

Seasonality and Meteorological Context of PM₁₀ Exceedance Episodes in Lithuanian Cities, 2019–2025

Sinilga Černulienė and Edita Abalikštienė*

Faculty of Environmental Engineering, Lietuvos inžinerijos kolegija Higher Education Institution, Tvirtovės Ave. 35, LT-50155 Kaunas, Lithuania

*Correspondence e-mail: sinilga.cernuliene@lik.tech

Abstract

Daily PM₁₀ limit-value exceedances remain an urban air-quality concern even where long-term mean concentrations are moderate. This study assessed PM₁₀ exceedance observations in six Lithuanian cities during 2019–2025 and examined their meteorological context. Daily PM₁₀ records were matched with precipitation, wind speed, relative humidity and air temperature. Exceedance observations were defined as station-days with PM₁₀ >50 µg/m³. Seasonality, episode duration, and dry and low-wind conditions were evaluated; station-level patterns, NO₂ concentrations and prevailing wind direction were additionally analysed in Vilnius and Kaunas. Exceedances were episodic and most frequent in spring in all cities. They were generally characterised by lower precipitation, lower relative humidity and, in most cities, lower wind speed than non-exceedance observations. Most occurred when daily precipitation was <1 mm. At the Vilnius and Kaunas stations, PM₁₀ was negatively correlated with precipitation, wind speed and relative humidity, while NO₂ concentrations were higher during exceedances. Higher exceedance rates were also observed under easterly and south-easterly winds. The findings associate PM₁₀ episodes with dry conditions and limited dispersion; their spring predominance is consistent with conditions favourable to road-dust resuspension, although individual source contributions were not directly quantified.

Keywords: air quality, road dust, precipitation, wind speed, relative humidity, non-exhaust emissions.



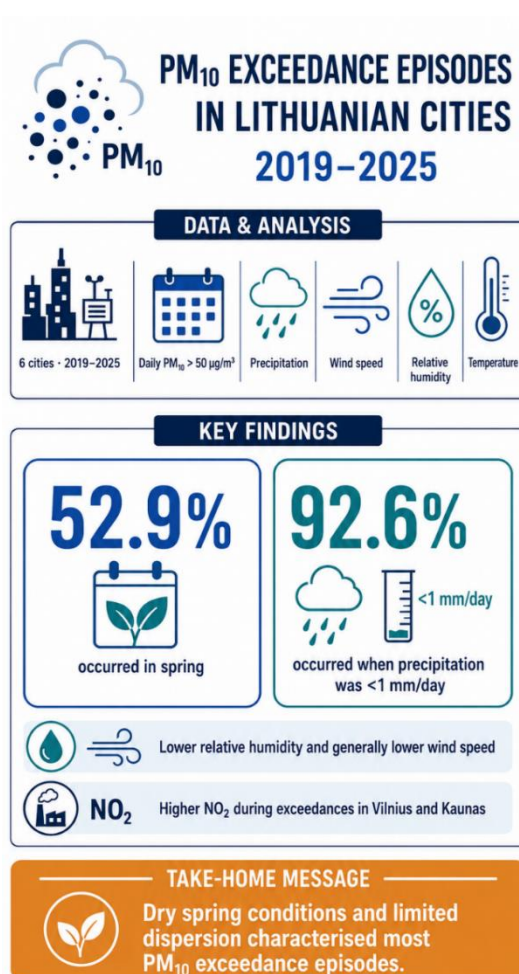
Received: 28/07/2026,

Accepted: 06/09/2026,

Available online: 01/10/2026

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Graphical abstract



1. Introduction

Particulate matter with an aerodynamic diameter of up to 10 µm (PM₁₀) is one of the principal indicators of ambient air quality in urban areas, as its concentrations depend not only on direct emission sources but also on meteorological conditions controlling particle dispersion, deposition and resuspension from surfaces. European air-quality studies show that, despite the long-term decline in the concentrations of many pollutants, exceedances of the daily PM₁₀ limit value remain relevant in certain urban areas and are associated with a combination of traffic, local emission sources and unfavourable atmospheric conditions (Guerreiro *et al.*, 2014). The daily PM₁₀ limit value applied in the European Union during the study period was 50 µg/m³; consequently, exceedance analysis makes it possible to assess not only general air-quality levels but also short-term episodes that may be relevant to the urban environment. Short-term PM₁₀ episodes may also be important from an exposure perspective, because the deposition of inhaled particles in the respiratory tract depends not only on ambient concentrations but also on breathing intensity, physical activity and age group (Linell *et al.*, 2024).

Previous studies have shown that variations in urban PM₁₀ concentrations are often episodic. Engler *et al.* (2012), analysing exceedances of the daily PM₁₀ limit value in Leipzig, emphasised that short-term daily exceedances may result from interactions between local and regional factors even when annual concentrations remain below the prescribed limits. Similarly, Ferenczi *et al.* (2021), examining long-term changes in PM₁₀ concentrations in Hungarian cities, assessed annual, seasonal and daily variations and the effects of meteorological conditions on PM₁₀ levels. These studies demonstrate the importance of considering not only mean concentrations but also exceedance frequency, seasonality and episode duration when assessing urban air quality.

Meteorological factors are among the most important environmental determinants of variation in PM₁₀ concentrations. Precipitation reduces airborne particle concentrations through wet scavenging and surface wetting, whereas low wind speeds restrict pollutant dispersion. Relative humidity, temperature and atmospheric pressure may also modify particle-concentration dynamics, although their effects often depend on local conditions and season. Lazurca (2015) investigated the influence of meteorological conditions on

PM₁₀ concentrations in the urban area of Suceava, Romania. Arslan and Toltar (2023) likewise found associations between PM₁₀ and PM_{2.5} concentrations and meteorological factors, particularly wind speed, while Li *et al.* (2017) showed that the relationships between PM₁₀ and meteorological variables may differ according to spatial scale and local conditions.

A substantial proportion of PM₁₀ in urban environments is associated with traffic and non-exhaust particles. Thorpe and Harrison (2008) noted that traffic-related particulate matter originates not only from combustion but also from brake, tyre and road-surface wear and the resuspension of deposited dust. These processes are particularly relevant to the PM₁₀ fraction because coarser particles are more readily resuspended from dry surfaces by vehicle movement. Road-traffic PM₁₀ and PM_{2.5} concentrations and emission factors have also been investigated under Nordic conditions (Ferm and Sjöberg, 2015). Studies in Nordic countries identify road dust as an important source of PM₁₀, especially in spring, when mineral particles accumulated during the cold season may be resuspended as street surfaces dry after winter (Kupiainen *et al.*, 2017). Stojiljkovic *et al.* (2019), assessing road-dust mitigation measures in a Helsinki street canyon, also emphasised the contribution of road dust to urban PM₁₀ concentrations. Recent urban monitoring studies have further shown that PM₁₀ concentrations and their relationships with wind speed, temperature and humidity vary by season and monitoring location (Sellamuthu and Jeyadharman, 2023).

