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Seasonal Variability and Trends of PM10 and PM2.5 Particulate Matter Pollution in Warsaw: A Multi-Year Analysis

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Abstract

The article examines the temporal variability and seasonal trends of PM10 and PM2.5 particulate matter pollution in Warsaw over six years from 2016 to 2021. The study utilizes data from air quality monitoring stations in various parts of Warsaw, including urban background and traffic stations. The analysis reveals distinct patterns in particulate matter concentrations, with higher levels observed during the colder months, particularly from January to March. Conversely, lower concentrations are recorded from June to August, in the summer. The study also highlights the influence of meteorological conditions and the heating season on air pollution levels. Statistical analyses demonstrate significant variability in pollution levels across different months and years, with the correlation between monitoring stations fluctuating over time. The findings provide valuable insights into the factors driving air pollution in Warsaw and underscore the importance of ongoing monitoring and mitigation efforts to improve air quality in urban environments.

1. INTRODUCTION

Warsaw, a heavily urbanized city, faces air pollution from factories, vehicles, and residential and commercial activities. The building density and layout vary throughout neighborhoods, and land use patterns frequently change [Degórska 2012]. This variety leads to significant differences in air quality between districts. This diversity results in significant differences in air quality between stations situated in the city center, primarily affected by emissions from transportation, and urban background stations, where pollutants from municipal and residential sources predominate [Podawca, Rutkowska 2013]. The difference in air quality is not limited to overall levels. It also changes throughout the day, especially between busy traffic areas and suburban locations [Starzomska, Strużewska 2024].

A substantial reduction in particulate matter pollution observed in 2020 is attributed to the global economic slowdown during the COVID-19 pandemic and, in Poland, also to an exceptionally warm winter period [GIOŚ 2021].

The permissible standard for the annual average PM10 concentrations is 40 μg/m^3, while for the daily mean, the threshold is 50 μg/m^3, with a permissible number of 35 exceedances per year. The permissible level of PM2.5 as an annual average is 20 μg/m^3 [Dz.U. 2020 poz. 2279].

Available studies indicate a problem with particulate matter pollution in many European cities, especially during the winter season [Houthuijs et al. 2001]. The analysis conducted for Warsaw 2008 showed a 20% approximate exceedance of the permissible standard. Authors suggest that the elevated PM10 concentrations at Niepodległości Avenue in Warsaw, compared to other stations, are due to its central location [Podawca, Rutkowska 2013]. Studies conducted in Eastern and Central Europe have shown a significant difference in concentrations depending on the season, with PM10 and PM2.5 concentrations in winter being twice as high as in the warm season [Cembrzyńska, Krakowiak 2012]. Concentrations in the center of Krakow were higher than in Warsaw. During the study period, PM10 and PM2.5 concentrations ranged from 20.0 to 92.5 μg/m^3 and 8.9 to 84.1 μg/m^3, respectively [Styszko et al. 2017].

In 2017, the PM10 particulate matter pollution level in Kraków ranged from 38 μg/m^3 to 55 μg/m^3 at the traffic control station. The traffic control station recorded 132 days of exceedances, which exceeded the daily norm. The situation in Warsaw is similar, as the permissible PM10 daily norms are exceeded for one-third of the year. Regarding the average annual PM10 concentration near roads, Warsaw ranks ingloriously third among the most polluted capitals in Europe [Kuchcik, Milewski 2018].

In the 2012 study conducted in Sosnowiec, situated in Upper Silesia, the concentrations of PM10 and PM2.5 were examined during autumn and winter. Significant statistical variances in concentrations were observed between these two periods. The highest PM10 concentrations were recorded in December (median: 115 μg/m^3), while the lowest concentrations were recorded in October and

Table 1. Monitoring stations analyzed in the Warsaw agglomeration

Name of station	Location	Location		Type	Pollution		Sampling frequency
		Latitude	Longitude				
MzWarAlNiepo	Warsaw, Niepodległości 227/233	52.22	21.00	communication	PM2.5	PM10	1h
MzPiasPulask	Piastów, Pułaskiego 6/8	52.19	20.84	suburban background	PM2.5	-	1h
MzLegZegrzyn	Legionowo, Zegrzyńska 38	52.41	20.96	suburban background	PM2.5	-	1h
MzWarWokalna	Warsaw, Wokalna 1	52.16	21.03	urban background	-	PM10	1h

November (median: 70 μg/m^3 and 56 μg/m^3). Over the six months of the study period, PM2.5 concentrations reached the highest value in December (median: 97 μg/m^3), while generally lower values were observed in the autumn months. During the analyzed period, 70% of days exceeded the limit value for the daily concentrations. The average concentration value calculated for the six months was 83 μg/m^3.

This study investigates monthly variations in PM10 and PM2.5 concentrations in Warsaw and examines the number of days exceeding the permissible limits for both pollutants from 2016 to 2021. The analysis focuses on air quality monitoring stations and aims to identify patterns in PM10 and PM2.5 pollution levels.

2. DATA AND METHODS

The analysis was based on PM10 and PM2.5 measurements obtained from the National Air Quality Monitoring Network, operated by the Chief Inspectorate for Environmental Protection (GIOŚ). The monitoring followed the guidelines set by Directive 2008/50/EC and Polish Regulation. Statistical analyses of the concentration variability at the traffic stations and urban background stations were carried out from 2016 to 2021.

PM10 (particles ≤10 μm) and PM2.5 (particles ≤2.5 μm) were measured using two complementary methods:

Gravimetric Method (Reference Method): This is the gold standard method known for its precision. Air is drawn through filters in sampling devices, which are then meticulously weighed in a laboratory to calculate particulate concentrations. While it is time-consuming, taking approximately three weeks for results, its precision is unmatched, instilling confidence in the accuracy of the data.

Automatic Method: Certified automatic monitors were used for real-time measurements. These devices, which have been validated to be equivalent to the gravimetric method, provide hourly data that are averaged to daily values. These results are updated regularly on public portals, keeping the audience informed in real time and up-to-date with the latest air quality information.

Data completeness was ensured by adhering to a requirement of at least 90% valid data per year, with measurement uncertainty not exceeding 25%. Data were verified in a four-step process, including daily, monthly, and annual checks, to ensure technical and atmospheric accuracy. This rigorous verification process is crucial in maintaining the integrity of the data and ensuring its reliability for further analysis and decision-making.

The daily concentrations of PM10 and PM2.5 were calculated as the arithmetic mean of hourly measurements, ensuring consistency with European air quality standards. This adherence to standards reassures the audience about the reliability of the data.

Concentrations of both fractions of particulate matter, PM10 and PM2.5, are measured at the MzWawAlNiepo traffic station, located in the city center on Niepodległości Avenue. In addition, PM10 particulate matter concentrations are monitored at the MzWawWokalna urban background station, situated on Wokalna Street. Measurements of PM2.5 concentrations measurements are carried out at stations located in suburban areas of Warsaw, such as in Piastow (MzPiasPulask) on Pulaski Street and in Legionowo (MzLegZegrzyn) on Zegrzynska Street (Fig. 1). The following tables and figures have been independently compiled based on GIOŚ data.

Analyzing particulate matter (PM10 and PM2.5) concentrations employed a systematic approach to characterize variability in non-normally distributed data. Descriptive statistics, specifically the median and interquartile range (IQR), were calculated for each monitoring station and month from 2016 to 2021. The median served as a robust indicator of central tendency, being less sensitive to outliers, while the IQR reflected variability within the central 50% of the data. The non-parametric Mann-Kendall test was applied to identify long-term trends in pollutant concentrations, which is suitable for detecting monotonic trends in environmental data. Additionally, correlation analyses, including the Pearson correlation coefficient, assessed relationships between different monitoring stations.

