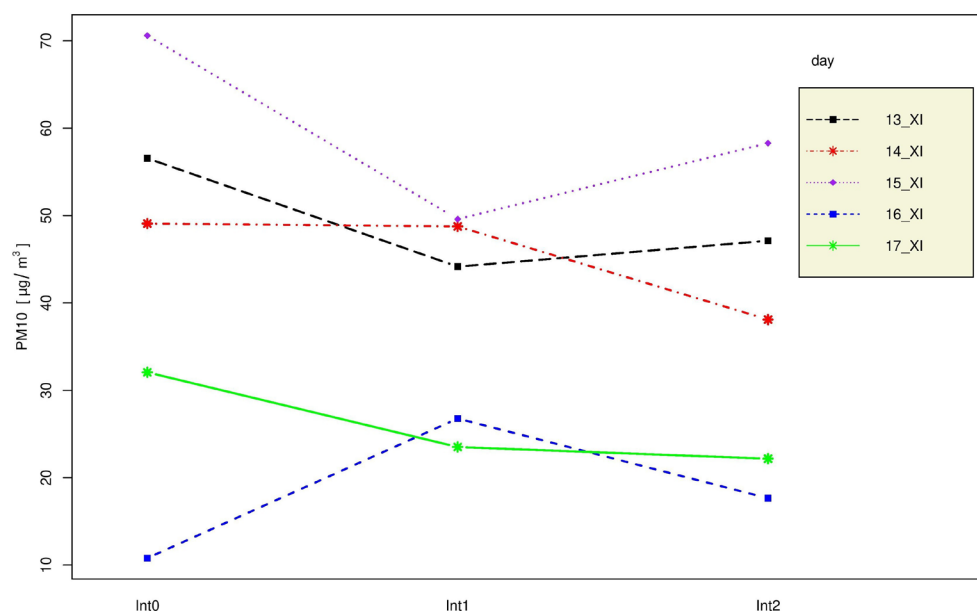


Figure 17. Average PM₁₀ values in intervals for selected days, 13–17 November 2022.

In the next steps, detailed research and statistical analyses were performed to answer the question of whether the differences between the PM₁₀ values for the three considered intervals are statistically significant, i.e., whether the time intervals do not differ in terms of PM₁₀ values.

We put forward the null hypothesis H_0 which states that the average PM₁₀ values for all three intervals are the same (within one 24 h period):

$$H_0 : \mu_{Int0} = \mu_{Int1} = \mu_{Int2} \quad (5)$$

where

- μ_{Int0} means the average concentration of PM₁₀ during the time interval Int0, i.e., in the hourly interval from [3:00 PM to 9:00 PM];
- μ_{Int1} means the average concentration of PM₁₀ during the time interval Int1, i.e., in the hourly interval from [9:00 PM to 9:00 AM];

- μ_{Int2} means the average concentration of PM₁₀ during the time interval Int2, i.e., in the hourly interval from [9:00 AM to 3:00 PM).

We assume that we are testing at a significance level of $\alpha = 0.01$ (with an error of 0.01). After conducting an analysis of variance (ANOVA) on the observed data, we obtain p values. If the p value $< \alpha$, we reject H_0 . The ANOVA results for each of the five sample days are presented independently in Table 4.

Table 4. p values for analysis of variance (comparisons of average PM₁₀ contents) of three time intervals (ANOVA) for five sample days in November 2022.

Day	p Value of ANOVA
13 November 2022	<0.001 ***
14 November 2022	<0.001 ***
15 November 2022	<0.001 ***
16 November 2022	<0.001 ***
17 November 2022	<0.001 ***

*** significance at the 0.001 level.

Table 4 shows that (for each day independently) the null hypothesis H_0 should be rejected; hence, we claim that (for a given day) the average PM₁₀ values for all three intervals are not the same, and they differ statistically significantly.

Next, Tukey's test for homogeneous groups was performed. The results are presented in Table 5.

Table 5. Tukey's test results for homogeneous groups for five sample days in November 2022. Mean value of PM₁₀.

