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Analysis of Air Quality in Three Slovenian Municipalities During the New Year Holiday Period

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Abstract

Festive fireworks can substantially affect air quality by causing short-term increases in particulate matter (PM) concentrations. This study analysed spatial and temporal PM pollution patterns in three Slovenian municipalities—Novo mesto, Hrastnik, and Jesenice—during the 2025/2026 Christmas–New Year holiday period. Using descriptive statistics, threshold-based peak detection, temporal segmentation, Pearson correlation analysis, and normalized descriptive indicators, the study evaluated $PM_{2.5}$, PM_{10}, relative humidity, and CO_2 levels from late December to mid-January. Results revealed pronounced short-term pollution episodes, with $PM_{2.5}$ peaking at 109 $\mu g/m^3$ in Novo mesto, 128 $\mu g/m^3$ in Hrastnik, and 133 $\mu g/m^3$ in Jesenice. Most peaks occurred during late-night and early-morning hours, although Jesenice showed a more dispersed peak pattern. Fine particles represented the dominant PM fraction, with mean $PM_{2.5}/PM_{10}$ ratios ranging from 0.91 to 0.93. Normalized indicators showed that Jesenice had the highest relative variability and peak-to-mean ratios despite the lowest average PM concentrations. These findings show that holiday-period air-quality assessment should consider not only average concentrations, but also short-term peak intensity, timing, and local pollution profiles.

Keywords: festive fireworks; air quality; particulate matter; health risks

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1. Introduction

Fireworks and festive activities are recognised as short-term sources of particulate matter ($PM_{2.5}$ and PM_{10}), with holiday-period peaks often exceeding typical ambient concentrations several-fold [1–3]. Extreme $PM_{2.5}$ episodes have also been documented during the Chinese New Year, when pyrotechnic activity coincides with dense population activity and other anthropogenic emissions [4]. Such episodes rapidly deteriorate air quality and increase human exposure [5], particularly when low wind speed, temperature inversions and other unfavourable atmospheric conditions reduce dispersion [6]. Fireworks contribute directly through pyrotechnic mixtures containing oxidisers, fuels and metal-based colourants [7].

The health relevance of these short-term increases is substantial. $PM_{2.5}$ and PM_{10} can penetrate the respiratory system and, in the case of fine particles, may enter systemic circulation [8]. Exposure is associated with respiratory and cardiovascular morbidity, increased vulnerability among children and older adults [9], toxicological effects linked to metal-rich firework particles [10], and chronic cardiopulmonary risks when exposure is repeated or prolonged [11].

Although international evidence is extensive, Slovenian data remain limited, especially for smaller municipalities and for short-term winter holiday peaks. This study therefore analyses the magnitude, timing and spatial variability of $PM_{2.5}$ and PM_{10} concentrations during the 2025/2026 Christmas–New Year period in Novo mesto, Hrastnik and Jesenice, with particular attention to relative humidity and the broader holiday-season emission context.

The study is framed as a case study of one winter holiday season and three monitoring locations. It does not aim to represent all Slovenian holiday periods, but to provide location-specific evidence of short-term PM variability during a culturally important period. The research was conducted within the Alpe-Adria Green project on the environmental effects of pyrotechnic activities. The paper is organised into a literature review, methodology, results, discussion, conclusions, and limitations with future research directions.

2. Literature Review

2.1. The Effect of Fireworks as a Source of Particulate Matter

Previous studies consistently report sharp short-term increases in $PM_{2.5}$ and PM_{10} during New Year's Eve and similar festive events, often exceeding background levels and air quality standards [12]. In Mexico, $PM_{2.5}$ increased from below 50 $\mu g/m^3$ to more than 340 $\mu g/m^3$ during a holiday episode [13,14], while studies from China show comparable rapid increases during the Spring Festival followed by post-event decreases [15].

These peaks are mainly associated with fireworks, which emit primary particles and may contribute to secondary aerosol formation, especially under humid and oxidising atmospheric conditions [16]. Reported $PM_{2.5}$ concentrations during such events can reach very high levels, including values up to 471 $\mu g/m^3$, with parallel increases in $PM_{2.5}$, PM_{10} and SO_2 [17]. Low-emission alternatives, including drone-assisted light shows and laser displays, have therefore been proposed as ways to preserve festive practices while reducing PM and noise impacts [18].

Evidence for Slovenia is still comparatively scarce. Pirker et al. [19] reported increases in $PM_{2.5}$, PM_{10}, black carbon, nanoparticles and metals such as aluminium, barium, strontium and copper during New Year's Eve in Ljubljana, confirming fireworks as an important short-term local source. However, PM variability is also shaped by traffic and other seasonal activities [20], which makes smaller-municipality case studies relevant for understanding how firework-related peaks occur within broader winter emission conditions.

2.2. The Effects of Transport and Residential Heating as Sources of Particulate Matter

Transport and residential heating are major anthropogenic contributors to particulate matter. Traffic emissions include exhaust particles as well as non-exhaust particles from brake, tyre and road wear [21]. Traffic-intensive environments are also often associated with elevated noise and PM levels, and recent studies suggest links between traffic-generated noise, particle pollution and dispersion dynamics [22]. During winter, residential heating from biomass, wood and coal further increases ambient and indoor PM, especially under inversions and weak dispersion [23].

The health effects of particles from these sources are well established. Fine particles reach the alveolar region and may enter systemic circulation, inducing oxidative stress

and inflammation [24]. PM exposure is associated with cardiovascular disease, stroke, hypertension, asthma and chronic obstructive pulmonary disease [25], while $PM_{2.5}$ has also been linked to metabolic disorders and carcinogenic risks associated with metals and polycyclic aromatic hydrocarbons [26].

Environmental effects are also significant. Particulate matter influences radiation balance and cloud processes [27], contributes to smog and reduced visibility [28], and can affect ecosystems through deposition on leaves and soils, disruption of photosynthesis, and changes in biogeochemical cycles [29]. Zhang et al. [30] showed that indoor PM in urban households can exceed outdoor levels because of infiltration and domestic activities, while Hime et al. [31] concluded that PM from different sources is consistently associated with adverse respiratory and cardiovascular outcomes. Because no stable hierarchy of source toxicity has been established, reducing total exposure remains a central public health priority [32].

Ecological and chronic-health evidence reinforces this need. PM may exert genotoxic effects on plants and disrupt photosynthesis and protein synthesis [33], reduce photosynthetic rates and stomatal conductance [34], while plants may also act as sinks and bioindicators of PM pollution [35]. Long-term urban PM exposure is associated with cardiovascular disease, hypertension, type 2 diabetes, obesity and cancer [36], with finer particles posing greater systemic risks because of deeper respiratory penetration [37].

2.3. Research Gap

Despite extensive international research, three gaps remain relevant for the present study: limited evidence from smaller or semi-urban municipalities, insufficient attention to intra-day peak timing, and limited integration of fireworks with concurrent winter sources such as transport, heating and local dispersion conditions. Meteorological factors, especially humidity, are often acknowledged, but their role in short-term holiday episodes remains difficult to isolate without broader meteorological datasets.

This study addresses these gaps by comparing $PM_{2.5}$ and PM_{10} in three Slovenian municipalities, identifying peak episodes by time of day, and interpreting the results within a cautious multi-source holiday-season framework. The analysis is descriptive and comparative rather than a full source-apportionment or meteorological modelling study.