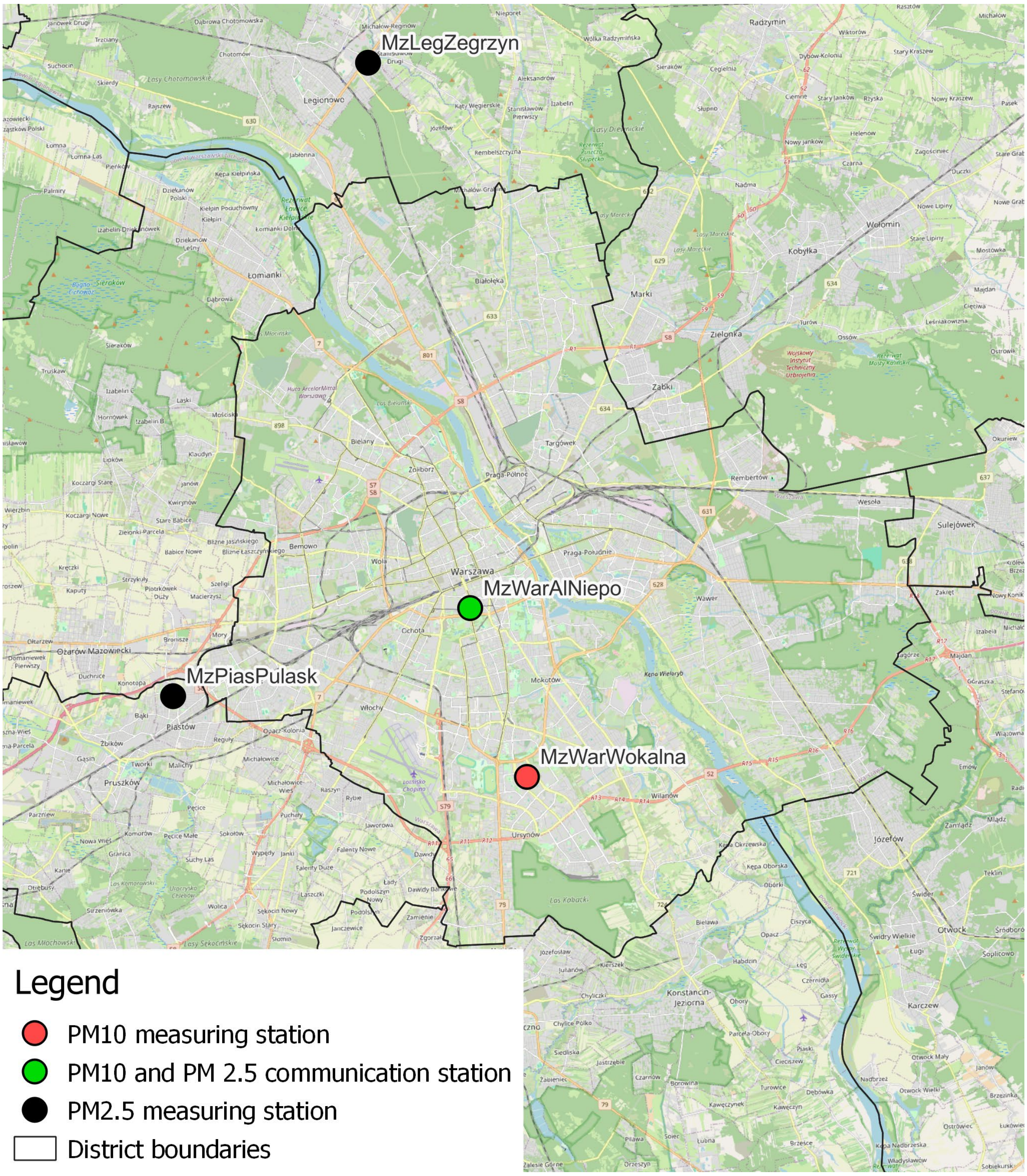

Figure 1. Distribution of measurement stations of the State Environmental Monitoring (PMŚ) department in Warsaw and its surroundings

3. RESULTS

3.1. Monthly and interannual variability

Figures 1 to 5 show the results of data analysis on maps depicting monthly air pollution of PM10 and PM2.5 particulate matter.

The highest concentrations of PM10 dust at the station in Warsaw at Niepodległości Avenue occurred in January 2017, and in March 2017 and 2018, they exceeded 60 µg/m^3 (Fig. 2). The lowest concentrations occurred in September 2017, and June and July 2020, below 30 µg/m^3. Low concentrations occurred mainly in the warm months and sometimes in autumn. The highest were from January to April.

The highest concentration of PM10 particulate matter at the MzWarWokalna station occurred in January 2017 and exceeded 50 µg/m^3 (Fig. 3). The lowest was in February

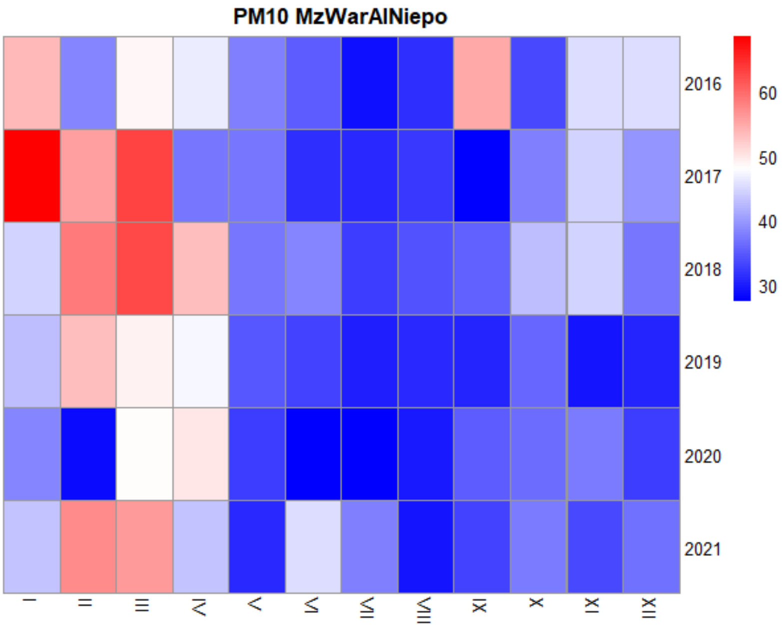

Figure 2. PM10 concentration levels from 2016 to 2021 at the MzWarAlNiepo station

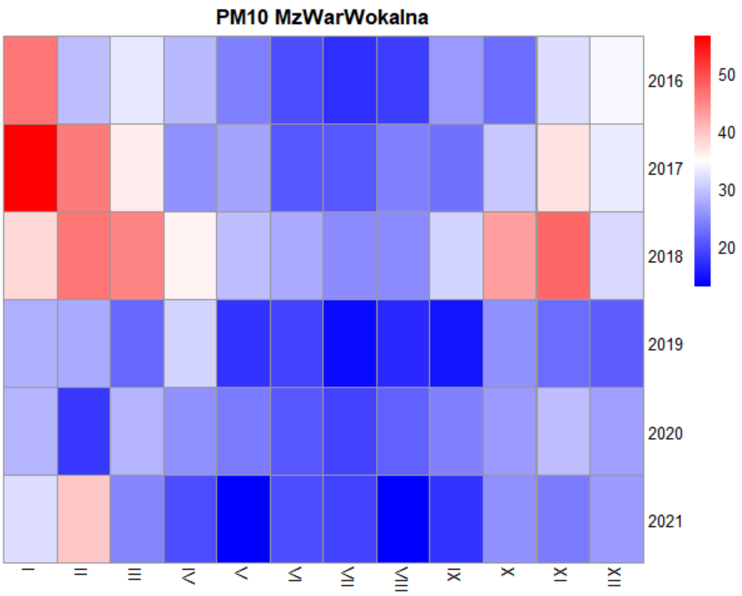

Figure 3. PM10 concentration level in 2016-2021 at MzWarWokalna station

2020: about 18 µg/m^3. As of 2019, concentrations were decidedly lower, mainly in warm months. High concentrations typically occurred in the cool months (I–III, X–XI) in 2016–2018.