Day	Hour	Interval	Mean Value of PM ₁₀	Tukey Group
13 November 2022	[3:00 PM–9:00 PM)	Int0	56.55556	a
	[9:00 AM–3:00 PM)	Int2	47.12500	b
	[9:00 PM–9:00 AM)	Int1	44.15278	b
14 November 2022	[3:00 PM–9:00 PM)	Int0	49.08333	a
	[9:00 PM–9:00 AM)	Int1	48.75694	a
	[9:00 AM–3:00 PM)	Int2	38.09722	b
15 November 2022	[3:00 PM–9:00 PM)	Int0	70.59722	a
	[9:00 AM–3:00 PM)	Int2	58.29167	b
	[9:00 PM–9:00 AM)	Int1	49.59722	c
16 November 2022	[9:00 PM–9:00 AM)	Int1	26.77083	a
	[9:00 AM–3:00 PM)	Int2	17.63889	b
	[3:00 PM–9:00 PM)	Int0	10.79167	c
17 November 2022	[3:00 PM–9:00 PM)	Int0	32.05556	a
	[9:00 PM–9:00 AM)	Int1	23.50694	b
	[9:00 AM–3:00 PM)	Int2	22.16667	b

Groups marked with the same letters do not differ statistically significantly. Groups marked with different letters differ statistically significantly in terms of the average value of PM₁₀. Groups a and b differ statistically significantly, groups b and c differ statistically significantly, groups a and c differ statistically significantly.

Column 4 lists the average PM₁₀ content for each hourly interval for a given day. The averages are arranged in descending order (within a day). The letters in the fourth column indicate Tukey's homogeneous group. We can deduce which time intervals (within a single day) belong to the same group in terms of PM₁₀ content.

And so, for example, for 13 November, the hourly intervals from [9:00 AM to 3:00 PM) and from [9:00 PM to 9:00 AM) belong to the same homogeneous group "b" (i.e., do

not differ statistically significantly) in terms of the average PM₁₀ value. Similarly, on 14 November, the hourly intervals from [3:00 PM to 9:00 PM) and from [9:00 PM to 9:00 AM) belong to the same homogeneous group “a” (i.e., do not differ statistically significantly) in terms of the average PM₁₀ value. The remaining results should be interpreted analogously.

The results in Table 5 confirm what we observe in Figure 17, namely, that for almost all days, the average PM₁₀ values were the highest during Interval 0, i.e., between 3:00 PM and 9:00 PM. Furthermore, on 15 November and 13 November, between 3:00 PM and 9:00 PM, the PM₁₀ level significantly exceeded 50 µg/m³. This may confirm the assumption that, during these hours, the operation of boilers with manual fuel loading was very intense and caused high air pollution.

The exception was 16 November. On that day, PM₁₀ levels were low during all time intervals. The air temperature, humidity, and atmospheric pressure on that day were similar to those on other days, so the low PM₁₀ levels must be attributed to other factors, such as strong winds.

Table 6 presents the results of the Tukey’s test for the randomly selected days from the heating period in 2023.

Table 6. Tukey’s test results for homogeneous groups for three sample days in 2023. Mean value of PM₁₀.

Day	Hour	Interval	Mean Value of PM ₁₀	Tukey Group
15 March 2023	[3:00 PM–9:00 PM)	Int0	57.38889	a
	[9:00 PM–9:00 AM)	Int1	32.04167	b
	[9:00 AM–3:00 PM)	Int2	10.61111	c
23 October 2023	[3:00 PM–9:00 PM)	Int0	40.86111	a
	[9:00 PM–9:00 AM)	Int1	27.13889	b
	[9:00 AM–3:00 PM)	Int2	17.5000	c
1 December 2023	[3:00 PM–9:00 PM)	Int0	240.7222	a
	[9:00 PM–9:00 AM)	Int2	186.3611	b
	[9:00 AM–3:00 PM)	Int1	153.9028	c

Groups marked with the same letters do not differ statistically significantly. Groups marked with different letters differ statistically significantly in terms of the average value of PM₁₀. Groups a and b differ statistically significantly, groups b and c differ statistically significantly, groups a and c differ statistically significantly.

The results in Table 6 confirm the thesis that PM₁₀ pollution is the highest between 3:00 PM and 9:00 PM.

Additionally, the above analyses were performed for randomly selected days, taking into account the combustion process and heat reception:

Standard combustion process (SCP)—Working days:

- 15 November 2022—Tuesday;
- 15 March 2023—Wednesday;
- 23 October 2023—Monday;
- 14 April 2024—Monday.

Weekend (WEEKEND)—Days off from work, different lifestyle of residents:

- 19 November 2022—Saturday;
- 10 February 2024—Saturday.

Constant heat reception (CHR)—Due to the low outside air temperature, a continuous cycle of boiler operation is forced:

- 12 November 2024—Tuesday—Temperature around 0 °C all day.