Air-quality studies in Lithuanian cities indicate that traffic and characteristics of the urban environment are also important in explaining particulate-matter concentrations. Orru *et al.* (2012) assessed the health effects of particulate matter in Vilnius and Kaunas, while the more recent study by Kecorius *et al.* (2025), conducted in six Lithuanian cities, demonstrated the relevance of assessing traffic emissions and urban pollution under Lithuanian conditions. Nevertheless, detailed multi-city studies of daily PM₁₀ limit-value exceedance episodes, their seasonality and duration, and their relationships with meteorological conditions remain limited in Lithuania.

The relevance of this study stems from the fact that urban PM₁₀ problems often arise not from persistently high pollution levels but from short-term episodes in which local particle sources coincide with dry conditions, lower relative humidity and reduced dispersion. Analyses based solely on annual or mean concentrations may therefore fail to reveal the circumstances under which such episodes develop. This study examines daily PM₁₀ concentration exceedances in Lithuanian cities during 2019–2025, including their frequency, seasonal distribution, episode duration and associations with meteorological conditions. A more detailed station-level analysis was conducted in Vilnius and Kaunas because these cities included several monitoring stations representing different site types.

Previous Lithuanian studies have addressed the health effects of particulate matter and traffic-related pollution, but a harmonised multi-city assessment of the duration,

seasonal distribution and meteorological context of daily PM₁₀ exceedance episodes during 2019–2025 has not yet been reported. The same methodology was applied to six Lithuanian cities, enabling exceedance observations, episode duration and accompanying meteorological conditions to be assessed across different urban environments.

The aim of this study was to assess daily PM₁₀ concentration exceedances in Lithuanian cities during 2019–2025 and determine their associations with meteorological conditions.

2. Materials and Methods

Daily PM₁₀ data published in the air-quality summaries of the Environmental Protection Agency of Lithuania for 2019–2025 were analysed. The analysis included air-quality monitoring stations in Vilnius, Kaunas, Klaipeda, Siauliai, Panevezys and Mazeikiai. PM₁₀ concentrations were assessed against the daily limit value of 50 µg/m³; station-days on which this value was exceeded were classified as PM₁₀ exceedance observations. The locations of the monitoring stations are shown in Figure 1.



Figure 1. Locations of the analysed air-quality monitoring stations in Lithuania

The types and coordinates of the analysed air-quality monitoring stations were determined from the description of the national air-monitoring network provided by the Environmental Protection Agency of Lithuania (2024). The following stations were analysed: Vilnius Senamiestis (urban background; N 54°40'53", E 25°17'17"), Lazdynai (urban background; N 54°41'08", E 25°12'39"), Zirmunai (traffic; N 54°42'55", E 25°17'22") and Savanoriai Ave. (industrial; N 54°40'24", E 25°14'56"); Kaunas Petrasiumai/Dainava (traffic; Petrasiumai: N 54°53'42", E 23°59'10"; Dainava: N 54°55'00", E 23°58'59") and Noreikiskes (urban background; N 54°53'01", E 23°50'09"); Klaipeda Centras (traffic; N 55°42'27", E 21°08'29") and Silutes Ave. (traffic; N 55°41'24", E 21°10'46"); Siauliai (traffic; N 55°56'16", E 23°18'29"); Panevezys Centras (urban background; N 55°43'30", E 24°21'56"); and Mazeikiai (industrial; N 56°18'35", E 22°19'53"). PM₁₀ mass concentrations were measured using automatic analysers based on beta-ray absorption.

Meteorological data were obtained from the archive of the Lithuanian Hydrometeorological Service, using daily

observations from meteorological stations serving the respective cities. Air-quality and meteorological data were matched by city and observation date. The meteorological variables used in the analysis were mean air temperature, daily precipitation, mean wind speed and relative humidity. The unit of analysis was the station-day, defined as one valid daily PM₁₀ record from one monitoring station. Because the number of monitoring stations differed among cities, absolute exceedance counts were interpreted descriptively.

To assess the seasonality of PM₁₀ exceedances, observations were grouped into four seasons: winter, spring, summer and autumn. The number of PM₁₀ exceedance observations was calculated for each season and city, and the dominant exceedance season was identified. The monitoring stations in Vilnius and Kaunas were examined in greater detail because these cities included several stations representing different site types.

At station level, the mean, median and maximum PM₁₀ concentrations, number and rate of exceedance observations, mean NO₂ concentration and number of PM₁₀ observations were calculated. On 17 December 2022, the traffic-oriented air-quality monitoring station in Kaunas Petrasiunai was relocated to the Dainava district; data from these two consecutive periods were treated as one continuous traffic-site series (Environmental Protection Agency of Lithuania, 2023).

Episode duration was analysed to characterise PM₁₀ exceedances. An episode was defined as one or more consecutive days at the same station on which the PM₁₀ concentration exceeded 50 µg/m³. Station-level episodes were summarised by city in terms of their number, mean and maximum duration, proportion of single-day episodes and number of longer episodes. The proportion of PM₁₀ exceedance observations occurring under dry or nearly dry conditions (daily precipitation <1 mm) and low-wind conditions (mean wind speed <2.5 m/s) was also assessed.

Non-parametric methods were used for the statistical analysis. Differences in meteorological conditions between PM₁₀ exceedance and non-exceedance observations were assessed using the Wilcoxon rank-sum test. Spearman's rank correlation was used to evaluate associations between PM₁₀ concentrations and meteorological variables. These methods were selected because the distributions of daily PM₁₀ concentrations and meteorological variables may not satisfy the assumption of normality, and relationships between variables may be monotonic but not necessarily linear. Differences and associations were considered statistically significant at $p < 0.05$.

Prevailing daily wind direction was additionally analysed in Vilnius and Kaunas. It was derived from hourly observations of the Lithuanian Hydrometeorological Service, with wind direction assigned to eight sectors: N, NE, E, SE, S, SW, W and NW. This analysis was used only as an additional indicator of meteorological conditions and

not as a method for identifying specific pollution sources. Wind-direction analysis was limited to Vilnius and Kaunas, where station-level patterns were examined in greater detail. Data processing, statistical analysis and figure preparation were performed in R version 4.5.2 (R Core Team, 2025).

3. Results

During 2019–2025, daily PM₁₀ concentrations in the analysed Lithuanian cities were generally below the limit value of 50 µg/m³, although episodic concentration increases occurred in every city. The overall distribution of daily PM₁₀ concentrations by city is shown in **Figure 2**.