An additional gap concerns the limited use of normalized descriptive indicators when comparing short-term particulate matter episodes across locations. Many holiday-period air-quality studies report mean and maximum concentrations, but these values can obscure relative variability when baseline pollution levels differ between municipalities. For this reason, the present study also considers coefficient of variation, peak-to-mean ratio, and the mean $PM_{2.5}/PM_{10}$ ratio as complementary indicators of relative variability, episodic peak intensity, and fine-particle dominance.

2.4. Hypotheses Development

Based on the literature and the identified gaps, the study examines six hypotheses related to holiday-period increases, temporal peak clustering, spatial variability, relative humidity, the broader multi-source winter context, and normalized indicators of particulate matter variability.

H1. *Particulate matter concentrations ($PM_{2.5}$ and PM_{10}) increase during the New Year holiday period compared to baseline levels.*

H2. *Descriptive time-series peak analysis shows that the highest $PM_{2.5}$ and PM_{10} concentrations are concentrated during late-night and early-morning hours in the holiday period.*

H3. *There are observable differences in $PM_{2.5}$ and PM_{10} concentration levels across the municipalities of Novo mesto, Hrastnik, and Jesenice.*

H4. *Higher relative humidity levels are associated with increased $PM_{2.5}$ and PM_{10} concentrations during peak pollution episodes.*

H5. *Holiday-period PM peaks were temporally consistent with the holiday period and may reflect the combined influence of fireworks, heating, traffic, and local dispersion conditions.*

H6. *The three municipalities differ in relative PM variability, peak intensity, and fine-particle dominance when assessed using normalized descriptive indicators, namely the coefficient of variation, peak-to-mean ratio, and mean $PM_{2.5}/PM_{10}$ ratio.*

3. Materials and Methods

Time-series peak detection was conducted descriptively by identifying local maxima exceeding baseline variability thresholds (mean and standard deviation) and analyzing their temporal distribution.

3.1. Study Area and Data Collection Period

Data collection was conducted in three municipalities in Slovenia: Novo mesto, Hrastnik, and Jesenice. The research focused on identifying spatial and temporal patterns of particulate matter during the 2025/2026 Christmas–New Year period. For the municipalities of Novo mesto and Hrastnik, the monitoring period extended from 24 December 2025 to 14 January 2026, while in Jesenice data were gathered from 25 December 2025 to 8 January 2026. These periods were selected to capture fluctuations in air quality associated with Christmas and New Year celebrations.

The selected municipalities differ substantially in their geographical, industrial, and environmental characteristics, enabling a comparative assessment of spatial variability in particulate matter concentrations. Hrastnik is a strongly industrialised area with a long tradition of heavy industry and glass manufacturing, whereas Jesenice is characterised by intensive metallurgical and steel production activities. In contrast, Novo mesto represents a more urbanized and traffic-influenced environment with a different industrial structure. The municipalities also differ in topography, population density, and residential heating characteristics, providing an opportunity to examine how local environmental and anthropogenic factors may influence spatial and temporal variations in air quality during the 2025/2026 Christmas–New Year period. Figure 1 presents the locations of this case study.



Figure 1. Locations for obtaining the data of this case study.

For each municipality, one sensor was installed at a single representative monitoring location, and continuous measurements were taken 24 h per day throughout the study period. Monitoring sites were deliberately selected in central urban areas, in locations where increased human activity and New Year fireworks events were expected to occur. This approach enabled the capture of short-term pollution peaks associated with holiday celebrations and related anthropogenic activities.

3.2. Instrumentation and Measured Parameters

Data was collected using instruments designed for monitoring particulate matter concentrations and microclimatic conditions. Aerosol particle measurements were performed using the Extech VPC260 (Teledyne FLIR LLC, Wilsonville, OR, USA), a 6-channel optical particle counter based on the light-scattering principle. The instrument simultaneously measures particle concentrations in six size fractions (0.3, 0.5, 1.0, 2.5, 5.0, and 10 μm) at a controlled airflow rate of 1.0 L/min provided by an internal pump. The main variables analysed in this study were fine inhalable particles ($PM_{2.5}$) and inhalable particles (PM_{10}), expressed in $\mu g/m^3$. The instrument supports cumulative, differential, and concentration counting modes, with a counting efficiency of 50% at 0.3 μm and 100% for particles larger than 0.5 μm. In addition to particulate matter, the device simultaneously recorded air temperature and relative humidity (RH%), allowing assessment of meteorological influences on particle formation and dispersion. Measurement resolution and operating ranges complied with the manufacturer's specifications, and all data were stored and exported in CSV format via a USB-C connection. Prior to the measurement campaign, the factory calibration was verified, and zero-count checks using the manufacturer's HEPA/zero filter were performed before each sampling cycle. Additional QA/QC procedures included repeated measurements and verification of instrument stability before field deployment.

Microclimatic parameters and carbon dioxide concentrations were monitored using the Kimo KCC 320 (Kimo Instruments, Montpon-Ménestérol, France) multifunctional data logger. The instrument measures air temperature, relative humidity, atmospheric pressure, and CO_2 concentration using capacitive sensors for temperature and humidity, a piezoresistive sensor for atmospheric pressure, and NDIR (non-dispersive infrared) technology for CO_2 measurements. Measurement ranges include −20 to +70 °C for temperature, 0–100% RH for relative humidity, 800–1100 hPa for atmospheric pressure, and 0–5000 ppm for CO_2. The corresponding measurement resolutions are 0.1 °C, 0.1% RH, 1 hPa, and 1 ppm CO_2. According to the manufacturer, measurement uncertainties are ±0.4 °C for temperature, ±2% RH for relative humidity, ±3 hPa for pressure, and ±50 ppm ±3% of the reading for CO_2. The instrument allows storage of up to 2,000,000 measurement points and supports several recording modes. For the Novo mesto region, CO_2 concentrations were monitored in parallel with PM measurements during the same time, although at a different measurement location from the PM sensors. Before deployment, sensor stabilization and operational verification procedures were conducted, and all measurements were performed under non-condensing environmental conditions in accordance with manufacturer recommendations.

3.3. Data Analysis and Statistical Methods

The collected datasets were analysed using Microsoft Excel and Gretl (2025b). These tools were used to perform descriptive statistics, threshold-based peak detection, and correlation analysis. Descriptive statistics included the mean, median, and standard deviation. These were calculated for $PM_{2.5}$, PM_{10}, relative humidity (RH%), and CO_2 concentrations. This helped establish baseline air quality conditions and quantify variability across the observed period. To identify short-term pollution episodes, a threshold-based peak detec-

tion approach was applied. Peak events were defined as observations exceeding baseline variability, i.e., values greater than the mean plus 2 standard deviations (mean + 2SD). The threshold was defined following the empirical rule for normal distribution, which states that approximately 95% of data falls within 2 standard deviations of the mean. This way, we consider the remaining 5% as the outliers or peaks. The ten highest and ten lowest values for each parameter were also extracted. This highlighted extreme conditions and supported comparative analysis across municipalities. This approach enabled the identification of significant pollution spikes linked with festive activities. Temporal analysis examined the distribution of peak values at different times of day. The dataset was segmented into intervals: daytime, evening, and late night/early morning. Daytime was defined as the time between 7 am and 5 pm, evening as the time between 5 pm and 10 pm, and late-night/early-morning as the time between 10 pm and 7 am. This assessed intra-day variability and determined whether elevated particulate matter concentrations were concentrated during specific hours. These hours were of particular interest during the New Year celebrations. To evaluate the influence of meteorological conditions, correlation analysis was performed between relative humidity and particulate matter concentrations. Pearson correlation coefficients assessed the strength and direction of the relationship. This provided insight into the role of atmospheric conditions in the accumulation and dispersion of pollutants.