The PM2.5 concentration level at the Warsaw traffic station was highest in the cold months and lowest in the warm months from May to September (Fig. 4). The highest concentration level occurred in 2017 in January and exceeded 50 µg/m^3. The lowest was in May 2021: under 30 µg/m^3.

The highest concentration of PM2.5 at the urban background station in Piastow occurred in January 2017 and exceeded 60 µg/m^3 (Fig. 5). High concentrations happened in the months of I–III and X–XI in 2018. The lowest concentrations occurred in July 2019 and 2020, below 8.5 µg/m^3.

The highest concentration of PM2.5 occurred in February 2017 and exceeded 60 µg/m^3 (Fig. 6). The lowest occurred in July 2020 and was below 8 µg/m^3. Lower values occurred in the warm months and higher values in the winter months of January–March over 2016–2021.

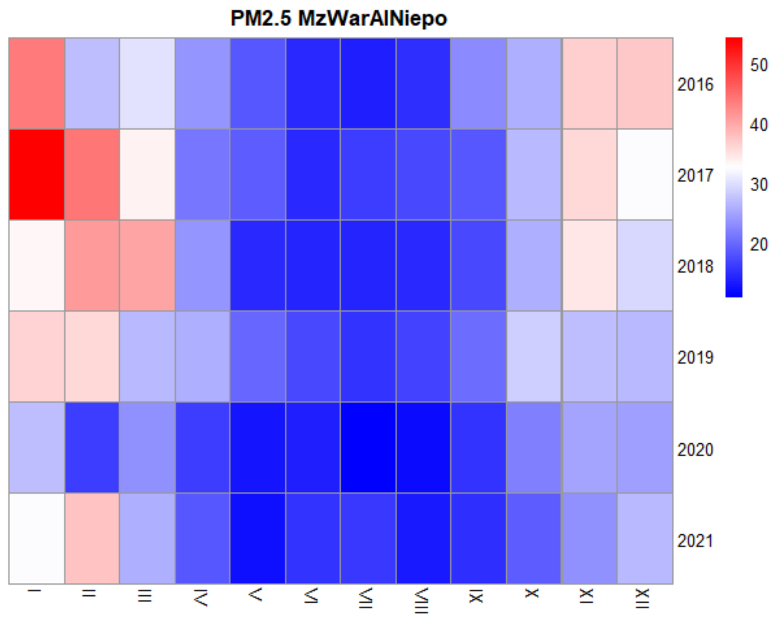

Figure 4. PM2.5 concentration levels from 2016 to 2021 at MzWarAlNiepo station

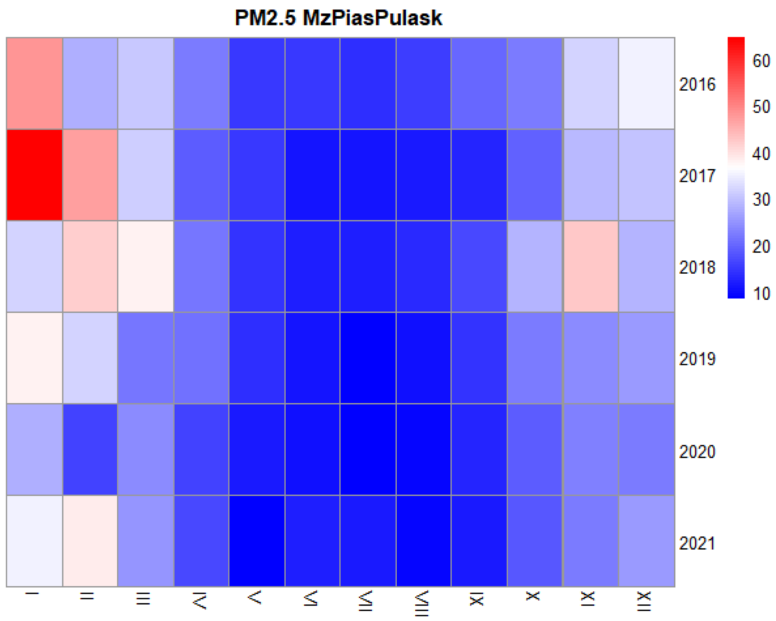

Figure 5. PM2.5 concentration levels from 2016 to 2021 at MzPiasPulask station

3.2. Exceedances of dust concentration limits

Exceedances of the PM10 limit value above 40 µg/m^3 and PM2.5 above 20 µg/m^3 and the number of days exceeding the 24–hour average PM10 value above 50.49 µg/m^3 were determined.

In 2016–2021, exceedances of the permissible annual average PM10 dust value above 40 µg/m^3 occurred at the station on Niepodległości Avenue in 2016, 2017, 2019, and 2021 (Fig. 7). At the station on Wokalna Street, exceedances did not happen even once.

Between 2016 and 2021, exceedances of the permissible annual average PM2.5 value above 20 occurred at every station (Fig. 8). At the station on Niepodległości Avenue, exceedances of the allowable value occurred in every year except 2020. The same situation happened at the stations in Legionowo and Piastow; exceedances occurred between 2016 and 2018.