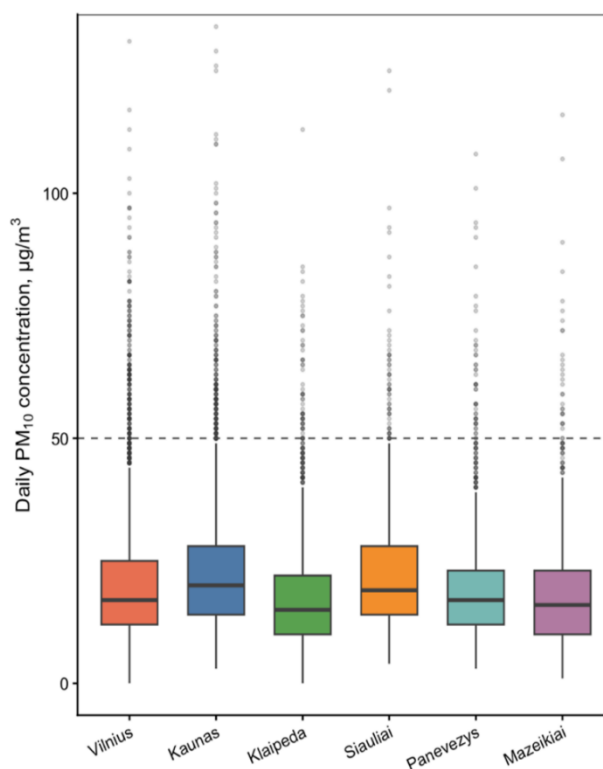


Figure 2. Distribution of daily PM₁₀ concentrations by city, 2019–2025

Median PM₁₀ concentrations in all cities remained well below 50 µg/m³, whereas the upper tails of the distributions and individual high values demonstrate the episodic nature of elevated PM₁₀ concentrations. More pronounced clusters of high values were observed in Vilnius, Kaunas and Šiauliai; the subsequent analysis therefore focused on exceedance observations and their accompanying meteorological conditions rather than on general background levels.

Comparison of meteorological conditions between PM₁₀ exceedance and non-exceedance observations revealed clear differences between the two groups. In all analysed cities, exceedance observations were characterised by less precipitation, lower relative humidity and, in most cases, lower mean wind speed than non-exceedance observations (**Table 1**).

Table 1. Meteorological contrast between PM₁₀ exceedance and non-exceedance observations by city.

City	PM ₁₀ exceedance observation, n	Mean PM ₁₀ during exceedance, µg/m ³	Mean PM ₁₀ during non- exceedance, µg/m ³	Precipitation difference, mm	Wind- speed difference, m/s	Relative- humidity difference, %	PM ₁₀ observation, n
Vilnius	217	68.1	19.1	-1.36	-0.39	-16.4	9366
Kaunas	198	67.9	21.4	-1.11	-0.73	-8.6	4856
Klaipeda	54	68.7	17.0	-1.88	-0.32	-20.1	2767
Siauliai	52	66.1	21.1	-1.37	-0.46	-12.3	1733
Panevezys	46	65.2	18.0	-0.79	-0.90	-9.8	2392
Mazeikiai	28	67.1	17.1	-1.61	-0.47	-8.4	2430

Note. Differences were calculated as the mean value during PM₁₀ exceedance observations minus the mean value during non-exceedance observations.

As shown in **Table 1**, the difference in precipitation between PM₁₀ exceedance and non-exceedance observations was negative in every city. The largest precipitation differences were found in Klaipeda (–1.88 mm), Mazeikiai (–1.61 mm), Siauliai (–1.37 mm) and Vilnius (–1.36 mm). Relative humidity was also lower during PM₁₀ exceedance observations in all cities, with the largest differences in Klaipeda (–20.1%) and Vilnius (–16.4%). Wind-speed differences were likewise negative, although their magnitude varied among cities.

Wilcoxon rank-sum tests showed significant differences in precipitation between PM₁₀ exceedance and non-

exceedance observations in all cities ($p < 0.001$). Differences in relative humidity were also significant in every city ($p < 0.001$ in most cities; $p = 0.021$ in Mazeikiai). Wind-speed differences were significant in Kaunas, Panevezys and Vilnius ($p < 0.001$), Siauliai ($p = 0.001$) and Mazeikiai ($p = 0.023$), whereas no statistically significant difference was found in Klaipeda ($p = 0.196$).

Seasonal analysis showed a clear association between PM₁₀ exceedances and time of year. Spring accounted for the largest number of exceedance observations within each analysed city (**Table 2**).

Table 2. Seasonal distribution of PM₁₀ exceedance observations by city

City	Winter	Spring	Summer	Autumn	Exceedance observations, n	Dominant season
Vilnius	27	127	20	43	217	Spring
Kaunas	41	87	26	44	198	Spring
Klaipeda	12	35	0	7	54	Spring
Siauliai	11	28	4	9	52	Spring
Panevezys	16	26	3	1	46	Spring
Mazeikiai	10	12	0	6	28	Spring

Table 3. PM₁₀ exceedance characteristics at selected monitoring stations in Vilnius and Kaunas

Monitoring station	Mean PM ₁₀ , µg/m ³	Median PM ₁₀ , µg/m ³	Maximum PM ₁₀ , µg/m ³	PM ₁₀ exceedance observations, n	PM ₁₀ exceedance rate, %	Mean NO ₂ , µg/m ³	PM ₁₀ observations, n
Kaunas Petrasiunai /Dainava	23.9	20	144	124	5.07	47.0	2447
Kaunas Noreikiskes	22.7	20	164	74	3.07	28.2	2409
Vilnius Zirmunai	24.9	22	152	100	4.38	53.0	2284
Vilnius Senamiestis	21.5	19	155	53	2.22	36.4	2392
Vilnius Savanoriai Ave.	16.7	14	140	43	1.83	43.9	2344
Vilnius Lazdynai	17.7	16	149	21	0.90	34.5	2346

Note. Kaunas Petrasiunai/Dainava represents a continuous traffic-site series: the station was relocated from Petrasiunai to Dainava on 17 December 2022.

As shown in **Table 2**, spring was the dominant season for PM₁₀ exceedance observations in all cities. The numbers recorded in spring were 127 in Vilnius, 87 in Kaunas, 35 in Klaipėda, 28 in Šiauliai, 26 in Panevėžys and 12 in Mazeikiai. Exceedances were much less frequent in summer, with none recorded in Klaipėda or Mazeikiai. This seasonal pattern is consistent with spring conditions under which the drying of road surfaces after winter may increase the likelihood of accumulated particles being resuspended.