Subsequently, these findings informed a comparative spatial analysis across the three municipalities (Novo mesto, Hrastnik, and Jesenice). Here, differences in average concentrations, variability, and peak intensities were examined to identify location-specific pollution patterns and to assess the extent of spatial heterogeneity in air quality during the study period.

To ensure methodological consistency with the study objectives, each hypothesis was tested with a specific analytical approach. H1 (increase in PM concentrations during the holiday period) was tested using descriptive statistics comparing baseline and peak values. H2 (temporal concentration of pollution peaks) relied on threshold-based time-series peak detection and temporal segmentation. H3 (spatial differences across municipalities) used comparative analysis of mean values, variability, and extremes across locations. H4 (relationship between relative humidity and PM concentrations) was tested with Pearson correlation analysis between RH% and PM variables. H5 was assessed interpretatively by comparing temporal PM patterns, pollutant behaviour and contextual evidence from the literature. Because traffic volume and residential heating intensity were not directly measured, H5 was not treated as a source-apportionment hypothesis, but as a cautious interpretation of whether the observed PM patterns were consistent with a broader multi-source holiday-season context.

H6 was tested using an exploratory ratio-based descriptive comparison. Three normalized indicators were calculated: coefficient of variation (CV = standard deviation/mean $\times$ 100), peak-to-mean ratio (maximum value/mean value), and mean $PM_{2.5}/PM_{10}$ ratio. These indicators were selected because the municipalities differed in baseline PM concentrations and monitoring duration. CV standardizes variability by the mean, the peak-to-mean ratio expresses the relative intensity of extreme episodes, and the $PM_{2.5}/PM_{10}$ ratio shows the dominance of the fine-particle fraction. Because the observations are time-series measurements and are therefore not fully independent, this comparison was treated as an exploratory descriptive test rather than as a formal inferential between-group test.

4. Results

This section presents the findings in a structured sequence. First, descriptive statistics are used to show average $PM_{2.5}$ and PM_{10} concentrations, extreme observations and

location-specific patterns. Second, threshold-based peak detection identifies short-term exceedance episodes and their timing. Third, correlation analysis examines the relationship between relative humidity and particulate matter. The section then provides a qualitative comparison of municipal PM profiles and, finally, additional normalized indicators that support the comparison of relative variability, peak intensity and fine-particle dominance.

4.1. Descriptive Statistics

The descriptive results show clear differences among the three municipalities. Novo mesto recorded the highest average $PM_{2.5}$ and PM_{10} concentrations, indicating a more persistent particulate matter burden during the monitored period. Hrastnik had lower average values but still experienced a pronounced short-term episode. Jesenice showed the lowest average concentrations, yet individual peaks reached very high values. These findings confirm that average concentrations alone are insufficient for understanding holiday-period exposure.

The timing of the highest values further indicates that PM episodes were structured rather than random. Most $PM_{2.5}$ and PM_{10} peaks occurred during late-night and early-morning hours, which is consistent with the expected timing of holiday activities and reduced nocturnal dispersion. At the same time, several important evening peaks were also observed, especially in Hrastnik and Jesenice. This pattern suggests that local conditions and short-term activities may have influenced PM dynamics differently across the three municipalities.

4.1.1. Novo Mesto

In Novo mesto, the average $PM_{2.5}$ concentration was 19.94 $\mu g/m^3$ and the average PM_{10} concentration was 21.84 $\mu g/m^3$, with standard deviations of 15.44 and 17.05, respectively. The average relative humidity during the observed period was 70.81% (SD = 6.14). The highest $PM_{2.5}$ and PM_{10} values were recorded at the same time, on 9 January 2026 at 22:47:20, when $PM_{2.5}$ reached 109 $\mu g/m^3$ and PM_{10} reached 122 $\mu g/m^3$. Tables 1 and 2 present the ten highest $PM_{2.5}$ and PM_{10} observations.

Table 1 shows that the highest $PM_{2.5}$ values in Novo mesto were concentrated mainly in early to mid-January 2026, particularly during late-night and early-morning hours. Several peak observations coincided with relatively high humidity, but this association should be interpreted cautiously because humidity was only one of several possible influencing factors.

Table 1. The 10 highest $PM_{2.5}$ observations in Novo mesto.

Date	Time	$PM_{2.5\ \mu g/m^3}$	RH%
All time average (24 December to 14 January)	-	19.94	70.81%
Standard deviation	-	15.44	6.14
9 January 2026	22:47:20	109	68.06
10 January 2026	03:17:20	103	76.52
9 January 2026	01:17:20	96	73.72
9 January 2026	19:47:20	81	59.71
10 January 2026	03:47:20	76	76.68
10 January 2026	02:47:20	75	76.25
11 January 2026	04:47:20	73	76.26
10 January 2026	06:47:20	70	77.49
10 January 2026	05:17:20	69	76.62
11 January 2026	01:47:20	68	80.85

Table 2 confirms that the highest PM_{10} observations in Novo mesto occurred at the same times as the highest $PM_{2.5}$ values, with the maximum PM_{10} concentration of 122 $\mu g/m^3$ recorded at 22:47:20 on 9 January 2026. This parallel behaviour suggests that

fine and inhalable particle fractions increased simultaneously during the main late-night pollution episode.

Table 2. The 10 highest PM_{10} observations in Novo mesto.

Date	Time	PM_{10} μg/m³	RH%
All time average (24 December to 14 January)	-	21.84	70.81%
Standard deviation	-	17.05	6.14
9 January 2026	22:47:20	122	68.06
10 January 2026	03:17:20	111	76.52
9 January 2026	01:17:20	108	73.72
9 January 2026	19:47:20	88	59.71
10 January 2026	03:47:20	85	76.68
11 January 2026	01:47:20	85	80.85
11 January 2026	04:47:20	82	76.26
10 January 2026	02:47:20	80	76.25
10 January 2026	06:47:20	77	77.49
11 January 2026	01:17:20	77	78.74

The lowest $PM_{2.5}$ and PM_{10} values in Novo mesto occurred at the same observation times, which is consistent with the close relationship between the two particle fractions. Table 3 shows that several observations reached 0 μg/m³, especially on 24 December 2025 and again around midday on 2 and 3 January 2026.

Table 3. The 10 lowest $PM_{2.5}$ and PM_{10} observations in Novo mesto.

Date	Time	$PM_{2.5}$ μg/m³	PM_{10} μg/m³	RH%
24 December 2025	19:06:10	0	0	55.04
24 December 2025	20:06:10	0	0	48.89
24 December 2025	20:36:10	0	0	52.75
2 January 2026	13:47:20	0	0	75.37
2 January 2026	14:17:20	0	0	68.84
3 January 2026	11:47:20	0	0	79.98
25 December 2025	00:47:20	1	1	74.27
25 December 2025	11:17:20	1	1	80.08
2 January 2026	14:47:20	1	1	68.14
3 January 2026	11:17:20	1	1	82.55

The zero or near-zero observations indicate short intervals of very low measured particulate matter. However, these lows occurred at different times of day and under varying RH% values, so they should not be interpreted as evidence of a single explanatory mechanism. Rather, they illustrate the marked short-term variability of PM levels during the monitoring period.