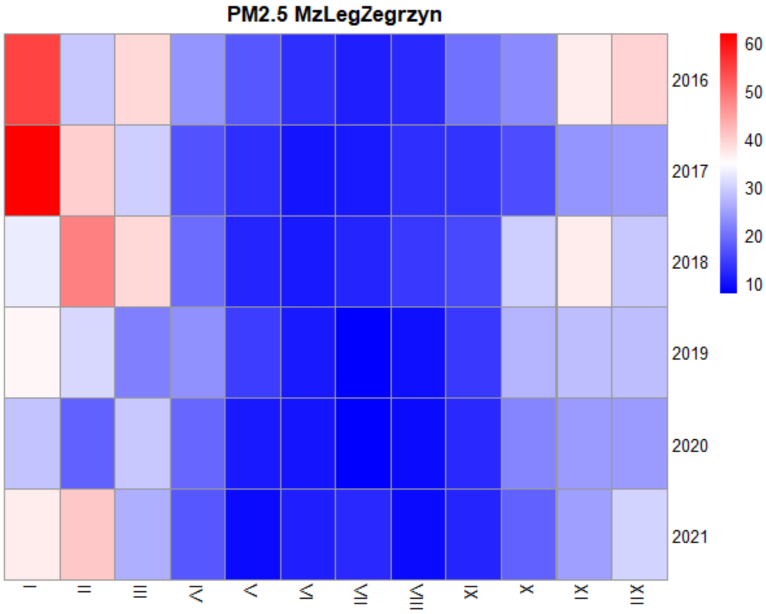

Figure 6. PM2.5 concentration level in 2016–2021 at MzLegZegrzyn station

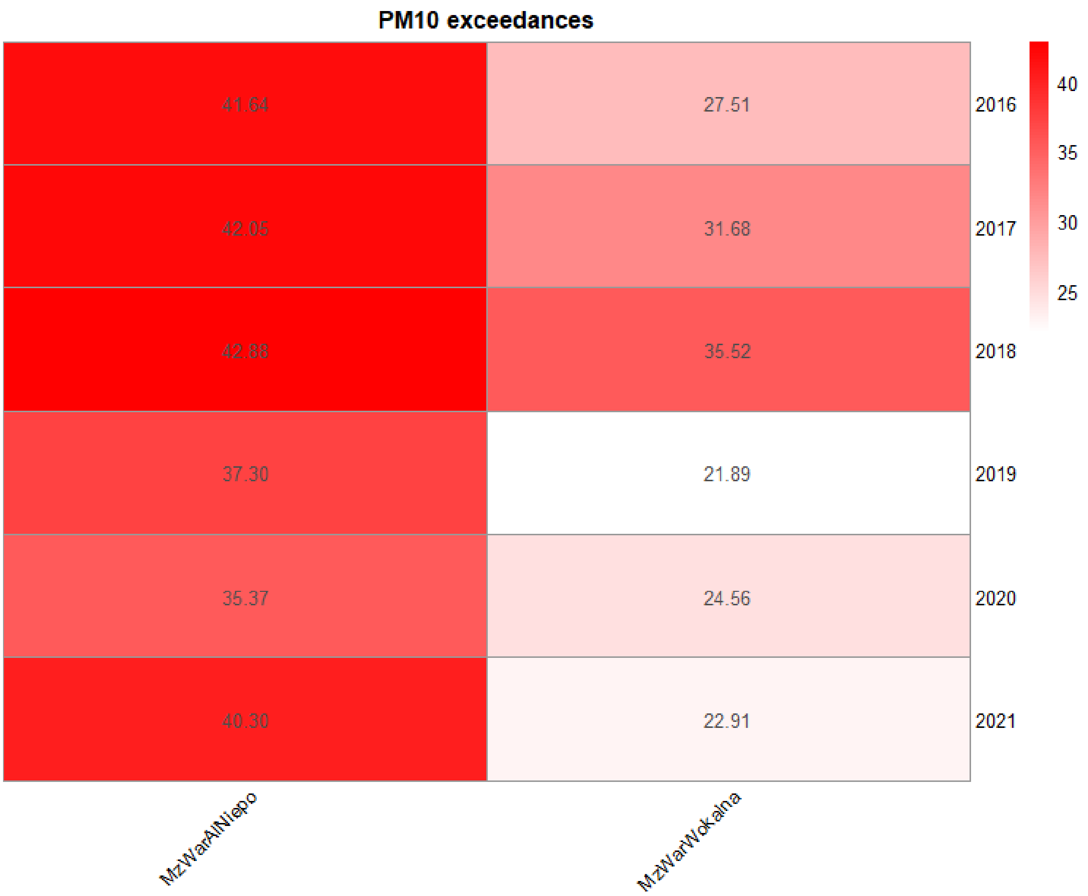

Figure 7. Exceedances of the permissible annual average concentration of PM10 dust from 2016 to 2021 in μg/m^3

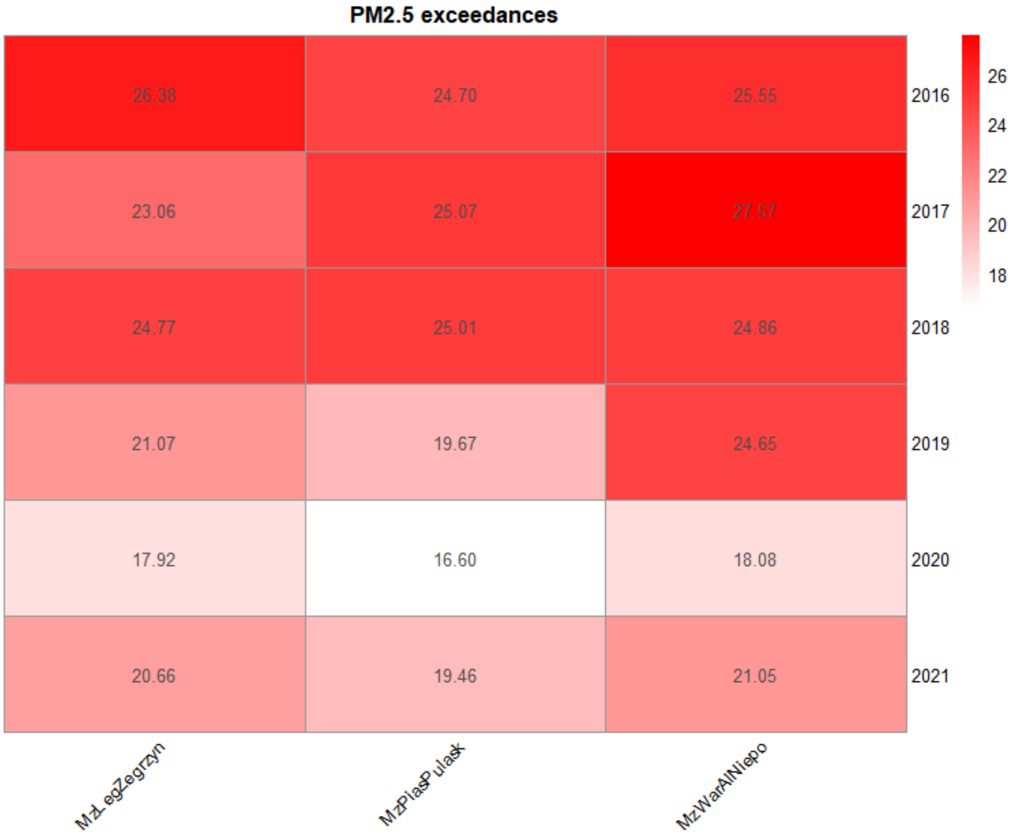

Figure 8. Exceedances of the permissible annual average concentration of PM2.5 dust in 2016–2021 in μg/m^3

The 24-hour average value of PM10 particulate matter was exceeded every year analyzed at the station on Niepodległości Avenue (Fig. 9). The highest number of days with exceedances occurred in 2018, as many as 94, and the lowest in 2020: 50 days. At the station on Wokalna Street, exceedances occurred in 2017 and 2018, with 42 and 62 days, respectively. In 2019 and 2020, only 7 days with an exceedance occurred.

3.3. Statistical analysis

The analysis of particulate matter (PM10 and PM2.5) concentrations involved a systematic approach to characterizing variability using statistical metrics that account for the non-normal distribution of the data. The focus was on calculating the median and interquartile range (IQR) for each monitoring station and each month, providing a robust representation of central tendency and dispersion. Unnormalized data for mean and standard deviation were also calculated in the tables.

For MzWarAlNiepo, the median PM10 concentrations ranged from 28.89 μg/m^3 in July to 68.63 μg/m^3 in February. The IQR values indicate significant variability, especially in winter, with an IQR of 14.98 μg/m^3 in February. This suggests that seasonal factors heavily influence the concentrations, mainly heating emissions during colder months. The MzWarWokalna station showed median concentrations ranging from 17.23 μg/m^3 in July to 56.38 μg/m^3 in February. The maximum IQR of 16.13 μg/m^3 in February further emphasizes the impact of winter pollution sources on particulate matter levels.