The monitoring stations in Vilnius and Kaunas were examined in greater detail because these cities included several stations representing different site types. This analysis enabled assessment of whether exceedance rates varied among monitoring locations within the same city.

A more detailed analysis of selected monitoring stations in Vilnius and Kaunas (**Table 3**) showed that PM₁₀ exceedance rates differed among monitoring locations. The highest rate was recorded at the Kaunas Petrusiūnai/Dainava station (5.07%); in Vilnius, the highest rate was observed at Zirmunai (4.38%). The lowest rate was recorded at Vilnius Lazdynai (0.90%).

Higher PM₁₀ exceedance rates were generally observed at monitoring locations with higher NO₂ concentrations. In Kaunas, mean NO₂ concentration increased from 36.3 µg/m³ on PM₁₀ non-exceedance observations to 71.4 µg/m³ on exceedance observations. The corresponding values in Vilnius were 41.1 and 76.6 µg/m³. The Wilcoxon

test showed statistically significant differences in NO₂ concentrations between PM₁₀ exceedance and non-exceedance observations in both cities ($p < 0.001$). Spearman's correlation also indicated positive associations between PM₁₀ and NO₂ in Kaunas ($p = 0.300$; $p < 0.001$) and Vilnius ($p = 0.333$; $p < 0.001$).

These results support the use of NO₂ as an indicator of traffic influence and a more intensively urbanised environment. However, the associations were only moderate, and PM₁₀ exceedances cannot be explained by traffic emissions alone. The episodes were likely associated with a combination of traffic influence, local dust resuspension from dry surfaces and meteorological conditions.

Analysis of episode duration showed that most PM₁₀ exceedances were short-lived (**Table 4**). Mean episode duration ranged from 1.56 days in Mazeikiai to 1.93 days in Šiauliai. Single-day episodes accounted for more than half of all episodes in most cities and exceeded 70% in Vilnius and Klaipėda. The station-level episodes summarised by city included 17 episodes lasting three or more days in both Vilnius and Kaunas; the longest episodes lasted 15 and 14 days, respectively. Thus, PM₁₀ exceedances were usually brief, although longer periods of unfavourable meteorological and local pollution conditions occasionally occurred in the largest cities.

Table 4. Duration of station-level PM₁₀ exceedance periods summarised by city

City	PM ₁₀ exceedance observations, n	Number of PM ₁₀ exceedance episodes	Mean episode duration, days	Maximum episode duration, days	Single-day episodes, %	Episodes lasting 2 days	Episodes lasting ≥3 days
Vilnius	217	119	1.82	15	75.6	12	17
Kaunas	198	108	1.83	14	69.4	16	17
Klaipėda	54	31	1.74	10	71.0	3	6
Šiauliai	52	27	1.93	6	59.3	4	7
Panevėžys	46	26	1.77	5	57.7	5	6
Mazeikiai	28	18	1.56	4	61.1	5	2

Table 5. PM₁₀ exceedance observations under dry and low-wind conditions

City	PM ₁₀ exceedance observations, n	Exceedance observations with precipitation <1 mm, n	Share of exceedance observations with precipitation <1 mm, %	Exceedance observations with wind speed <2.5 m/s, n	Share of exceedance observations with wind speed <2.5 m/s, %	Share of exceedance observations with precipitation <1 mm and wind speed <2.5 m/s, %
Vilnius	217	203	93.5	128	59.0	56.2
Kaunas	198	184	92.9	95	48.0	47.0
Klaipėda	54	48	88.9	26	48.1	40.7
Šiauliai	52	49	94.2	34	65.4	61.5
Panevėžys	46	41	89.1	33	71.7	65.2
Mazeikiai	28	26	92.9	17	60.7	53.6

Because **Table 1** showed that precipitation, wind speed and relative humidity were lower during PM₁₀ exceedance observations than during non-exceedance observations, the proportion of exceedances coinciding with dry and low-wind conditions was also evaluated. Dry or nearly dry

conditions were defined as daily precipitation <1 mm, and low-wind conditions as mean wind speed <2.5 m/s.

As shown in **Table 5**, most PM₁₀ exceedance observations in all cities coincided with dry or nearly dry conditions. Daily

precipitation <1 mm occurred during 88.9–94.2% of all PM₁₀ exceedances. The highest proportions were found in Siauliai (94.2%), Vilnius (93.5%), and Kaunas and Mazeikiai (92.9% each). Low-wind conditions were also common, although their frequency varied more among cities, from 48.0% in Kaunas to 71.7% in Panevezys. The combination of dry and low-wind conditions was most frequent in Panevezys (65.2%) and Siauliai (61.5%) and least frequent in Klaipeda (40.7%) and Kaunas (47.0%). These findings

Table 6. PM₁₀ concentrations and exceedance rates according to daily precipitation

Daily precipitation	n	Median PM ₁₀ , µg/m ³	Mean PM ₁₀ , µg/m ³	PM ₁₀ exceedance observations, n	Exceedance rate, %
<1 mm	16350	19	22.1	551	3.37
≥1 mm	7194	15	16.4	44	0.61

Table 7. Spearman correlations between PM₁₀ and meteorological variables at monitoring stations in Vilnius and Kaunas

Monitoring station	Precipitation	Wind speed	Relative humidity	Air temperature	n
Kaunas Petrasinai/Dainava	-0.270	-0.213	-0.203	0.133	2447
Kaunas Noreikiskes	-0.239	-0.153	-0.219	0.099	2409
Vilnius Senamiestis	-0.325	-0.205	-0.313	0.146	2392
Vilnius Lazdynai	-0.251	-0.161	-0.284	0.201	2346
Vilnius Savanoriai Ave.	-0.320	-0.197	-0.346	0.139	2344
Vilnius Zirmūnai	-0.354	-0.232	-0.410	0.213	2284

Note. All correlations were statistically significant at $p < 0.001$.

The additional comparison confirmed the importance of precipitation conditions. On observations with daily precipitation <1 mm, the median PM₁₀ concentration was 19 µg/m³, the mean was 22.1 µg/m³ and the exceedance rate was 3.37%. When precipitation was ≥1 mm, the median decreased to 15 µg/m³, the mean to 16.4 µg/m³ and the exceedance rate to 0.61%. Overall, 551 of 595 PM₁₀ exceedance observations (92.6%) occurred with precipitation <1 mm. The Wilcoxon rank-sum test confirmed a significant difference in PM₁₀ concentrations between the two precipitation groups ($p < 0.001$).

Associations between PM₁₀ concentrations and meteorological variables were subsequently assessed at selected monitoring stations in Vilnius and Kaunas.