CO_2 was also monitored in the Novo mesto area. From 24 December 2025 to 14 January 2026, the average CO_2 concentration was approximately 386.72 ppm, with a median of 383 ppm. The lowest recorded value was 295 ppm on 12 January 2026, while the highest value was 491 ppm on 31 December 2025. Tables 4 and 5 show the ten lowest and ten highest CO_2 observations.

Table 4 shows that the lowest CO_2 concentrations occurred on different dates and times across the monitoring period, with the minimum value of 295 ppm recorded on 12 January 2026. These values provide the lower boundary of the observed CO_2 variability, but they should not be interpreted together with PM minima because CO_2 and PM were measured at different locations.

Table 4. The 10 lowest ppm observations.

Date	Time	ppm
All time average (24 December to 14 January)	-	386.72
Standard deviation	-	27.97
12 January 2026	01:46	295
3 January 2026	04:46	316
8 January 2026	15:46	316
5 January 2026	15:46	321
14 January 2026	06:46	328
5 January 2026	03:46	329
5 January 2026	16:46	330
2 January 2026	12:46	332
9 January 2026	19:46	335
3 January 2026	16:46	336

Table 5. The 10 highest ppm observations.

Date	Time	ppm
31 December 2025	09:46	491
30 December 2025	08:46	478
30 December 2025	10:46	477
27 December 2025	18:46	463
7 January 2026	08:46	463
29 December 2025	22:46	459
30 December 2025	09:46	459
28 December 2025	08:46	457
30 December 2025	21:46	457
24 December 2025	09:46	456

Table 5 indicates that the highest CO_2 values occurred mainly around the end of December, including 30 and 31 December 2025. These observations may reflect holiday-period activity, but they cannot be directly linked to $PM_{2.5}$ and PM_{10} peaks because CO_2 and PM were measured at different locations. For this reason, CO_2 results are treated as contextual information rather than as direct evidence of particulate matter sources.

Because CO_2 and particulate matter were not measured at the same location, no direct temporal or spatial linkage between CO_2 concentrations and $PM_{2.5}/PM_{10}$ peaks can be inferred from these data.

4.1.2. Hrastnik

In Hrastnik, the average $PM_{2.5}$ concentration was 13.86 $\mu g/m^3$ and the average PM_{10} concentration was 15.12 $\mu g/m^3$, with standard deviations of 11.04 and 12.23, respectively. These averages were lower than those observed in Novo mesto, while the close difference between $PM_{2.5}$ and PM_{10} again indicates that fine particles represented a large share of inhalable particulate matter. The average RH% was 67.60% (SD = 9.83). The highest $PM_{2.5}$ and PM_{10} values occurred on 10 January 2026 at 18:06:28, when $PM_{2.5}$ reached 128 $\mu g/m^3$ and PM_{10} reached 146 $\mu g/m^3$.

Table 6 shows that the highest $PM_{2.5}$ episode in Hrastnik reached 128 $\mu g/m^3$ on 10 January 2026 at 18:06:28, substantially above the average of 13.86 $\mu g/m^3$. Most other high $PM_{2.5}$ values occurred during late-night or early-morning hours, indicating a predominantly nocturnal peak pattern with one pronounced evening outlier.

Table 6. The 10 highest $PM_{2.5}$ observations in Hrastnik.

Date	Time	$PM_{2.5}$ μg/m³	RH%
All time average (24 December to 14 January)	-	13.86	67.60
Standard deviation	-	11.04	9.83
10 January 2026	18:06:28	128	73.02
28 December 2025	03:36:28	78	73.97
28 December 2025	03:06:28	71	71.87
30 December 2025	05:06:28	71	72.14
11 January 2026	02:36:28	71	74.37
11 January 2026	02:06:28	69	74.42
30 December 2025	05:36:28	57	72.33
30 December 2025	04:36:28	56	72.73
30 December 2025	00:36:28	51	68.00
30 December 2025	03:36:28	49	72.20

Table 7 confirms that the highest PM_{10} observations in Hrastnik largely coincided with the highest $PM_{2.5}$ observations. Most high values occurred during late-night or early-morning hours, particularly on 28 and 30 December 2025, but the absolute maximum occurred in the evening on 10 January 2026. This indicates a generally nocturnal peak pattern with one strong evening episode.

Table 7. The 10 highest PM_{10} observations in Hrastnik.

Date	Time	PM_{10} μg/m³	RH%
All time average (24 December to 14 January)	-	15.12	67.60
Standard deviation	-	12.23	9.83
10 January 2026	18:06:28	146	73.02
28 December 2025	03:36:28	87	73.97
28 December 2025	03:06:28	82	71.87
11 January 2026	02:36:28	80	74.37
30 December 2025	05:06:28	79	72.14
11 January 2026	02:06:28	76	74.42
30 December 2025	05:36:28	63	72.33
30 December 2025	04:36:28	62	72.73
30 December 2025	00:36:28	56	68.00
30 December 2025	04:06:28	56	72.96

Relative humidity during the highest Hrastnik observations was relatively stable, mostly around the low 70% range. In contrast, the lowest PM observations in Tables 8 and 9 occurred under more varied RH% conditions. This again suggests that humidity alone cannot explain the observed PM pattern.

Table 8. The 10 lowest $PM_{2.5}$ observations in Hrastnik.

Date	Time	$PM_{2.5}$ μg/m³	RH%
24 December 2025	23:06:28	0	76.16
24 December 2025	20:06:28	0	57.58
24 December 2025	20:36:28	0	66.70
24 December 2025	22:06:28	0	73.50
25 December 2025	00:06:28	0	73.33
25 December 2025	02:06:28	0	73.63
24 December 2025	21:06:28	1	68.45
24 December 2025	21:36:28	1	71.72
25 December 2025	00:36:28	1	73.48
25 December 2025	01:06:28	1	74.03

Table 8 indicates that the lowest $PM_{2.5}$ values in Hrastnik were concentrated on 24 and 25 December 2025, when several observations reached 0 $\mu g/m^3$. This clustering suggests a short period of very low fine-particle concentrations at the beginning of the monitoring interval, before later holiday-period peaks emerged.

Table 9. The 10 lowest PM_{10} observations in Hrastnik.

Date	Time	$PM_{10\ \mu g/m^3}$	RH%
24 December 2025	20:06:28	0	57.58
24 December 2025	20:36:28	0	66.70
24 December 2025	22:06:28	0	73.50
25 December 2025	00:06:28	0	73.33
25 December 2025	02:06:28	0	73.63
24 December 2025	23:06:28	1	76.16
24 December 2025	21:06:28	1	68.45
24 December 2025	21:36:28	1	71.72
25 December 2025	00:36:28	1	73.48
25 December 2025	01:06:28	1	74.03

Table 9 shows that the lowest PM_{10} values in Hrastnik were tightly clustered on 24 and 25 December 2025, similar to the pattern seen for $PM_{2.5}$. These low values occurred mainly between the evening and early-night hours. They may reflect temporary reductions in local activity or favourable short-term dispersion conditions, but the available data do not allow a firm source-based explanation.

4.1.3. Jesenice

Jesenice showed the lowest average particulate matter concentrations among the three municipalities. The average $PM_{2.5}$ concentration was 7.86 $\mu g/m^3$ (SD = 10.95), while the average PM_{10} concentration was 8.44 $\mu g/m^3$ (SD = 11.71). Despite these low averages, the municipality recorded very high short-term peaks. This contrast makes Jesenice an important case for distinguishing between average pollution burden and episodic exposure risk. Table 10 presents the ten highest $PM_{2.5}$ and PM_{10} observations.