At MzPiasPulask, the median PM2.5 concentrations varied from 10.91 μg/m^3 in July to 64.64 μg/m^3 in February, indicating a considerable rise during the winter months. The IQR values, with a maximum of 12.82 μg/m^3 in January, reflect substantial variability, likely due to increased emissions during this period. The MzWarAlNiepo station exhibited median concentrations ranging from 14.20 μg/m^3 in July to 37.79 μg/m^3 in January. The IQR, which peaked at 9.10 μg/m^3 in January, underscores the increased variability in concentrations during the heating season. Similarly, MzLegZegrzyn displayed significant variability, with median PM2.5 concentrations ranging from 10.36 μg/m^3 in July to 41.78 μg/m^3 in January. The maximum IQR of 12.79 μg/m^3 in January indicates heightened levels of PM2.5 during winter months.

Analysis of the median and IQR for PM10 and PM2.5 concentrations illustrates the considerable variability in particulate matter levels, particularly during the winter months at all monitoring stations. Tables 4 and 5 present detailed data with mean and standard deviation.

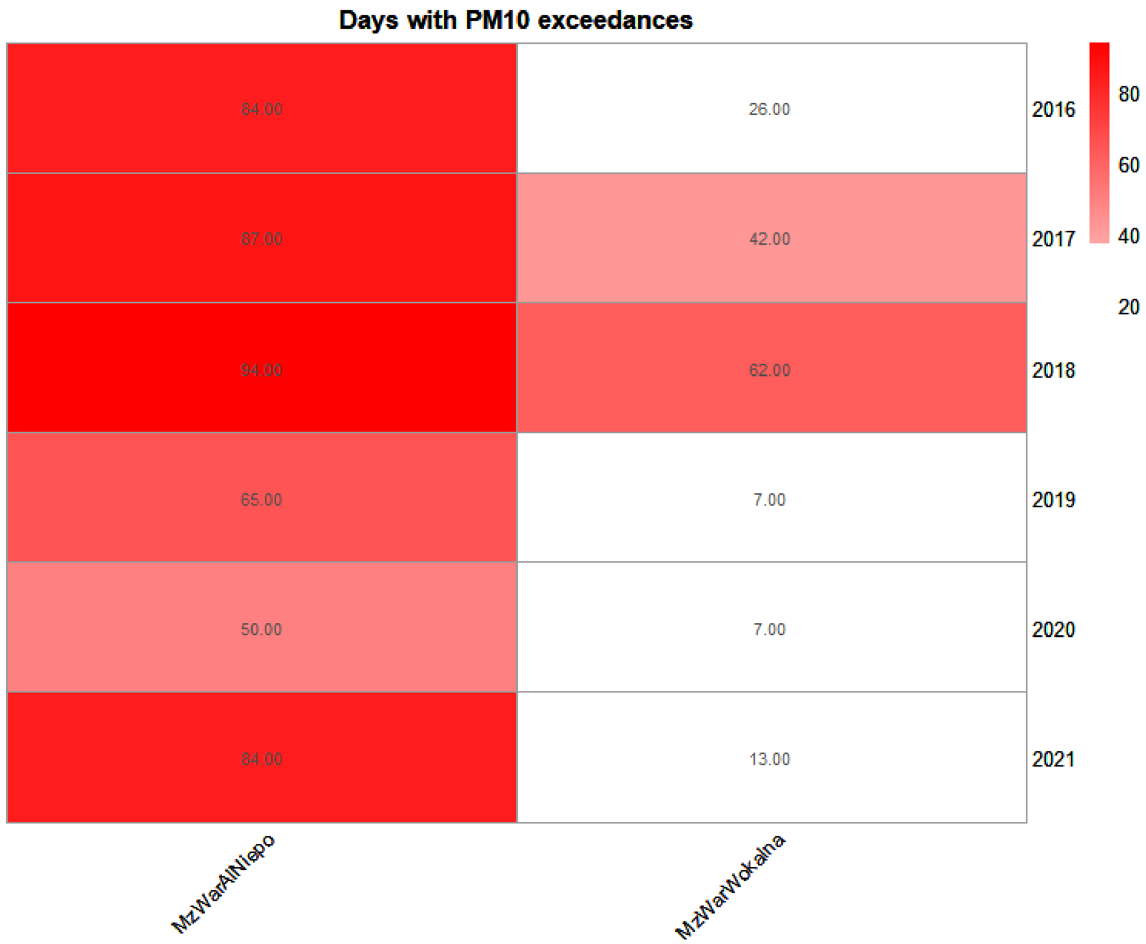

Figure 9. Number of days with exceedances of the 24-hour average value of PM10 dust in μg/m^3

Table 2. PM10 Monthly Median and IQR at the stations MzWarAlNiepo and MzWarWokalna

Month	MzWarAlNiepo		MzWarWokalna	
	Median [μg/m^3]	IQR [μg/m^3]	Median [μg/m^3]	IQR [μg/m^3]
I	48.61	8.37	38.16	14.75
II	48.57	14.98	34.42	16.13
III	54.55	12.17	31.59	9.8
IV	46.23	4.92	27.76	5.35
V	35.05	4.06	22.57	7.31
VI	35.09	5.62	21.33	0.76
VII	31.42	2.83	19.21	2.66
VIII	31.3	1.82	19.84	6.14
IX	36.14	4.28	22.88	6.7
X	37.27	1.77	28.71	3.87
XI	39.05	10.24	32.01	10.84
XII	36.94	5.25	28.9	6.2

Table 3. PM2.5 Monthly Median and IQR at the stations MzPiasPulask, MzWarAlNiepo, and MzLegZegrzyn

Month	MzPiasPulask		MzWarAlNiepo		MzLegZegrzyn	
	Median [μg/m³]	IQR [μg/m³]	Median [μg/m³]	IQR [μg/m³]	Median [μg/m³]	IQR [μg/m³]
I	40.93	12.82	37.79	9.1	41.78	12.79
II	33.79	12.53	33.56	11.1	34.54	7.2
III	28.43	6.93	29.86	6.59	30.7	6.14
IV	19.4	4.46	21.47	4.56	19.86	5.58
V	12.96	2.56	15.91	5.38	12.72	2.9
VI	11.84	1.42	14.83	0.89	11.08	2.88
VII	10.91	3.03	14.2	2.01	10.36	2.48
VIII	11.49	2.96	14.57	2.97	11.31	1.88
IX	14.57	3.23	17.97	3.68	14.59	2.84
X	21.47	3.42	24.54	3.61	22.65	4.77
XI	28.7	8.18	30.33	10.03	29.03	5.34
XII	27.88	4.4	29.32	4.66	29.27	5.14

Table 4. PM10 monthly mean concentrations for the period 2016-2021 at stations MzWarAlNiepo and MzWarWokalna