Based on the results in Table 7, it can be seen that, on SCP days, when residents return from work in the afternoon, air pollution with PM₁₀ is at different levels, but on each of the four days analyzed, it was the highest during the time interval Int0, i.e., [3:00 PM–9:00 PM].

Table 7. Tukey’s test results for homogeneous groups for days with different heat reception (SCP, WEEKEND, CHR).

	Day	Hour	Interval	Mean Value of PM ₁₀	Tukey Group
SCP (Tuesday)	15 November 2022	[3:00 PM–9:00 PM)	Int0	70.59722	a
		[9:00 AM–3:00 PM)	Int2	58.29167	b
		[9:00 PM–9:00 AM)	Int1	49.59722	c
SCP (Wednesday)	15 March 2023	[3:00 PM–9:00 PM)	Int0	57.38889	a
		[9:00 PM–9:00 AM)	Int1	32.04167	b
		[9:00 AM–3:00 PM)	Int2	10.61111	c
SCP (Monday)	23 October 2023	[3:00 PM–9:00 PM)	Int0	40.86111	a
		[9:00 PM–9:00 AM)	Int1	27.13889	b
		[9:00 AM–3:00 PM)	Int2	17.5000	c
SCP (Monday)	14 April 2024	[3:00 PM–9:00 PM)	Int0	21.861111	a
		[9:00 PM–9:00 AM)	Int1	10.722222	b
		[9:00 AM–3:00 PM)	Int2	5.111111	b
WEEKEND (Saturday)	19 November 2022	[9:00 PM–9:00 AM)	Int1	39.22222	a
		[3:00 PM–9:00 PM)	Int0	30.31944	b
		[9:00 AM–3:00 PM)	Int2	28.500	b
WEEKEND (Saturday)	10 February 2024	[9:00 PM–9:00 AM)	Int1	58.47222	a
		[3:00 PM–9:00 PM)	Int0	53.58333	b
		[9:00 AM–3:00 PM)	Int2	46.33333	c
CHR (Tuesday)	12 November 2024	[9:00 AM–3:00 PM)	Int2	55.36111	a
		[9:00 PM–9:00 AM)	Int1	52.90278	ab
		[3:00 PM–9:00 PM)	Int0	51.63889	b

Groups marked with different letters differ statistically significantly in terms of the average value of PM₁₀. Groups a and b differ statistically significantly, groups b and c differ statistically significantly, groups a and c differ statistically significantly. Groups marked with the same letters do not differ statistically significantly. Groups a and ab do not differ statistically significantly (these groups are homogeneous).

On WEEKEND days, air pollution with PM₁₀ was the highest during the Int1 time interval, i.e., [9:00 PM–9:00 AM]. On these days, residents are often away from home during the day, and the boiler is loaded and fired up in the evening.

On the CHR day, where constant heat reception occurred, the PM₁₀ air pollution was comparable among the three time intervals. This was a day when low temperatures persisted throughout the day. On this day, during each time interval, not only the daily standards recommended by the WHO (45 µg/m³) but also the EU standards (50 µg/m³) were exceeded.

To better illustrate the observed PM₁₀ concentrations, a graphical illustration of the data for four sample days was created (Figures 18 and 19).

Figures 18 and 19 present violin plots of the observed PM₁₀ concentrations. The black rectangle is the boxplot, the bottom of the boxplot is the lower quartile, and the top is the upper quartile. The white circle in the center of the rectangle is the median. The width of the “violin” indicates the number of observed concentrations (the wider the violin, the more observations there were at a given level). The graphs show the mean concentration values in each time interval—Mean.