Spearman correlations showed that PM₁₀ concentrations at the selected Vilnius and Kaunas stations were significantly and negatively associated with precipitation, wind speed and relative humidity (**Table 7**). The strongest negative association with precipitation was found at Vilnius Zirmūnai ($\rho = -0.354$), and the strongest association with relative humidity was also observed at this station ($\rho = -0.410$). Associations with wind speed were weaker but negative at all stations. Correlations with air temperature were positive but weak, indicating that temperature was not the principal factor associated with variation in PM₁₀ concentrations.

Additional analysis in Vilnius and Kaunas, using prevailing daily wind directions (**Figure 3**) calculated from hourly meteorological observations, showed that PM₁₀ exceedance rates varied among wind-direction sectors.

indicate an association with dry conditions, under which particles may be more readily resuspended from surfaces and are not efficiently removed by precipitation.

PM₁₀ concentrations and exceedance rates were additionally compared between observations with daily precipitation <1 mm and ≥1 mm (**Table 6**).

The highest exceedance rates in both cities occurred under easterly and south-easterly winds. In Vilnius, the highest rates were recorded for SE (9.64%) and E (8.05%) winds; in Kaunas, they occurred under SE (13.1%), E (10.8%) and S (10.5%) winds. The lowest rates in both cities were observed under westerly winds. These results suggest that prevailing wind direction may have contributed to the meteorological context of PM₁₀ episodes. However, without a detailed spatial analysis of emission sources, these associations should not be interpreted as direct identification of particular pollution sources.

4. Discussion

The results showed that daily PM₁₀ limit-value exceedances in Lithuanian cities during 2019–2025 were predominantly episodic rather than persistent. PM₁₀ concentrations remained below 50 µg/m³ on most observations, although short-term concentration increases occurred in every analysed city. The air-quality issue was therefore associated less with a persistently high urban background and more with individual periods in which local particle sources coincided with meteorological conditions favourable to accumulation. A similar interpretation of PM₁₀ episodes was presented by Kukkonen *et al.* (2005), who emphasised interactions between local emissions, regional background and meteorological conditions during episodes of high PM₁₀ concentrations.

The episodic nature of PM₁₀ exceedances was also supported by episode-duration analysis. Most episodes lasted one day or were otherwise short-lived, although episodes of three or more days also occurred at stations in

Vilnius and Kaunas. This suggests that some PM₁₀ exceedances were related to short-term local processes, whereas others coincided with longer periods of unfavourable meteorological conditions. Kassomenos *et al.* (2014) likewise emphasised the importance of intra-urban variability, station surroundings and seasonal conditions for PM₁₀ and PM_{2.5} concentrations. The differences identified among cities and monitoring locations may therefore reflect not only variations in the general urban background but also station surroundings, traffic influence, road-surface conditions and the proximity of local dust sources.

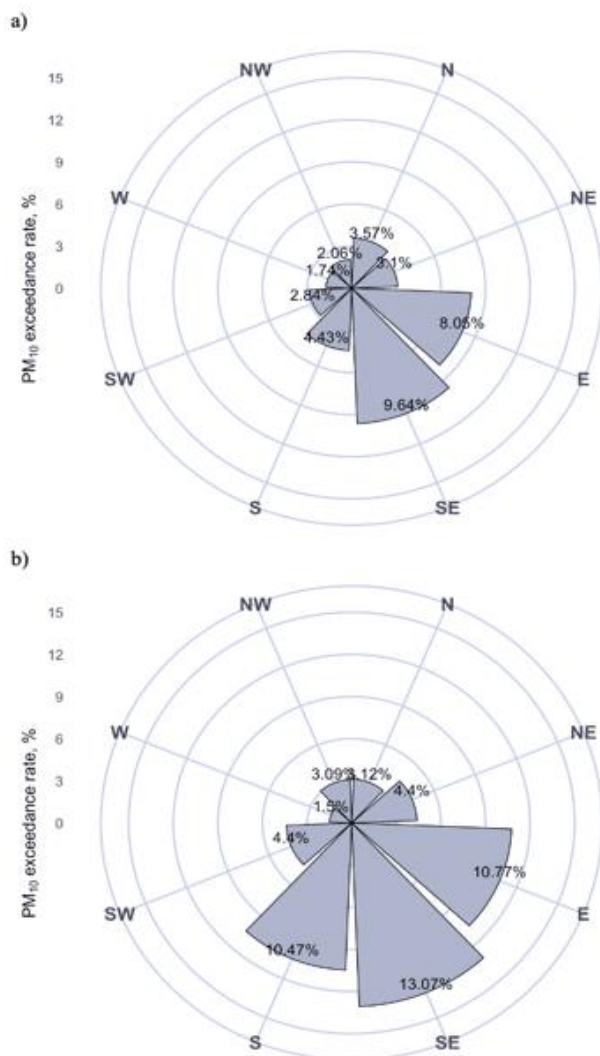


Figure 3. PM₁₀ exceedance rates by prevailing daily wind direction in Vilnius (a) and Kaunas (b)

One of the clearest findings was the association between PM₁₀ exceedances and dry or nearly dry conditions. Precipitation was lower during exceedance observations than during non-exceedance observations in every city, and most exceedances coincided with daily precipitation <1 mm. Lower relative humidity and, frequently, lower wind speed also indicated conditions more favourable to particle accumulation and resuspension from surfaces. Spearman correlations at the Vilnius and Kaunas stations confirmed negative associations of PM₁₀ with precipitation, wind speed and relative humidity. These results are consistent with the findings of Birim *et al.* (2023) and Zender-Świercz

et al. (2024), who showed that relationships between PM₁₀ and meteorological variables depend on environmental setting and local air quality; meteorological effects should therefore not be assumed to be uniform across monitoring locations.

The seasonality of PM₁₀ exceedances was another important finding. Spring accounted for the largest number of exceedance observations in every analysed city. This pattern is consistent with conditions under which mineral particles accumulated on roads and other surfaces during winter may be resuspended as those surfaces dry.

The importance of road-dust resuspension has been described in previous studies. Source-apportionment analysis based on elemental composition has identified road dust, soil dust and vehicle exhaust as distinct contributors to urban PM₁₀ concentrations (Triantafyllou *et al.*, 2020). Amato *et al.* (2009) showed that dust resuspended from road surfaces may contribute substantially to PM₁₀ concentrations. Rienda and Alves (2021) likewise identified road-dust resuspension as an important source of air pollution in road environments and noted that its intensity depends on meteorological conditions, road-surface condition and traffic flow. Similar processes have been described in northern European cities (Norman and Johansson, 2006; Gustafsson *et al.*, 2008). The seasonal and meteorological patterns observed in the present study are consistent with dry spring conditions being favourable to road-dust resuspension in Lithuanian cities, although the contribution of this source was not quantified directly.