Table 10. The 10 highest $PM_{2.5}$ and PM_{10} observations in Jesenice.

Date	Time	$PM_{2.5\ \mu g/m^3}$	$PM_{10\ \mu g/m^3}$	RH%
All time average (25 December to 8 January)	-	7.86	8.44	67.20
Standard deviation	-	10.95	11.71	5.82
29 December 2025	18:10:24	133	143	70.02
8 January 2026	00:40:24	123	133	71.23
7 January 2026	19:10:24	83	88	65.57
5 January 2026	16:10:24	71	73	60.22
2 January 2026	18:40:24	60	64	73.04
31 December 2025	22:40:24	57	64	65.77
2 January 2026	18:10:24	55	57	73.58
1 January 2026	17:40:24	49	52	57.26
5 January 2026	01:10:24	48	52	69.98
6 January 2026	14:10:24	47	50	76.62

Table 10 shows that the highest $PM_{2.5}$ and PM_{10} values in Jesenice were closely aligned. The absolute maximum occurred on 29 December 2025 at 18:10:24, when $PM_{2.5}$ reached 133 $\mu g/m^3$ and PM_{10} reached 143 $\mu g/m^3$. Additional high values were observed around the New Year period and during the first week of January. This pattern indicates that,

although average PM concentrations were comparatively low, short-term exposure episodes could still be substantial.

The average RH% in Jesenice was 67.20%, which was close to the average value observed in Hrastnik and slightly lower than in Novo mesto. Some high PM observations occurred under RH% values close to the seasonal average, while others occurred under lower or higher humidity conditions. This reinforces the need to interpret humidity as one contextual factor rather than as a sufficient explanation for PM variability.

Appendix A presents the lowest $PM_{2.5}$ and PM_{10} observations for Jesenice. Unlike Novo mesto and Hrastnik, Jesenice included a larger number of zero observations: 37 for $PM_{2.5}$ and 30 for PM_{10}. These values suggest that the monitored location experienced several periods with very low measured particulate matter, especially around late-night hours between 27 and 29 December and again on 6 and 7 January.

Taken together, the Jesenice results point to a low-baseline/high-peak profile. For much of the monitoring period, particulate matter concentrations remained low, but individual episodes produced marked short-term increases. This finding is important because it shows that locations with lower average PM levels may still experience relevant short-term exposure risks during holiday periods.

4.2. Threshold-Based Peak Detection

Threshold-based peak detection was applied using the mean + 2SD criterion for $PM_{2.5}$ and PM_{10} at each location. This approach identified observations that substantially exceeded local baseline variability. As shown in Table 11, Novo mesto had the highest thresholds for both $PM_{2.5}$ (50.81 $\mu g/m^3$) and PM_{10} (55.94 $\mu g/m^3$), as well as the largest number of threshold exceedances.

Table 11. Thresholds and counts of values for all three locations.

Place	Novo Mesto	Hrastnik	Jesenice
Threshold for $PM_{2.5\ \mu g/m^3}$	50.81	35.93	29.75
Count of values above the threshold for $PM_{2.5\ \mu g/m^3}$	52	43	24
Threshold for $PM_{10\ \mu g/m^3}$	55.94	39.58	31.87
Count of values above the threshold for $PM_{10\ \mu g/m^3}$	53	39	24

Table 11 shows that Novo mesto had the highest threshold values and the largest number of observations above the $PM_{2.5}$ and PM_{10} thresholds. Hrastnik followed, while Jesenice had the lowest thresholds and fewer exceedances, indicating clear differences in exceedance frequency and baseline-adjusted variability across the three municipalities.

Figures 2–4 illustrate the temporal distribution of $PM_{2.5}$ and PM_{10} peaks in the three municipalities. Although the two particle fractions followed similar patterns, $PM_{2.5}$ values remained below PM_{10} values, as expected. Their close movement during many peak episodes suggests that fine particles formed a substantial part of total inhalable particulate matter. In Novo mesto, the largest peak occurred at 22:47:20, and most exceedances were concentrated during late-night and early-morning hours: 36 of 52 $PM_{2.5}$ peaks and 39 of 53 PM_{10} peaks occurred in this period.

In Hrastnik, the calculated thresholds were 35.93 $\mu g/m^3$ for $PM_{2.5}$ and 39.58 $\mu g/m^3$ for PM_{10}. Figure 3 shows fewer exceedance episodes than in Novo mesto, but one very pronounced evening peak at 18:06:28. Nevertheless, the overall temporal pattern remained predominantly nocturnal: 33 of 43 $PM_{2.5}$ peaks and 34 of 39 PM_{10} peaks occurred during the late-night/early-morning interval.

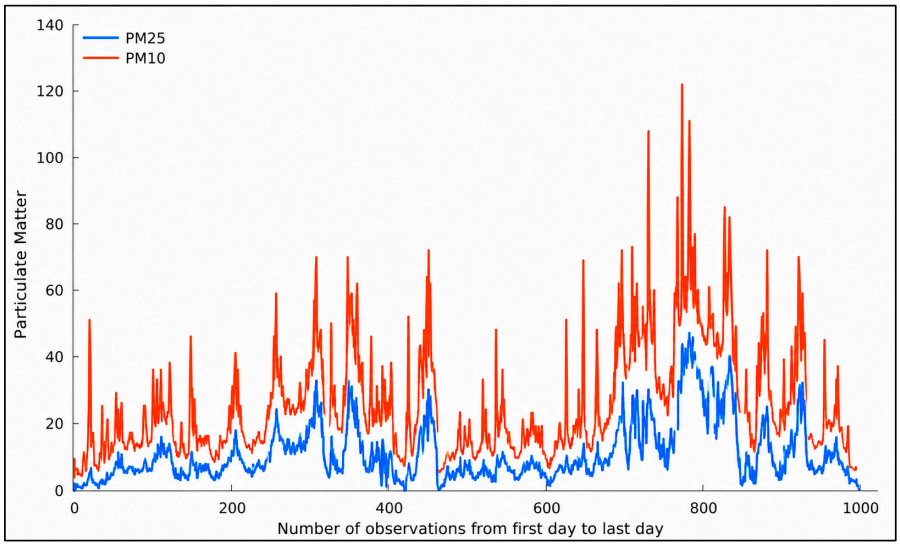


Figure 2. All-time $PM_{2.5}$ and PM_{10} peaks in Novo mesto.

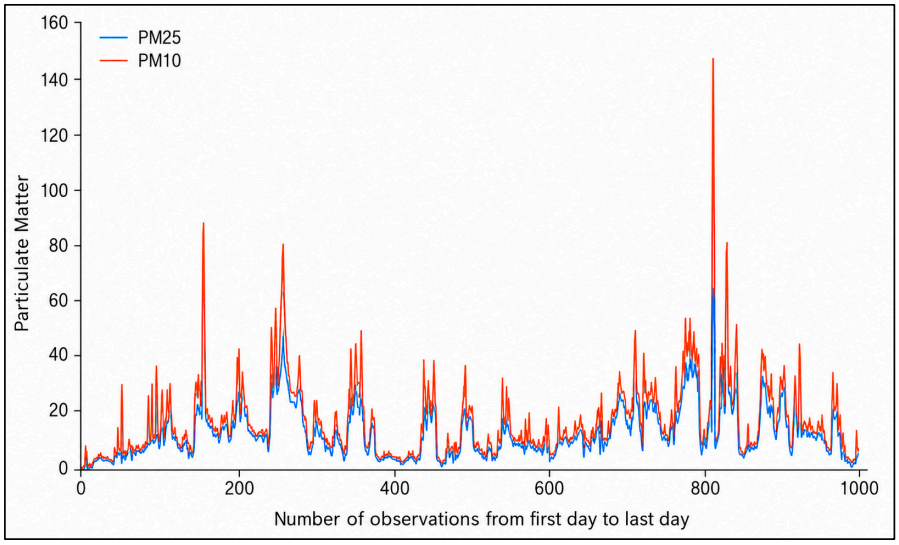


Figure 3. All-time $PM_{2.5}$ and PM_{10} peaks in Hrastnik.