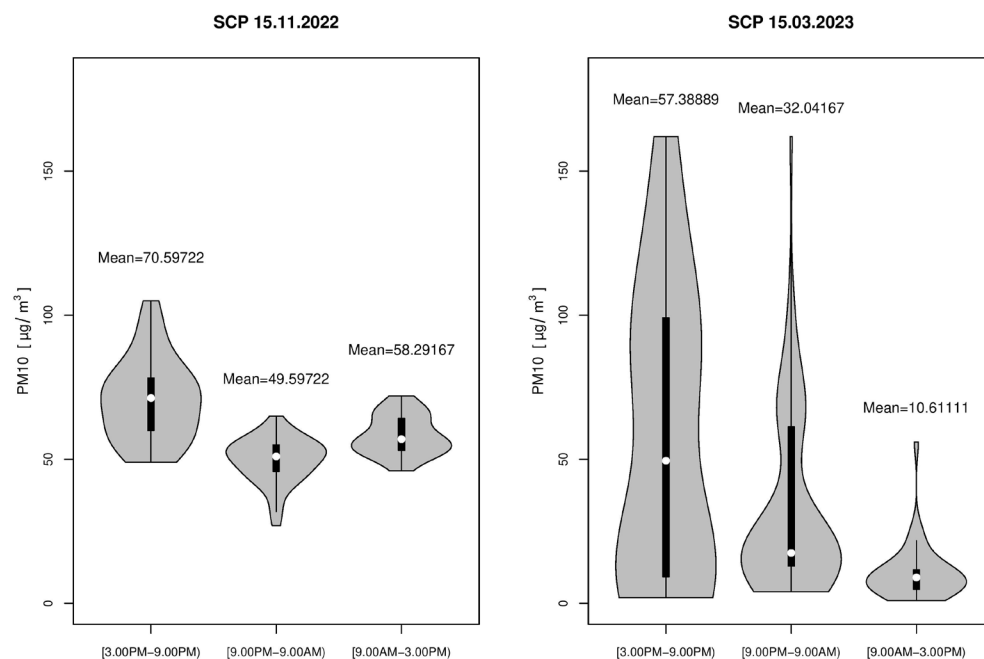


Figure 18. Violin plots of PM₁₀ concentration during time intervals for two example SCP days.

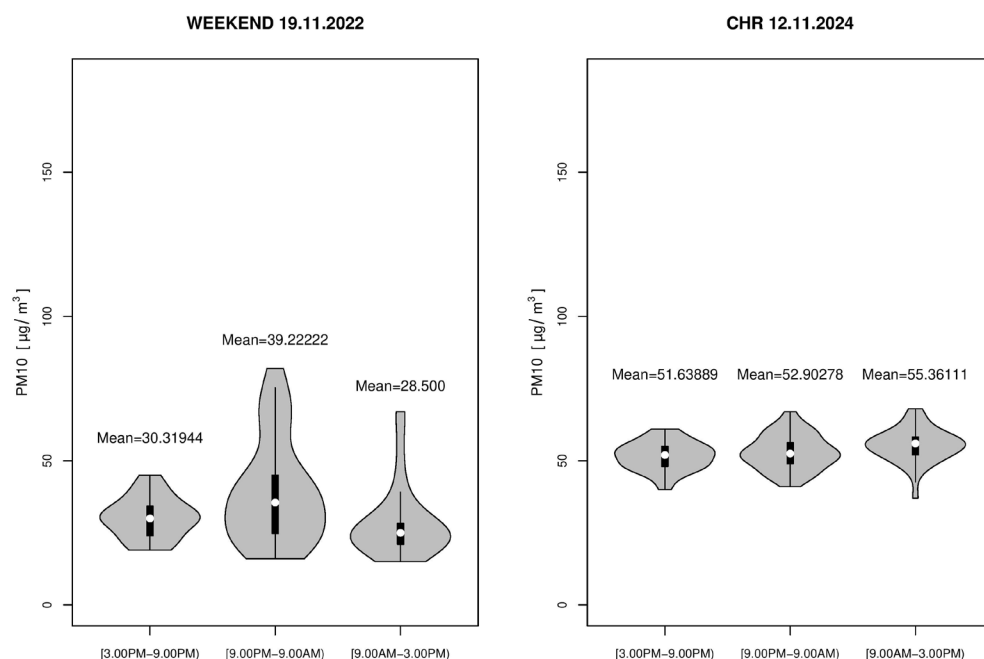


Figure 19. Violin charts of PM₁₀ concentration during time intervals for two example days: a WEEKEND day and a CHR day.

For example, for 19 November 2022—a WEEKEND day (Figure 19)—although the average value during the time interval [9:00 PM–9:00 AM) was Mean = 39.22222 $\mu\text{g}/\text{m}^3$, we can notice that the concentration values ranged from approx. Min = 16 $\mu\text{g}/\text{m}^3$ to approx. Max = 82 $\mu\text{g}/\text{m}^3$. The median was Me = 35.5 $\mu\text{g}/\text{m}^3$ (white circle). The highest concentrations were observed at the level of 25–45 $\mu\text{g}/\text{m}^3$ (the widest violin).

During the WEEKEND, most observations during all time intervals were below 50 $\mu\text{g}/\text{m}^3$.