Station	Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
MzWarAlNiepo	2016	53.65	38.18	48.54	46.63	37.80	34.90	28.89	31.30	54.95	33.41	45.39	45.38
	2017	68.63	55.54	62.93	37.02	37.04	31.37	30.95	32.11	27.44	37.90	44.47	39.44
	2018	44.52	58.63	62.46	53.07	37.29	38.21	32.44	34.25	35.66	42.75	44.56	37.09
	2019	42.83	53.34	49.03	47.38	34.49	32.93	30.28	30.88	30.60	35.85	29.19	30.57
	2020	38.52	28.32	48.40	49.80	32.72	27.74	27.82	29.82	35.07	36.40	37.40	32.60
	2021	43.50	57.42	55.93	43.49	30.98	45.40	38.11	29.47	33.13	37.33	33.27	36.59
	average	**48.61**	**48.57**	**54.55**	**46.23**	**35.05**	**35.09**	**31.42**	**31.30**	**36.14**	**37.27**	**39.05**	**36.94**
	stdev	**10.03**	**11.32**	**6.31**	**5.06**	**2.54**	**5.61**	**3.33**	**1.58**	**8.86**	**2.83**	**6.24**	**4.78**
	stdev/ average	**0.21**	**0.23**	**0.12**	**0.11**	**0.07**	**0.16**	**0.11**	**0.05**	**0.25**	**0.08**	**0.16**	**0.13**
MzWarWokalna	2016	46.12	29.20	32.95	29.05	23.96	20.00	17.23	18.41	26.38	22.29	31.96	34.23
	2017	56.38	45.69	36.25	25.30	27.40	20.79	20.67	24.00	22.81	30.10	37.25	33.17
	2018	38.00	46.30	45.04	35.72	29.43	27.43	25.20	24.96	30.99	42.94	47.62	31.43
	2019	28.03	27.59	22.13	31.27	17.73	19.05	14.12	16.81	15.11	25.26	22.33	21.21
	2020	28.46	18.32	28.49	25.57	23.74	20.69	19.17	21.41	24.10	26.30	29.21	26.95
	2021	31.96	39.43	24.67	19.67	13.15	20.01	18.87	13.43	17.88	25.35	23.71	26.39
	average	**38.16**	**34.42**	**31.59**	**27.76**	**22.57**	**21.33**	**19.21**	**19.84**	**22.88**	**28.71**	**32.01**	**28.90**
	stdev	**10.25**	**10.22**	**7.65**	**5.06**	**5.56**	**2.79**	**3.37**	**4.05**	**5.24**	**6.77**	**8.58**	**4.51**
	stdev/ average	**0.27**	**0.30**	**0.24**	**0.18**	**0.25**	**0.13**	**0.18**	**0.20**	**0.23**	**0.24**	**0.27**	**0.16**

The analysis of these data provides an understanding of the variability of PM10 and PM2.5 concentrations at different monitoring stations over twelve months and six years. High values of the ratio of standard deviations to averages indicate significant variability in the data, which may be necessary for assessing air quality at individual monitoring stations.

In 2017, the correlation (right y-axis) between the two stations located at Niepodległości Avenue and Wokalna Street was the highest (0.774), suggesting that both stations recorded similar variability in air pollutant concentration values in that year (Fig. 10). After 2017, the concordance of temporal variability between stations decreases slightly. This may be related to reducing emissions from the

Table 5. PM2.5 monthly mean concentrations for the period 2016-2021 at stations MzPiasPulask, MzWarAlNiepo and MzLegZegrzyn

Station	Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
MzPiasPulask	**2016**	48.19	27.60	30.86	21.97	14.75	14.77	13.54	15.56	19.95	22.13	31.80	35.27
	2017	64.64	46.92	31.27	18.89	14.84	10.73	10.89	11.46	12.67	19.15	28.93	30.31
	2018	32.02	41.94	37.75	21.82	14.09	12.20	12.25	13.01	16.53	28.66	42.69	28.56
	2019	37.81	31.53	21.54	21.01	14.01	10.78	8.51	10.32	14.16	22.17	23.75	25.68
	2020	27.84	16.10	23.89	16.14	11.37	10.49	8.45	9.45	12.80	18.61	22.62	22.09
	2021	35.04	38.64	25.28	16.58	8.73	12.05	11.80	9.11	11.29	18.10	22.41	25.40
	average	**40.93**	**33.79**	**28.43**	**19.40**	**12.96**	**11.84**	**10.91**	**11.49**	**14.57**	**21.47**	**28.70**	**27.88**
	stdev	**12.31**	**10.16**	**5.46**	**2.38**	**2.22**	**1.47**	**1.89**	**2.24**	**2.90**	**3.59**	**7.15**	**4.19**
	stdev/ average	**0.30**	**0.30**	**0.19**	**0.12**	**0.17**	**0.12**	**0.17**	**0.19**	**0.20**	**0.17**	**0.25**	**0.15**
MzWarAlNiepo	**2016**	43.67	26.87	30.22	23.49	18.22	14.50	13.51	14.88	22.51	25.75	36.53	36.94
	2017	54.31	44.08	33.42	21.11	18.60	14.51	15.96	17.02	18.16	26.52	35.86	32.10
	2018	33.26	41.08	39.94	23.75	14.25	14.05	13.98	14.31	17.01	25.86	34.40	29.08
	2019	36.02	35.61	26.49	25.93	19.60	17.24	15.25	16.68	20.02	28.46	26.91	26.80
	2020	27.00	16.31	23.21	16.10	12.75	13.43	10.71	11.61	15.50	21.74	24.98	24.35
	2021	32.45	37.39	25.88	18.46	12.03	15.23	15.76	12.91	14.65	18.93	23.30	26.65
	average	**37.79**	**33.56**	**29.86**	**21.47**	**15.91**	**14.83**	**14.20**	**14.57**	**17.97**	**24.54**	**30.33**	**29.32**
	stdev	**8.91**	**9.39**	**5.56**	**3.34**	**3.00**	**1.21**	**1.79**	**1.92**	**2.68**	**3.21**	**5.41**	**4.16**
	stdev/ average	**0.24**	**0.28**	**0.19**	**0.16**	**0.19**	**0.08**	**0.13**	**0.13**	**0.15**	**0.13**	**0.18**	**0.14**
MzLegZegrzyn	**2016**	54.74	29.26	38.69	23.74	17.07	12.77	11.08	12.66	19.81	22.54	36.59	39.51
	2017	61.87	40.20	29.50	16.94	12.75	10.24	10.94	12.91	13.62	16.19	23.70	24.41
	2018	33.22	47.98	38.78	19.18	12.12	11.00	11.80	14.04	15.53	29.81	36.53	29.16
	2019	35.83	30.73	21.54	23.47	14.33	10.70	8.02	9.90	14.11	27.12	27.98	27.96
	2020	28.51	18.43	29.43	18.70	10.79	10.35	7.83	9.41	12.68	22.09	24.57	24.09
	2021	36.52	40.68	26.28	17.10	9.29	11.41	12.52	8.93	11.78	18.18	24.83	30.48
	average	**41.78**	**34.54**	**30.70**	**19.86**	**12.72**	**11.08**	**10.36**	**11.31**	**14.59**	**22.65**	**29.03**	**29.27**
	stdev	**12.14**	**9.59**	**6.27**	**2.77**	**2.50**	**0.85**	**1.80**	**1.96**	**2.61**	**4.71**	**5.49**	**5.14**
	stdev/ average	**0.29**	**0.28**	**0.20**	**0.14**	**0.20**	**0.08**	**0.17**	**0.17**	**0.18**	**0.21**	**0.19**	**0.18**

residential sector and the relatively increasing influence of pollutants from transport at the traffic station.

The MzWarAlNiepo station had the highest standard deviation of the data in 2017, while the variability was lowest in 2019. Station MzWarWokalna shows a similar pattern, with the highest standard deviation in 2017 and the lowest in 2019. Where air quality study stations show similar trends in correlation and standard deviation, this may suggest that factors affecting air quality in Warsaw operate on a city-wide scale, not just locally.

The lowest correlation at MzWarAlNiepo and MzLegZegrzyn stations occurred in 2018 (0.746), while the highest was in 2021 (0,845). This suggests that both stations have the same source of pollution (Fig. 11). The correlation between MzWarAlNiepo and MzPiasPulask te was relatively low in 2016–2018 but increased significantly in 2019 (0.783), remaining at a similar level in subsequent years. Between the stations MzLegZegrzyn and MzPiasPulask, the highest correlation was recorded in 2021 (0.873), which is a significant increase compared to earlier years. This indicates an increasingly similar variability of pollution from these stations.