This interpretation is also relevant to the new European Union air-quality framework. Article 17 of Directive (EU) 2024/2881 provides separately for the assessment of PM₁₀ exceedances attributable to particle resuspension following winter sanding or salting of roads, while requiring evidence of the contribution and reasonable measures to reduce concentrations (European Parliament and Council of the European Union, 2024). The spring pattern and association with dry conditions observed here are therefore relevant to the seasonal management of road dust in Lithuanian cities.

Station-level analysis in Vilnius and Kaunas showed that higher PM₁₀ exceedance rates occurred at stations representing more intensively urbanised environments and recording higher NO₂ concentrations. NO₂ concentrations were significantly higher during PM₁₀ exceedance observations than during non-exceedance observations, and correlations between PM₁₀ and NO₂ were positive. Similar patterns were observed during mobility restrictions, when concurrent decreases in NO₂ and PM₁₀ were associated with reduced anthropogenic urban emissions (Elass *et al.*, 2020). These findings support the use of NO₂ as an indicator of traffic influence and a more intensively urbanised environment. They are also consistent with Liu *et al.* (2023), who showed that peaks in lung-deposited particle surface-area concentrations in European urban environments frequently coincided with morning and evening traffic peaks and varied with emission sources and meteorological conditions. However, the

relationships observed in the present study were not strong, and PM₁₀ episodes cannot be explained by traffic exhaust alone. Traffic influence was more likely to have acted together with non-exhaust particle processes, road-dust resuspension and dry meteorological conditions.

Recent research on traffic-related particles supports this interpretation. Harrison *et al.* (2021) emphasised the increasing relative importance of non-exhaust particles generated by brake, tyre and road-surface wear and by road-dust resuspension. Beddows and Harrison (2021) also analysed emission factors for non-exhaust PM₁₀ and PM_{2.5} and highlighted the relevance of vehicle mass and wear processes. In the context of Lithuanian cities, this interpretation is complemented by the study of Andriulė *et al.* (2024) in Klaipėda, which showed that the distribution of NO₂ and particulate matter was related to urban functional zones and local pollution sources.

When interpreting PM₁₀ exceedances, it is important to recognise that the PM₁₀ fraction is not an indicator of a single source. It may include contributions from combustion, traffic, road dust, mineral particles, industry, construction and regional transport. Meteorological variables or NO₂ concentrations alone therefore cannot distinguish specific sources, although they may help identify the conditions under which PM₁₀ exceedances occurred. This is consistent with recent studies showing that particle mass concentration does not always adequately represent differences among urban environments and local pollution sources (Lepistö *et al.*, 2023). Studies of particle composition in European cities further confirm the diversity of PM₁₀ sources. Querol *et al.* (2004) showed that PM₁₀ and PM_{2.5} concentrations and composition depend on site type, geographical setting and anthropogenic sources. Putaud *et al.* (2010), summarising data from rural, urban and kerbside environments across Europe, emphasised that particulate matter is a mixture of components from different origins, while Pérez *et al.* (2008) found that mineral particles may constitute an important fraction of PM₁₀.

Additional wind-direction analysis in Vilnius and Kaunas showed that PM₁₀ exceedance rates were not distributed uniformly among wind-direction sectors. Higher rates in both cities were observed under easterly to south-easterly winds. This finding indicates that the direction of air-mass movement may have formed part of the meteorological context of PM₁₀ episodes. Nevertheless, the association should be interpreted as directional and meteorological rather than as direct identification of specific pollution sources.

The findings have practical relevance for urban air-quality management. Because most PM₁₀ exceedance observations occurred under dry or nearly dry conditions and were especially frequent in spring, air-quality measures could address seasonal road-dust management alongside general emission reduction. Such measures may include timely street cleaning after winter, reduction of dust resuspension during dry periods, and control of unpaved surfaces, construction sites and high-traffic zones.

4.1. Limitations

This study has several limitations. The analysis was based on daily PM₁₀ mass concentrations and meteorological variables; particle chemical composition could therefore not be assessed, and the contributions of individual pollution sources could not be quantified. Data on traffic intensity, street cleaning, winter road treatment and other local activities were not analysed. In addition, observations from urban meteorological stations may not fully represent conditions at every air-quality monitoring location.

5. Conclusions

Daily PM₁₀ limit-value exceedances in Lithuanian cities during 2019–2025 were episodic rather than persistent. Although PM₁₀ concentrations remained below the limit value of 50 µg/m³ on most observations, short-term concentration increases occurred in every analysed city. Most episodes were single-day or otherwise short-lived.

PM₁₀ exceedance observations showed clear seasonality, with the largest numbers recorded in spring in all analysed cities. This pattern is consistent with the period when road and other surfaces dry after winter and conditions may become favourable to the resuspension of mineral particles and road dust.

PM₁₀ exceedance observations were clearly associated with meteorological conditions. They were characterised by lower precipitation and relative humidity in every city and by lower wind speed in most cities. Most exceedances coincided with dry or nearly dry conditions, with daily precipitation <1 mm.

Station-level analysis in Vilnius and Kaunas showed higher PM₁₀ exceedance rates at more intensively urbanised and traffic-influenced monitoring locations where NO₂ concentrations were also higher. These findings are consistent with a combined role of traffic influence, road-dust resuspension and meteorological conditions in the occurrence of PM₁₀ episodes, although the contribution of individual sources was not quantified.

Wind-direction analysis in Vilnius and Kaunas showed higher PM₁₀ exceedance rates under easterly and south-easterly winds. These findings complement the assessment of meteorological conditions and suggest that air-mass movement direction may also have contributed to the context in which PM₁₀ episodes occurred.

Data availability

The primary daily air-quality indicators of the Environmental Protection Agency of Lithuania and meteorological observations from the archive of the Lithuanian Hydrometeorological Service used in this study are publicly available on the websites of the respective institutions (Environmental Protection Agency of Lithuania; Lithuanian Hydrometeorological Service).

Funding

This research received no external funding.

Conflicts of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization, S.Č.; methodology, S.Č.; data curation, S.Č.; formal analysis, S.Č.; investigation, S.Č.; visualization, S.Č. and E.A.; writing—original draft preparation, S.Č. and E.A.; writing—review and editing, S.Č. and E.A. Both authors have read and agreed to the published version of the manuscript.

Declaration on the use of generative AI

During preparation of the manuscript a generative artificial intelligence tool was used solely for language editing and visual layout assistance. No scientific content, data, analyses, interpretations or conclusions were generated by AI. The authors verified all elements and take full responsibility for the final content.