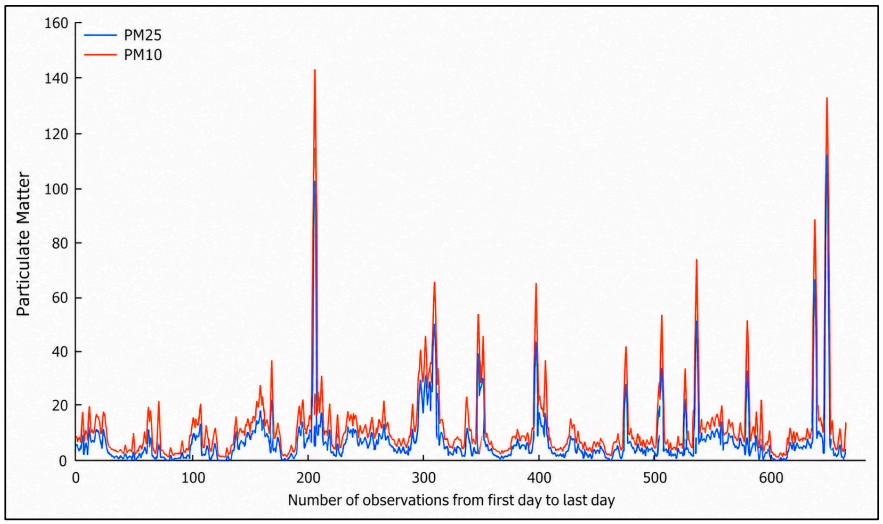


Figure 4. All-time $PM_{2.5}$ and PM_{10} peaks in Jesenice.

In Jesenice, the thresholds were lower, at 29.75 μg/m^3 for $PM_{2.5}$ and 31.87 μg/m^3 for PM_{10}, reflecting the lower average concentrations at this location. Figure 4 shows a more dispersed temporal pattern than in Novo mesto and Hrastnik. The two largest peaks occurred in the evening and shortly after midnight, while the exceedances were distributed across all three time intervals: 8 in the late-night/early-morning period, 7 during the daytime, and 9 in the evening. This distribution suggests that peak timing in Jesenice was less closely tied to the late-night pattern observed in the other two municipalities.

Although most $PM_{2.5}$ and PM_{10} peaks were concentrated during late-night and early-morning hours, the absolute maximum values in Hrastnik and Jesenice occurred in the evening, at 18:06 and 18:10, respectively. These deviations suggest that not all peak pollution episodes followed the typical midnight-related New Year pattern. A possible explanation is that localised evening activities, early celebrations, residential heating, traffic-related emissions, or specific short-term local conditions contributed to these peaks. However, because the present study did not include direct observations of fireworks use, traffic intensity, residential heating activity, wind speed, or local event records, these evening peaks cannot be attributed to a specific source with certainty. Sensor anomalies also cannot be fully excluded, although the simultaneous increase in both $PM_{2.5}$ and PM_{10} suggests that these observations may reflect real short-term pollution episodes rather than isolated measurement noise. Future studies should combine particulate matter monitoring with meteorological data, local activity logs, and source-specific tracers to better explain such deviations.

4.3. Correlation Analysis

The relationship between $PM_{2.5}/PM_{10}$ and relative humidity (RH%) was examined separately for each municipality using Pearson correlation coefficients (Table 12). The purpose of this analysis was to assess whether higher humidity coincided with higher particulate matter concentrations during the monitored period.

Table 12. Pearson correlation coefficient between $PM_{2.5}/PM_{10}$ and RH%.

Place	Novo Mesto	Hrastnik	Jesenice
Pearson correlation coefficient ($PM_{2.5}$/RH%)	0.0548	0.1046	0.0452
Pearson correlation coefficient (PM_{10}/RH%)	0.0593	0.1028	0.0425

The correlations between relative humidity and particulate matter were weak to negligible in all three municipalities. The highest values were observed in Hrastnik, at approximately 0.10 for both $PM_{2.5}$ and PM_{10}, while the lowest values were observed in Jesenice, at approximately 0.04. These results indicate that RH% alone explained very little of the observed PM variability. Other factors, including emissions, local activity patterns and meteorological dispersion conditions, were therefore likely important.

4.4. Qualitative Comparative Results Across the Three Municipalities

This subsection provides a structured qualitative comparison of the observed quantitative monitoring patterns (Table 13). It does not represent a separate interview-, survey- or ethnography-based qualitative study. Instead, the purpose is to describe how the municipalities differed in their overall PM profiles, including average burden, peak behaviour, temporal distribution and local environmental context. This comparison helps translate the numerical findings into location-specific air-quality profiles.

Table 13. Qualitative comparative results of particulate matter profiles across the three municipalities.

Municipality	Observed Quantitative Pattern	Qualitative PM Profile	Main Interpretation
Novo mesto	Highest average $PM_{2.5}/PM_{10}$ and most threshold exceedances	Persistent short-term PM variability	Repeated increases indicate a recurrent holiday-period burden.
Hrastnik	Lower averages, but one very pronounced PM peak	Episodic pollution profile	Generally lower PM levels with sudden short-term deterioration.
Jesenice	Lowest averages, but highest absolute PM peak values	Low-baseline/high-peak vulnerability	Low mean values do not exclude relevant short-term exposure risk.

Novo mesto represents the most persistent particulate matter profile among the three observed municipalities. The results show that Novo mesto had the highest average $PM_{2.5}$ and PM_{10} concentrations and the largest number of observations above the threshold. Qualitatively, this indicates that air-quality deterioration in Novo mesto was not limited to one isolated event, but appeared as repeated short-term increases during the monitoring campaign. This pattern may reflect the combined influence of the urban setting, traffic-related activity, holiday mobility, residential heating, fireworks use, and local winter dispersion conditions. However, these explanations remain contextual because direct data on traffic intensity, heating activity, wind speed, wind direction, atmospheric stability, and chemical composition of particles were not available.

Hrastnik showed a different qualitative profile. Although its average $PM_{2.5}$ and PM_{10} concentrations were lower than those observed in Novo mesto, the municipality recorded a very pronounced short-term peak. This suggests that Hrastnik was less characterised by persistent particulate matter burden and more by episodic deterioration of air quality. In practical terms, this means that the general pollution level may remain moderate for much of the observed period, while individual events can produce substantial short-term exposure. The industrial background of Hrastnik, local settlement structure, residential heating, and restricted winter dispersion conditions may have contributed to this pattern. Nevertheless, the present data do not allow a clear distinction between fireworks-related emissions, industrial influence, traffic activity, heating emissions, and meteorological accumulation.

Jesenice displayed the most contrasting profile. It had the lowest average $PM_{2.5}$ and PM_{10} concentrations, but also the highest absolute PM peak values among the three municipalities. This is an important qualitative finding because it shows that average concentrations alone may underestimate short-term exposure risk. Jesenice can therefore be interpreted as a low-baseline but high-peak vulnerability location. The air was comparatively less burdened during much of the observed period, yet individual episodes reached very high values. This suggests that air-quality assessment during festive periods should not rely only on mean concentrations, but should also consider maximum values, exceedance intensity, and the timing of pollution episodes.