The highest standard deviation at the MzWarAlNiepo station occurred in 2017 (28.22 μg/m^3) and the lowest in 2020 (16.59 μg/m^3), while in 2021, it increased to 20.94 μg/m^3. Data analysis indicates that the highest variability occurred in 2017 and the lowest in 2020, possibly related to summer mobility restrictions. In Legionowo, as at the previous station, the highest variability was recorded in 2017 (26.61 μg/m^3), while the lowest was in 2020 (13.42 μg/

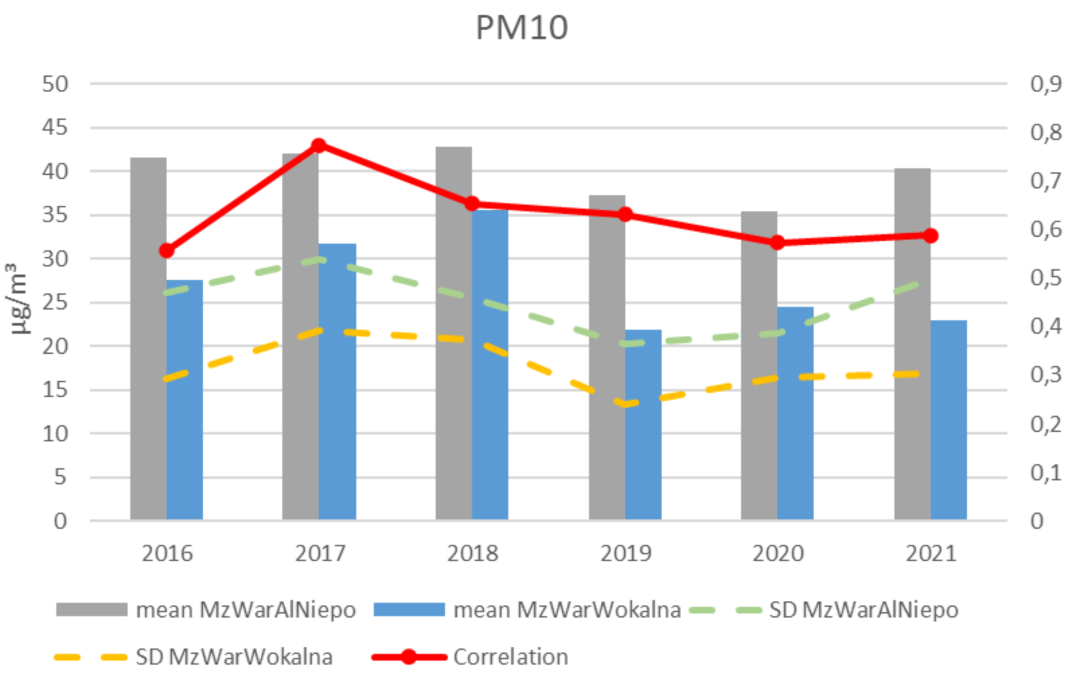

Figure 10. Statistical analysis with PM10 correlation

Table 6. Statistical analysis of stations measuring PM10 dust concentrations

Year	Correlation	SD MzWarAlNiepo		SD MzWarWokalna	
		SD	mean	SD	mean
2016	0.556	26.10	41.64	16.23	27.51
2017	0.774	29.91	42.05	21.76	31.68
2018	0.654	25.54	42.88	20.79	35.52
2019	0.631	20.26	37.30	13.40	21.88
2020	0.573	21.45	35.37	16.41	24.56
2021	0.589	27.72	40.3	16.82	22.91

m³). The station in Piastów also had the highest variability in 2017 (20.03 µg/m³) and the least in 2020 (11.29 µg/m³).
All three stations respond similarly to changing conditions, and the correlations indicate that the main factors will be meteorological conditions. In 2017, all stations recorded the most significant variability in the data, which may indicate exceptional air pollution conditions that year.
In 2020, all stations had the most minor standard deviation. This may have been due to the global decline in industrial activity and transport associated with the COVID-19 pandemic.
The analysis suggests that all three air quality monitoring stations react similarly to external factors affecting air quality. In 2017, all stations experienced exceptionally high fluctuations, while in 2020, air pollution was relatively lower than in previous years due to the COVID-19 pandemic.
The Mann-Kendall test was conducted to assess changes in PM10 particulate matter concentrations at the MzWarAlNiepo and MzWarWokalna monitoring stations from 2016 to 2021.

PM10

Station MzWarAlNiepo

$$Tau = -0.155$$

The tau value indicates a weak negative trend in PM10 concentrations. The closer the tau value is to -1, the more substantial the observed decrease. In this case, the result suggests a slight downward trend in PM10 concentrations, but it is minimal.

$$P\text{-}value = 0.054834$$

A p-value near 0.05 suggests a slight chance of rejecting the null hypothesis (no trend). Although this value is

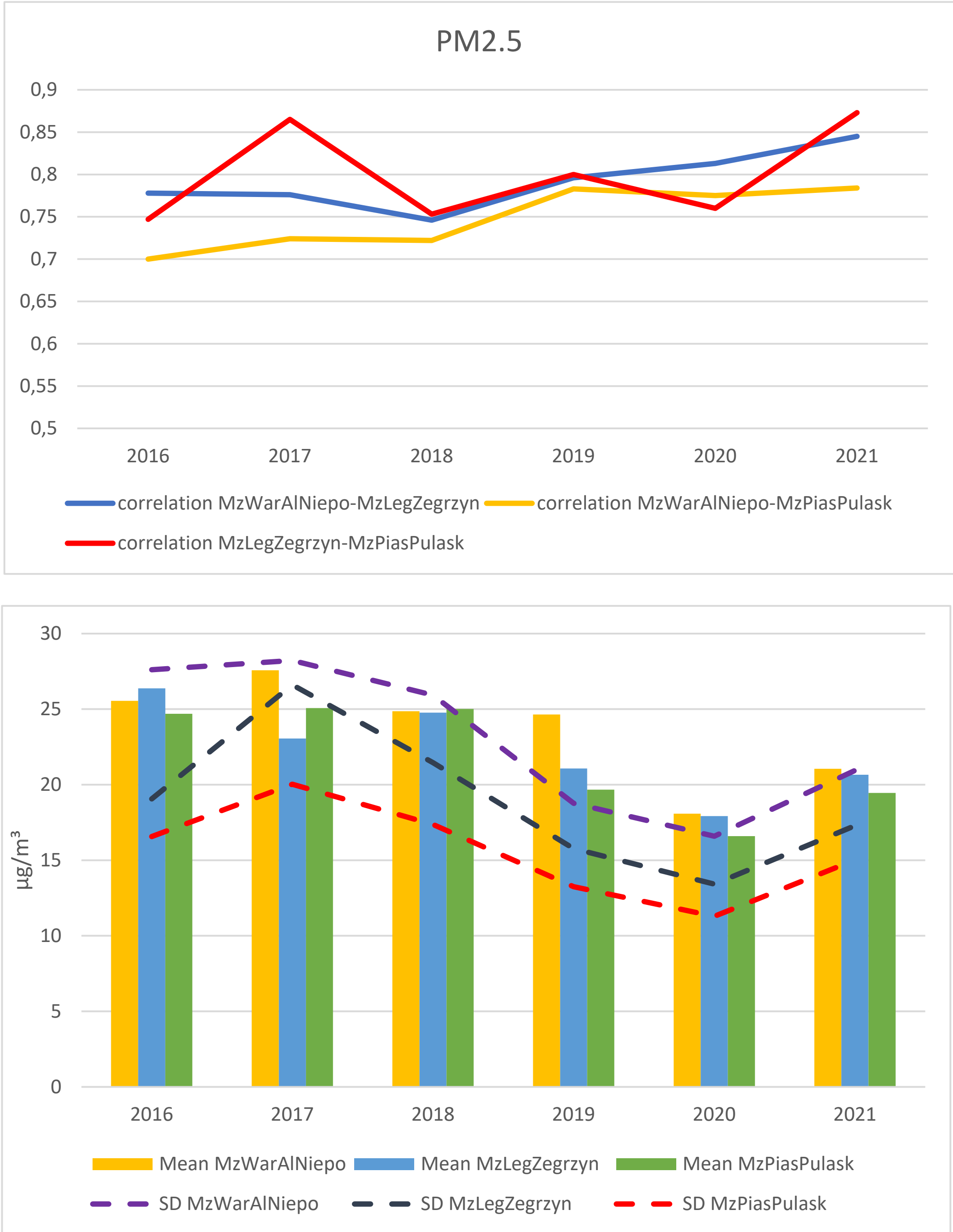

Figure 11. Statistical analysis with PM2.5 correlation

slightly above 0.05, it may be considered significant at the 0.10 level. This indicates initial signals of improvement in air quality, although further investigation is required.