References

- Amato, F., Pandolfi, M., Escrig, A., Querol, X., Alastuey, A., Pey, J., Perez, N., & Hopke, P. K. (2009). Quantifying road dust resuspension in urban environment by Multilinear Engine: A comparison with PMF2. *Atmospheric Environment*, 43(17), 2770–2780. <https://doi.org/10.1016/j.atmosenv.2009.02.039>
- Andriulė, A., Vasiliauskienė, E., Rapalis, P., & Dailidienė, I. (2024). Air Pollution in the Port City of Lithuania: Characteristics of the Distribution of Nitrogen Dioxide and Solid Particles When Assessing the Demographic Distribution of the Population. *Sustainability*, 16(19), 8413. <https://doi.org/10.3390/su16198413>
- Arslan, H., & Toltar, A. (2023). The influence of meteorological parameters on PM2.5 and PM10 values in Ümraniye and Silivri districts of Istanbul. *Environmental Research and Technology*, 6(4), 288–301. doi:10.35208/ert.1220649
- Beddows, D. C. S., & Harrison, R. M. (2021). PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. *Atmospheric Environment*, 244, 117886. <https://doi.org/10.1016/j.atmosenv.2020.117886>
- Birim, N. G., Turhan, C., Atalay, A. S., & Gokcen Akkurt, G. (2023). The influence of meteorological parameters on PM10: A statistical analysis of an urban and rural environment in Izmir/Türkiye. *Atmosphere*, 14(3), 421. <https://doi.org/10.3390/atmos14030421>
- Elass, A., Eddaif, A., Radey, Aitzaoui, O., El, Y., Chelhaoui, Y., & ASS, K. E. (2020). Effect of restricted emissions during Covid-19 lockdown on air quality in Rabat - Morocco. *Global NEST Journal*, 22(3), 348–353. <https://doi.org/10.30955/gnj.003431>
- Engler, C., Birmili, W., Spindler, G., & Wiedensohler, A. (2012). Analysis of exceedances in the daily PM10 mass concentration (50 µg m⁻³) at a roadside station in Leipzig, Germany. *Atmospheric Chemistry and Physics*, 12, 10107–10123. doi:10.5194/acp-12-10107-2012
- Environmental Protection Agency of Lithuania. (2023). *Air quality in the Kaunas agglomeration in 2022*. [in Lithuanian]. (accessed 28 May 2026). https://aaa.lrv.lt/uploads/aaa/documents/files/Ap%C5%BEvalga_%20Kauno%20aglomeracija_2022.pdf
- Environmental Protection Agency of Lithuania. (2024). *Air quality in Lithuania in 2023*. [in Lithuanian]. (accessed 28 May 2026). https://aaa.lrv.lt/public/canonical/1727672366/2513/Ap%C5%BEvalga.%20Oro%20kokybe%C4%97%20Lietuvoje_2023.pdf
- Environmental Protection Agency of Lithuania. (n.d.). Daily air quality indicators [in Lithuanian]. (accessed 28 May 2026). <https://aaa.lrv.lt/lt/veiklos-sritys/oras/oro-kokybes-statistika-ir-duomenys/paros-oro-kokybes-rodikliai/>
- European Parliament and Council of the European Union. Official Journal of the European Union, L 2024/2881. (2024). *Directive (EU) 2024/2881 of 23 October 2024 on ambient air quality and cleaner air for Europe (recast)*. (accessed 28 May 2026). <https://eur-lex.europa.eu/eli/dir/2024/2881/oj>
- Ferenczi, Z., Imre, K., Lakatos, M., Molnár, Á., Bozó, L., Homolya, E., & Gelencsér, A. (2021). Long-term characterization of urban PM10 in Hungary. *Aerosol and Air Quality Research*, 21, 210048. doi:10.4209/aaqr.210048
- Ferm, M., & Sjöberg, K. (2015). Concentrations and emission factors for PM2.5 and PM10 from road traffic in Sweden. *Atmospheric Environment*, 119, 211–219. <https://doi.org/10.1016/j.atmosenv.2015.08.037>
- Guerreiro, C. B. B., Foltescu, V., & de Leeuw, F. (2014). Air quality status and trends in Europe. *Atmospheric Environment*, 98, 376–384. doi:10.1016/j.atmosenv.2014.09.017
- Gustafsson, M., Blomqvist, G., Gudmundsson, A., Dahl, A., Swietlicki, E., Bohgard, M., Lindbom, J., & Ljungman, A. (2008). Properties and toxicological effects of particles from the interaction between tyres, road pavement and winter traction material. *Science of the Total Environment*, 393(2–3), 226–240. <https://doi.org/10.1016/j.scitotenv.2007.12.030>
- Harrison, R. M., Allan, J., Carruthers, D., Heal, M. R., Lewis, A. C., Marner, B., Murrells, T., & Williams, A. (2021). Non-exhaust vehicle emissions of particulate matter and VOC from road traffic: A review. *Atmospheric Environment*, 262, 118592. <https://doi.org/10.1016/j.atmosenv.2021.118592>
- Kassomenos, P. A., Vardoulakis, S., Chaloulakou, A., Grivas, G., Borge, R., & Lumberras, J. (2014). Study of PM10 and PM2.5 levels in three European cities: Analysis of intra and inter urban variations. *Atmospheric Environment*, 87, 153–163. <https://doi.org/10.1016/j.atmosenv.2014.01.004>
- Kecorius, S., Madueño, L., Birmili, W., Löndahl, J., Plauškaitė, K., Byčėnienė, S., Lovrić, M., Petrić, V., Carranza-García, M., Jiménez-Navarro, M. J., Martínez-Ballesteros, M., Weiss, M., Schmid, O., Cyrus, J., Peters, A., & Kecorius, G. (2025). Urban pollution impact assessment in six Lithuanian cities with a focus on road traffic emissions: Integrated framework for environmental health studies. *Journal of Hazardous Materials*, 497. <https://doi.org/10.1016/j.jhazmat.2025.139725>
- Kukkonen, J., Pohjola, M., Sokhi, R. S., Luhana, L., Kitwiroon, N., Fragkou, L., Rantamäki, M., Berge, E., Ødegaard, V., Slørdal, L. H., Denby, B., & Finardi, S. (2005). Analysis and evaluation of selected local-scale PM10 air pollution episodes in four European cities: Helsinki, London, Milan and Oslo. *Atmospheric Environment*, 39(15), 2759–2773. <https://doi.org/10.1016/j.atmosenv.2004.09.090>
- Kupiainen, K., Denby, B. R., Gustafsson, M., Johansson, C., Ketzel, M., Kukkonen, J., Norman, M., Pirjola, L., Sundvor, I., Bennet, C., Blomqvist, G., Janhäll, S., Karppinen, A., Kauhaniemi, M., Malinen, A., & Stojiljkovic, A. (2017). *Road dust and PM10 in the Nordic countries: Measures to reduce road dust emissions from traffic*. Nordic Council of Ministers.
- Lazurca, L. G. (2015). The influence of meteorological conditions on PM10 concentrations in Suceava City (North-Eastern