The comparison also shows that the municipalities differed not only in the magnitude of $PM_{2.5}$ and PM_{10} concentrations, but also in the type of pollution dynamics. Novo mesto showed recurrent and more persistent short-term variability; Hrastnik showed a more episodic profile with a strong isolated deterioration; and Jesenice showed lower baseline concentrations but greater vulnerability to sharp short-term peaks. These qualitative differences are relevant for local air-quality management. In Novo mesto, measures should focus on reducing repeated short-term increases and cumulative holiday-period exposure. In Hrastnik, priority should be given to identifying and preventing specific high-intensity episodes. In Jesenice, monitoring strategies should not rely only on average values, because occasional peaks may still represent relevant short-term exposure risks.

These qualitative comparative results support H3 by demonstrating that the three municipalities differed not only in average $PM_{2.5}$ and PM_{10} levels, but also in their overall

pollution profiles. They also support a cautious interpretation of H5, because the observed patterns are more consistent with a multi-source winter holiday context than with a single-source explanation. However, because detailed meteorological parameters, traffic counts, residential heating data, and chemical source markers were not available, these findings should be interpreted as descriptive and exploratory rather than as definitive source attribution.

4.5. Additional Comparative Indicators of PM Variability

To strengthen the comparison across municipalities and to test H6, three normalized descriptive indicators were calculated from the reported means, standard deviations and maximum values (Table 14). The coefficient of variation describes variability relative to the mean, the peak-to-mean ratio shows the intensity of the highest episode compared with the average level, and the $PM_{2.5}/PM_{10}$ ratio indicates the dominance of fine particles within the inhalable particulate fraction.

Table 14. Additional comparative indicators of particulate matter variability across the three municipalities.

Municipality	CV $PM_{2.5}/PM_{10}$ (%)	Peak-to-Mean Ratio $PM_{2.5}/PM_{10}$	Mean $PM_{2.5}/PM_{10}$ Ratio	Main Implication
Novo mesto	77.4/78.1	5.47/5.59	0.91	Highest average burden with repeated short-term variability.
Hrastnik	79.7/80.9	9.24/9.66	0.92	Moderate baseline levels but stronger episodic peak intensity.
Jesenice	139.3/138.7	16.92/16.94	0.93	Lowest baseline levels but the greatest relative variability and peak vulnerability.

The additional indicators support H6 and clarify how the municipalities differed beyond their average PM concentrations. Novo mesto had the highest average $PM_{2.5}$ and PM_{10} concentrations, but lower relative variability and lower peak-to-mean ratios than Hrastnik and Jesenice. Jesenice had the highest CV values and peak-to-mean ratios, showing that its low average PM levels were accompanied by the strongest relative episodic increases. Hrastnik occupied an intermediate position. Across all three municipalities, the mean $PM_{2.5}/PM_{10}$ ratio remained high (0.91–0.93), confirming the dominance of fine particles during the observed period.

5. Discussion

The results show that the 2025/2026 Christmas–New Year period was associated with short-term $PM_{2.5}$ and PM_{10} increases in all three municipalities. This finding is consistent with earlier Slovenian evidence from Ljubljana, where New Year's Eve fireworks were associated with increases in $PM_{2.5}$, PM_{10}, black carbon, nanoparticles and metal markers [19]. It also agrees with international evidence from countries such as China and Mexico, where festive events have been linked to rapid but short-lived deterioration in air quality [38,39].

The temporal pattern of the peaks indicates that the highest values occurred mainly during late-night and early-morning hours. This timing is compatible with firework activity and reduced nocturnal dispersion. However, the results should not be interpreted as direct source apportionment. Transport and residential heating are recognised contributors to winter PM pollution [40], while meteorological conditions such as humidity, inversions, weak mixing and low wind speed can increase near-surface accumulation [41]. Because wind, precipitation, boundary-layer height and source-specific chemical markers were not included, the contribution of each source cannot be quantified.

The dominance of $PM_{2.5}$ within total PM_{10} is relevant for public health. Firework-related particles often fall within the fine fraction [42], which can penetrate deeply into the lungs and may enter the bloodstream [43]. This exposure pathway is associated with cardiovascular disease, chronic respiratory conditions and inflammatory responses [44], with particular concern for children, older adults and other vulnerable groups [45].

The hypotheses were evaluated cautiously and in line with the descriptive design of the study. H1 is supported because all municipalities showed substantial $PM_{2.5}$ and PM_{10} peaks above baseline values, consistent with festive-period research [46]. H2 is supported because most peaks clustered in late-night and early-morning periods, in line with literature on nighttime pyrotechnic emissions and reduced atmospheric mixing [47]. H3 is partially supported because the municipalities differed in average levels, variability and peak intensity, although all recorded short-term episodes. H4 is only partly supported because higher RH% sometimes coincided with peaks, but the correlation analysis shows that humidity alone cannot explain PM variability [48].

H5 is also only partially supported. The observed patterns are consistent with a multi-source holiday-season context involving fireworks, heating, mobility and local dispersion conditions. Nevertheless, direct measurements of traffic volume, residential heating intensity, wind and chemical source markers were not available. The findings therefore provide descriptive evidence of short-term holiday-period pollution dynamics rather than a quantitative separation of emission sources.

H6 is supported by the normalized descriptive indicators. The coefficient of variation and peak-to-mean ratios show that the municipalities differed not only in mean pollution levels, but also in relative variability and episodic peak intensity. Novo mesto had the highest mean PM burden, whereas Jesenice had the strongest relative variability, with CV values of 139.3% for $PM_{2.5}$ and 138.7% for PM_{10} and peak-to-mean ratios of 16.92 and 16.94, respectively. This supports the low-baseline/high-peak vulnerability profile identified in the qualitative comparison. The consistently high $PM_{2.5}/PM_{10}$ ratios across municipalities (0.91–0.93) further indicate that fine particles dominated the observed inhalable particulate matter.

From an applied perspective, the findings support targeted, proportionate measures during predictable holiday episodes. Municipalities could combine short-term public advisories, real-time PM communication, time-limited restrictions on private fireworks and gradual replacement of high-emission pyrotechnics with lower-emission celebration formats [49]. Such measures would be most useful if adapted to the local profile: recurrent exposure in Novo mesto, episodic high-intensity peaks in Hrastnik and low-baseline/high-peak vulnerability in Jesenice.

6. Conclusions

This study examined short-term $PM_{2.5}$ and PM_{10} variability during the 2025/2026 New Year holiday period in Novo mesto, Hrastnik and Jesenice. All three municipalities experienced distinct short-term pollution episodes, with maximum $PM_{2.5}$ concentrations of 109 $\mu g/m^3$ in Novo mesto, 128 $\mu g/m^3$ in Hrastnik and 133 $\mu g/m^3$ in Jesenice. Peaks occurred most often during late-night and early-morning periods, although Jesenice showed a more dispersed temporal pattern. Fine particles represented the dominant fraction of inhalable particulate matter.

The findings suggest that New Year holiday activities can temporarily worsen air quality even in smaller municipalities. At the same time, the observed peaks should not be attributed exclusively to fireworks, because they occurred within a broader winter context that also included residential heating, local mobility and potentially unfavourable dispersion conditions. Relative humidity alone was not a sufficient explanatory factor,

and the absence of wind, precipitation, temperature-profile and atmospheric-stability data limits meteorological interpretation.