Station MzWarWokalna

Tau = -0.234

The tau value for this station indicates a stronger negative trend than MzWarAlNiepo. The harmful tau suggests a more pronounced decrease in PM10 concentrations over the analyzed period.

P-value = 0.0037634

The low p-value (below 0.01) allows for a confident rejection of the null hypothesis. This indicates a significant negative trend in PM10 concentrations at this station, suggesting effective measures for improving air quality or other factors influencing the reduction in concentrations.

Table 7. Statistical analysis of stations measuring PM2.5 concentrations

Year	correlation MzWarAlNiepo-MzLegZegrzyn	correlation MzWarAlNiepo-MzPiasPulask	MzLegZegrzyn-MzPiasPulask correlation	MzWarAlNiepo		MzLegZegrzyn		MzPiasPulask	
				SD	Mean	SD	Mean	SD	Mean
2016	0.778	0.700	0.747	27.61	25.55	19.06	26.38	16.57	24.69
2017	0.776	0.724	0.865	28.22	27.57	26.61	23.06	20.03	25.07
2018	0.746	0.722	0.753	25.93	24.86	21.46	24.77	17.37	25.01
2019	0.796	0.783	0.800	18.77	24.65	15.77	21.07	13.25	19.67
2020	0.813	0.775	0.760	16.59	18.08	13.42	17.92	11.29	16.6
2021	0.845	0.784	0.873	20.94	21.05	17.28	20.66	15.02	19.46

The negative trend in PM10 concentrations observed in MzWarAlNiepo Station is not statistically significant at the 0.05 level but may be considered at the 0.10 level. This suggests that there are some changes, but they require further analysis and confirmation in subsequent years. The significant negative trend in PM10 concentrations in MzWarWokalna Station indicates that actions taken in this area are yielding results. This suggests a notable improvement in air quality, which may be the result of regulations, pro-ecological measures, or a reduction in emissions from various sources.
The trend analysis of PM10 concentrations at the MzWarAlNiepo and MzWarWokalna stations revealed significant differences in the direction of trends. While MzWarAlNiepo shows a weak negative trend, MzWarWokalna exhibits an apparent, statistically significant decrease in PM10 concentrations.

PM2.5
Station MzPiasPulask

Tau = -0.178

The negative tau value indicates a weak to moderate downward trend in PM2.5 concentrations, suggesting a gradual reduction over the observed years.

P-value = 0.027655

The p-value is below 0.05, allowing for rejecting the null hypothesis (no trend). This indicates that the negative trend is statistically significant, suggesting meaningful improvements in air quality at this station.

Station MzWarAlNiepo

Tau = -0.186

Like MzPiasPulask, this tau value indicates a moderate negative trend in PM2.5 concentrations. It suggests a noticeable decrease in particulate matter levels.

P-value = 0.020938

The p-value is also below 0.05, indicating a statistically significant trend. This reinforces the finding of a meaningful decline in PM2.5 concentrations, pointing to effective interventions or changes affecting air quality.

Station MzLegZegrzyn

Tau = -0.145

This value indicates a weaker negative trend compared to the previous two stations. While there is still a downward tendency in PM2.5 concentrations, it is less pronounced.

P-value = 0.072845

Although this p-value is above 0.05, it is close to the significance threshold, suggesting that while the trend is not statistically significant at the 0.05 level, it may be necessary at the 0.10 level. This indicates that potential trends warrant further monitoring and analysis.
The statistically significant negative trend in PM2.5 in MzPiasPulask Station concentrations suggests effective measures have been implemented to improve air quality. This may be attributed to regulatory actions, community awareness, or other environmental initiatives. Like MzPiasPulask, the significant decline in PM2.5 in MzWarAlNiepo Station concentrations indicates successful interventions. This reinforces the need for continued efforts in air quality management to sustain these improvements. While there is a noted downward trend in MzLegZegrzyn Station, it is not statistically significant at the conventional 0.05 level. However, its proximity to significance suggests that continued observation and analysis may be necessary to determine whether this trend persists or strengthens.
The trend analysis of PM2.5 concentrations at the MzPiasPulask, MzWarAlNiepo, and MzLegZegrzyn stations reveals significant reductions at the first two locations, indicating effective air quality improvement measures. The results from MzLegZegrzyn, although not statistically significant, suggest a potential trend that should be monitored over time.

4. DISCUSSION

Based on the analysis of data from the State Environmental Monitoring stations located in the Warsaw agglomeration, it was possible to determine how the concentration of PM10 and PM2.5 particulate matter is distributed over the months of the year. It was observed that there was a definite increase in the concentration of studied dust, both PM10 and PM2.5, in the cold months— mainly from January to March. Lower concentrations were observed in the summer months from June to August. This may be related to the number and characteristics of individual emitters and meteorological conditions. Similar results were obtained in a study of PM10 dust concentrations in Warsaw's Ursynów district [Majewski 2005]. PM10 dust concentrations in the cold semester were significantly lower than in the warm semester, the difference being about 10 $\mu g/m^3$. Analysis of the results of measurements of PM10 and PM2.5 dust concentrations made at the measurement station at Poznański Square in Bydgoszcz also showed a tendency for higher values of concentrations to occur during the heating season [Pasela et al. 2017]. The occurrence of the highest pollutant concentrations during the winter season in cities across Wielkopolska, as evidenced by available studies, suggests that the phenomenon of low emissions is responsible for air pollution with particulate matter in the region [Chlebowska et al. 2015]. Higher values were observed in the winter season. This is the same as the research conducted. Our results confirm that significantly higher pollution levels are observed in winter.

5. CONCLUSIONS

Particulate pollution is a severe problem for large cities in Poland: high concentrations of PM10 and PM2.5 particulate matter have been observed for years. The highest concentrations of PM10 and PM2.5 particulate matter occur in the winter months—January and February, when air temperatures are lower and fuel is burned in cookers. Between May and September, concentrations are lower, and no exceedances of permissible standards are observed. The statistical calculations also confirm the dependence of the occurrence of high values of dust pollution concentrations in the period with low temperatures. Between 2016 and 2021, the annual average PM2.5 concentrations decreased at each of the analyzed stations, with the lowest values recorded in 2020. PM10 dust concentrations at the traffic station have remained high for years, exceeding the permissible level in 4 of the 6 years analyzed. At the station on Wokalna Street, concentrations are decreasing: in 2018, they were below 25 $\mu g/m^3$. The number of days exceeding the PM10 limit level at the traffic station was high every year analyzed. The days were exceeded in 2017 and 2018 at the urban background station.

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