- Romania). *Georeview*, 25(1), 103–116. doi:10.4316/GEOREVIEW.2015.25.1.278
- Lepistö, T., Lintusaari, H., Oudin, A., Barreira, L. M. F., Niemi, J. V., Karjalainen, P., Salo, L., Silvonen, V., Markkula, L., Hoivala, J., Marjanen, P., Martikainen, S., Aurela, M., Reyes Reyes, F., Oyola, P., Kuuluvainen, H., Manninen, H. E., Schins, R. P. F., Vojtisek-Lom, M., Ondracek, J., Rönkkö, T. (2023). Particle lung deposited surface area (LDSAal) size distributions in different urban environments and geographical regions: Towards understanding of the PM_{2.5} dose–response. *Environment International*, 180, 108224. <https://doi.org/10.1016/j.envint.2023.108224>
- Li, X., Chen, X., Yuan, X., Zeng, G., León, T., Liang, J., Chen, G., & Yuan, X. (2017). Characteristics of particulate pollution (PM_{2.5} and PM₁₀) and their space-scale-dependent relationships with meteorological elements in China. *Sustainability*, 9(12), 2330. doi:10.3390/su9122330
- Linell, J., Isaxon, C., Olsson, B., Stroh, E., Wollmer, P., Löndahl, J., & Rissler, J. (2024). Effects of breathing variables on modelled particle lung deposition at physical activity for children and adults. *Air Quality, Atmosphere & Health*, 17, 843–856. <https://doi.org/10.1007/s11869-023-01484-0>
- Lithuanian Hydrometeorological Service. *Archive of meteorological observations*. [in Lithuanian]. (accessed 28 May 2026). <https://archyvas.meteo.lt/>
- Liu, X., Hadiatullah, Zhang, X., Trechera, P., Savadkoobi, M., Garcia-Marlès, M., Reche, C., Pérez, N., Beddows, D. C. S., Salma, I., Thén, W., Kalkavouras, P., Mihalopoulos, N., Hueglin, C., Green, D. C., Tremper, A. H., Chazeau, B., Gille, G., Marchand, N., Niemi, J.V., Querol, X. (2023). Ambient air particulate total lung deposited surface area (LDSA) levels in urban Europe. *Science of the Total Environment*, 898, 165466. <https://doi.org/10.1016/j.scitotenv.2023.165466>
- Norman, M., & Johansson, C. (2006). Studies of some measures to reduce road dust emissions from paved roads in Scandinavia. *Atmospheric Environment*, 40(32), 6154–6164. <https://doi.org/10.1016/j.atmosenv.2006.05.022>
- Orru, H., Laukaitienė, A., & Zurlýtė, I. (2012). Particulate air pollution and its impact on health in Vilnius and Kaunas. *Medicina*, 48(9), 472–477. <https://doi.org/10.3390/medicina48090070>
- Pérez, N., Pey, J., Querol, X., Alastuey, A., López, J. M., & Viana, M. (2008). Partitioning of major and trace components in PM₁₀–PM_{2.5}–PM₁ at an urban site in Southern Europe. *Atmospheric Environment*, 42(8), 1677–1691. <https://doi.org/10.1016/j.atmosenv.2007.11.034>
- Putaud, J.-P., Van Dingenen, R., Alastuey, A., Bauer, H., Birmili, W., Cyrys, J., Flentje, H., Fuzzi, S., Gehrig, R., Hansson, H. C., Harrison, R. M., Herrmann, H., Hitztenberger, R., Hügl, C., Jones, A. M., Kasper-Giebl, A., Kiss, G., Kousa, A., Kuhlbusch, T. A. J., Löschau, G., Raes, F. (2010). A European aerosol phenomenology – 3: Physical and chemical characteristics of particulate matter from 60 rural, urban, and kerbside sites across Europe. *Atmospheric Environment*, 44(10), 1308–1320. <https://doi.org/10.1016/j.atmosenv.2009.12.011>
- Querol, X., Alastuey, A., Viana, M. M., Rodríguez, S., Artíñano, B., Salvador, P., García do Santos, S., Fernández Patier, R., Ruiz, C. R., de la Rosa, J., Sánchez de la Campa, A., Menéndez, M., & Gil, J. I. (2004). Speciation and origin of PM₁₀ and PM_{2.5} in Spain. *Journal of Aerosol Science*, 35(9), 1151–1172. <https://doi.org/10.1016/j.jaerosci.2004.04.002>
- R Core Team. (2025). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>
- Rienda, I. C., & Alves, C. A. (2021). Road dust resuspension: A review. *Atmospheric Research*, 261, 105740. <https://doi.org/10.1016/j.atmosres.2021.105740>
- Sellamuthu, S., & Jeyadharmanarajan, J. (2023). Analysis of seasonal variation and dispersion pattern of ambient air pollutants in an urban environment. *Global NEST Journal*, 25(5), 66–75. <https://doi.org/10.30955/gnj.004670>
- Stojiljkovic, A., Kauhaniemi, M., Kukkonen, J., Kupiainen, K., Karppinen, A., Denby, B. R., Kousa, A., Niemi, J. V., & Ketzel, M. (2019). The impact of measures to reduce ambient air PM₁₀ concentrations originating from road dust, evaluated for a street canyon in Helsinki. *Atmospheric Chemistry and Physics*, 19, 11199–11212. <https://doi.org/10.5194/acp-19-11199-2019>
- Thorpe, A., & Harrison, R. M. (2008). Sources and properties of non-exhaust particulate matter from road traffic: A review. *Science of the Total Environment*, 400(1–3), 270–282. doi:10.1016/j.scitotenv.2008.06.007
- Triantafyllou, A., Tolis, E., Diamantopoulos, C., Bartzis, J., & Garas, D. S. (2020). Positive matrix factorization on elemental concentrations of PM₁₀ samples collected in areas within, proximal and far from mining and power station operations in Greece. *Global NEST Journal*, 22(1), 132–142. <https://doi.org/10.30955/gnj.003128>
- Zender-Świercz, E., Galiszewska, B., Telejko, M., & Starzomska, M. (2024). The effect of temperature and humidity of air on the concentration of particulate matter - PM_{2.5} and PM₁₀. *Atmospheric Research*, 312, 107733. <https://doi.org/10.1016/j.atmosres.2024.107733>