For local air-quality management, the results point to the value of short-term monitoring, targeted public-health warnings and proportionate firework-management measures during high-risk periods. Lower-emission alternatives, including drone light shows and laser displays, should be further considered as culturally acceptable options for reducing short-term PM exposure while preserving public celebrations.

Limitations and Future Research Directions

Several limitations should be considered when interpreting the results. The monitoring campaign covered only one winter holiday season and three municipality-level locations, so the findings should be understood as case-study evidence rather than generalisable national estimates. The study focused primarily on $PM_{2.5}$ and PM_{10} and did not include detailed physicochemical, mineralogical, elemental or organic-compound analyses of particles. As a result, the toxicity profile, particle morphology and specific firework-related markers could not be determined. Traffic intensity, residential heating activity, environmental noise and other anthropogenic sources were also not directly monitored, which prevented precise source apportionment.

A specific limitation concerns the restricted use of meteorological parameters. Although relative humidity was included, other dominant meteorological drivers of pollutant variability were not analysed in sufficient detail. Wind speed and wind direction influence horizontal transport and dispersion; precipitation affects wet deposition and particle removal; temperature, atmospheric stability and boundary-layer height determine vertical mixing; and temperature inversions can trap pollutants near the surface. Without these parameters, the study can describe co-occurrence between PM peaks and observed RH%, but it cannot fully explain whether peaks resulted primarily from emissions, reduced dispersion, hygroscopic particle growth or regional transport.

CO_2 measurements were available only for the Novo mesto area and at a different site from the PM sensors. These data therefore provide contextual information only and cannot be used to infer direct temporal or spatial relationships between CO_2 and particulate matter. In addition, the use of one representative monitoring location per municipality limits the ability to capture within-city spatial gradients, micro-location effects and differences between residential, traffic-influenced and open public areas.

Future research should move beyond single-location, single-season monitoring. Longer multi-season campaigns, more monitoring points within each municipality, and co-located PM, gaseous-pollutant and meteorological measurements would provide a stronger evidence base. Future studies should integrate wind, precipitation, temperature, pressure, atmospheric stability and boundary-layer indicators with PM data, preferably through local meteorological stations or dispersion modelling. Chemical source markers, elemental and mineralogical analyses, particle morphology, size-distribution assessment, traffic indicators, residential-heating indicators and source-apportionment modelling would further help distinguish between fireworks, heating, traffic and meteorological accumulation processes.

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Abbreviations

The following abbreviations are used in this manuscript:

PM	Particulate Matter
RH	Relative Humidity
DNA	Deoxyribonucleic Acid
CO_2	Carbon Dioxide
PM_{10}	Particulate Matter with a Diameter Of 10 Micrometres or Less
$PM_{2.5}$	Particulate Matter with a Diameter of 2.5 Micrometres or Less

Appendix A

Table A1 confirms that Jesenice had repeated observations with 0 $\mu g/m^3$ for both $PM_{2.5}$ and PM_{10}, particularly during late-night periods. These low values support the interpretation that Jesenice had a low baseline particulate burden despite the occurrence of occasional high peaks during the monitored period.

Table A1. The 38 lowest $PM_{2.5}$ and PM_{10} amounts for Jesenice.

Date	Time	$PM_{2.5}$	PM_{10}	RH%
26 December 2025	11:40:24	0	0	53.01
26 December 2025	12:40:24	0	0	54.79
27 December 2025	02:40:24	0	0	73.76
27 December 2025	03:10:24	0	0	73.39
27 December 2025	05:10:24	0	0	74.39
27 December 2025	21:10:24	0	0	66.60
27 December 2025	21:40:24	0	0	66.80
28 December 2025	00:40:24	0	0	67.35
28 December 2025	01:10:24	0	0	67.67
28 December 2025	01:40:24	0	0	67.41
28 December 2025	02:10:24	0	0	62.54
28 December 2025	02:40:24	0	0	64.40
28 December 2025	03:10:24	0	0	63.61
28 December 2025	03:40:24	0	0	62.10
28 December 2025	04:10:24	0	0	62.45

Table A1. *Cont.*

Date	Time	$PM_{2.5}$	PM_{10}	RH%
28 December 2025	05:10:24	0	0	62.16
28 December 2025	05:40:24	0	0	64.11
28 December 2025	06:10:24	0	0	64.86
29 December 2025	04:40:24	0	0	75.07
29 December 2025	05:40:24	0	0	72.92
29 December 2025	06:40:24	0	0	68.36
4 January 2026	03:10:24	0	0	60.95
6 January 2026	19:10:24	0	0	64.46
6 January 2026	20:40:24	0	0	68.00
7 January 2026	02:10:24	0	0	63.99
7 January 2026	02:40:24	0	0	60.12
7 January 2026	03:10:24	0	0	62,09
7 January 2026	03:40:24	0	0	65.28
7 January 2026	05:10:24	0	0	65.73
7 January 2026	06:10:24	0	0	61.71
26 December 2025	13:10:24	0	1	55.69
27 December 2025	03:40:24	0	1	74.27
29 December 2025	05:10:24	0	1	73.62
29 December 2025	06:10:24	0	1	72.07
29 December 2025	07:10:24	0	1	70.15
4 January 2026	02:10:24	0	1	62.71
6 January 2026	21:10:24	0	1	68.15
26 December 2025	11:40:24	0	0	53.01
26 December 2025	12:40:24	0	0	54.79
27 December 2025	02:40:24	0	0	73.76
27 December 2025	03:10:24	0	0	73.39
27 December 2025	05:10:24	0	0	74.39
27 December 2025	21:10:24	0	0	66.60
27 December 2025	21:40:24	0	0	66.80
28 December 2025	00:40:24	0	0	67.35
28 December 2025	01:10:24	0	0	67.67
28 December 2025	01:40:24	0	0	67.41
28 December 2025	02:10:24	0	0	62.54
28 December 2025	02:40:24	0	0	64.40
28 December 2025	03:10:24	0	0	63.61
28 December 2025	03:40:24	0	0	62.10
28 December 2025	04:10:24	0	0	62.45
28 December 2025	05:10:24	0	0	62.16
28 December 2025	05:40:24	0	0	64.11
28 December 2025	06:10:24	0	0	64.86
29 December 2025	04:40:24	0	0	75.07
29 December 2025	05:40:24	0	0	72.92
29 December 2025	06:40:24	0	0	68.36
4 January 2026	03:10:24	0	0	60.95
6 January 2026	19:10:24	0	0	64.46
6 January 2026	20:40:24	0	0	68.00
7 January 2026	02:10:24	0	0	63.99
7 January 2026	02:40:24	0	0	60.12
7 January 2026	03:10:24	0	0	62.09
7 January 2026	03:40:24	0	0	65.28
7 January 2026	05:10:24	0	0	65.73
7 January 2026	06:10:24	0	0	61.71
26 December 2025	13:10:24	0	1	55.69
27 December 2025	03:40:24	0	1	74.27

Table A1. *Cont.*

Date	Time	$PM_{2.5}$	PM_{10}	RH%
29 December 2025	05:10:24	0	1	73.62
29 December 2025	06:10:24	0	1	72.07
29 December 2025	07:10:24	0	1	70.15
4 January 2026	02:10:24	0	1	62.71
6 January 2026	21:10:24	0	1	68.15
26 December 2025	05:40:21	1	1	73.44

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