On 12 November 2024—the constant heat reception (CHR) day—the concentrations during all time intervals were at the same level (the widest violin at the level of approx. 50 $\mu\text{g}/\text{m}^3$)

However, on the days when the standard combustion process (SCP, Figure 18) was in progress, the highest concentrations were observed during Interval 0, i.e., in the hours from [3:00 PM to 9:00 PM).

All statistical analyses were performed using the R (RStudio, R version 4.1.2) program [47].

4. Discussion and Conclusions

The ability to forecast air pollution levels for specific months of the year is an important tool supporting both individual and institutional decision-making processes. Knowledge of expected changes in air quality allows for informed physical activity and for planning time spent outdoors to minimize exposure to harmful substances. In situations requiring outdoor activities during times when elevated particulate matter concentrations are forecasted, protective measures such as filtering masks, limiting exposure time, or using air purifiers in enclosed spaces become possible.

Air quality forecasts are particularly important for high-risk groups, including children, the elderly, and patients with respiratory and circulatory system diseases. Early information about expected deteriorations in air quality allows these individuals to limit activities requiring intense physical exertion and take preventative measures that can reduce the risk of exacerbating disease symptoms.

Forecasting is becoming a crucial element of public health policy and adaptation strategies in the context of air pollution in urban agglomerations.

The obtained results clearly indicate that PM₁₀ concentrations in the study area strongly depend on both the type of day and the time of day. The highest concentrations were observed in the autumn and winter periods, during the afternoon and evening hours (Int0 interval: 3:00 PM–9:00 PM).

On days with persistently low outdoor temperatures, PM₁₀ concentrations remain high in each of the analyzed intervals. This indicates persistently unfavorable air quality conditions throughout the 24 h cycle, without natural improvement phases. This is crucial for public health protection and intervention planning.

The relationship demonstrated in this study between the use of hand-fired grate boilers and increased air pollutant concentrations indicates the direct impact of individual household decisions on environmental quality. Hand-fired grate boilers, due to their design and low energy efficiency, generate significantly higher emissions of particulate matter and other pollutants compared to modern heat sources. The empirical confirmation of this relationship should be a premise for decisions to gradually phase out the use of these devices in favor of ecological solutions such as gas boilers, heat pumps, or systems based on renewable energy sources.

From a social perspective, the obtained results also have educational significance and can contribute to increasing residents' awareness of the consequences of their heating source choices for air quality and public health. Demonstrating a clear correlation between individual behavior and the state of the natural environment strengthens the argument for pro-ecological actions and investments in low-emission technologies.

More broadly, eliminating hand-fired boilers and replacing them with modern heating devices should be supported not only by individual decisions of residents but also through appropriate public policy instruments, including subsidy programs, tax relief, and legal regulations. This will enable sustainable emission reductions and improved air quality at the local and regional levels.

Summary:

- The statistical analysis carried out in this study showed a significant relationship between the temperature drop and the increase in the concentration of suspended

PM₁₀ particulate matter in the heating season, which confirms the hypothesis about the dominant influence of atmospheric conditions (especially low temperature) on pollutant emissions.

- The key role of manually hand-fired boilers in shaping the level of particulate matter emissions was pointed out, which suggests the need for further regulation and modernization of this type of combustion source.
- The daily PM₁₀ standard, i.e., 50 µg/m³ (according to EU regulations), was exceeded on days when constant heat removal occurred due to low outside temperatures.
- Division of the day into three time intervals (Int0, Int1, Int2) proved to be an effective analytical tool enabling the identification of periods with the highest risk of high PM₁₀ concentrations.
- The highest concentrations were recorded in the autumn–winter season during the afternoon and evening hours (Int0) on weekdays, which is associated with the intensification of solid fuel combustion in households.
- The results confirm that pollutant emissions are not solely a function of technical factors but are also significantly related to residents' lifestyles, highlighting the importance of social aspects in air quality research.
- The developed linear regression model enables effective forecasting of local PM₁₀ concentrations depending on temperature, which is a useful tool in planning environmental policy and preventive measures.
- The conducted analysis of variance (ANOVA) and Tukey's post hoc tests revealed significant differences among the average particulate matter concentrations during the three daily intervals, indicating the complex nature of emission dynamics and the need to account for temporal variability in research and modeling.

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Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of Variance
CHR	Constant Heat Reception
EU	European Union
PM	Particulate Matter
SCP	Standard Combustion Process
WHO	World Health Organization

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