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VARIABILITY AND TRENDS OF PM CONCENTRATIONS NEAR BUCHAREST IN RELATION TO EUROPEAN AIR QUALITY STANDARDS

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This study examines the temporal variability of PM_1, $PM_{2.5}$, and PM_{10} concentrations (2020–2024) to assess compliance with the upcoming EU air quality standard. Seasonal, diurnal, and weekly trends reveal increased PM levels in winter due to heating and distinct peaks linked to traffic. A regulatory analysis highlights exceedances of daily and annual thresholds, emphasizing challenges in meeting 2030 targets.

Keywords: particulate matter, air quality, EU Directive, variability and trend

1. Introduction

Bucharest, the largest urban area in Romania, has experienced substantial growth and development in recent years [1] accompanied by the expansion of its peri-urban areas [2], such as Măgurele. The rapid urbanization and increased industrial and residential activities in these areas have contributed to changes in local air quality, driven by factors such as traffic emissions, construction, and

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other anthropogenic sources overlaying natural sources. Air pollution remains a major environmental and public health issue in Romania, with several studies reporting significant levels of airborne pollutants, particularly in urban and industrialized areas [3][4][5]. Among these pollutants, particulate matter (PM) has been recorded at significant concentrations in major cities like Bucharest [6], Iași [7] or Ploiești [8], where traffic, industrial activities, and residential heating contribute to deteriorating air quality, posing challenges for pollution control and mitigation efforts.

Understanding air quality dynamics in these rapidly developing regions is essential for assessing the impact of urban growth on public health and the environment [9], [10]. Remote sensing techniques, including LIDAR based aerosol profiling, have been increasingly used to complement ground-based measurements, providing vertical distribution and tracking pollutant transport [11][12][13]. Airborne PM represents a critical component of atmospheric composition [14][15][16][17][18], with significant implications for air quality [19][20], human health [21][22], and climate [23][24][25]. The fine fraction, particularly $PM_{2.5}$ (particulate matter with a diameter smaller than 2.5 μm) and PM_1 (particulate matter with a diameter smaller than 1 μm), are of major concern due to their ability to penetrate deep into the respiratory system and even reach the bloodstream [26], aggravating respiratory and cardiovascular diseases.

The paper presents the results of the analysis of temporal variability of the mass concentrations of PM_1, $PM_{2.5}$, and PM_{10} measured at the Măgurele, Ilfov site between February 2020 and the end of September 2024. Temporal trends of these PM fraction concentrations are evaluated, with comparisons to regulatory thresholds established by the current European Union directive regarding air quality [27], which align more closely with the guidelines recommended by the World Health Organization (WHO) [28].

2. Site description

Măgurele is a small, satellite city located in Ilfov, on the outskirts of Bucharest, Romania's capital city. Măgurele is part of the rapidly developing peri-urban area surrounding the city. The region is characterized by a mix of residential, agricultural, and industrial zones, which contribute to diverse sources of PM emissions [29][30][31]. In addition to traffic and construction activities, uncontrolled biomass burning—often associated with agricultural waste disposal or household heating—may further increase PM concentrations, particularly during colder months.

The city is home to the Măgurele Center for Atmosphere and Radiation Studies (MARS), part of the RADO-Bucharest ACTRIS National Facility, where the measurements were conducted (44.344°N, 26.012°E, 77 m a.s.l., Fig. 1).

Positioned approximately 5 km southwest of Bucharest, MARS' proximity to Bucharest's dense urban environment, coupled with local sources of pollution, makes it a strategic location for monitoring air quality and studying PM dynamics. Additionally, the local climate, classified as humid continental, with hot summers and cold winters, plays a crucial role in PM variability [32][33]. Winters are often marked by frequent temperature inversions, particularly during stable atmospheric conditions, which trap pollutants near the surface and lead to elevated PM concentrations [34]. These inversions are more common during clear, calm nights when radiative cooling creates a layer of cold air near the ground, preventing vertical mixing. In contrast, summers bring higher temperatures, increased solar radiation, and convective processes that enhance atmospheric mixing [35].

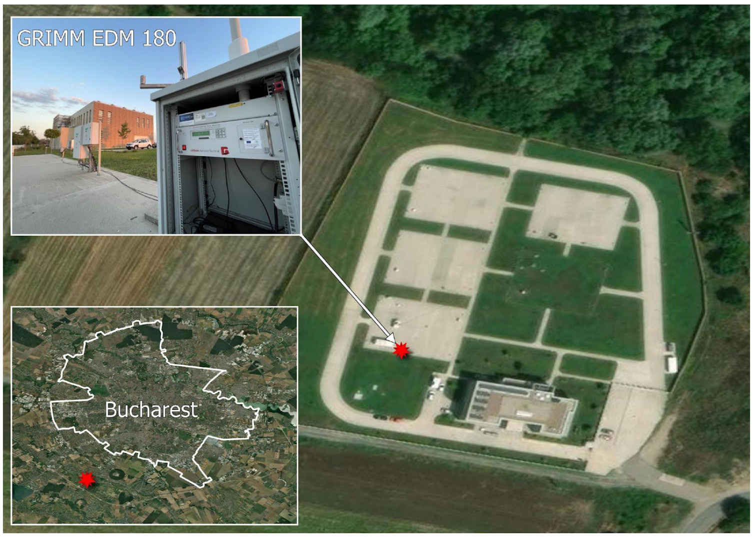

Fig. 1: Measurements site location and PM optical counter place

3. Data collection and analysis

Measurements were conducted using the GRIMM EDM 180, a high-precision optical dust monitor capable of measuring PM_1, $PM_{2.5}$, and PM_{10} mass concentrations. The instrument uses the principle of light scattering to detect individual particles, providing accurate real-time data across various particle size fractions. The EDM 180 adheres to several international standards, including EN12341, EN14907 and US-EPA, which ensure the accuracy and comparability of its measurements within regulatory frameworks [36]. The instrument has been calibrated regularly each second year. Measurements were conducted from February 2020 to the end of September 2024, although data collection was partially interrupted at certain times due to calibration and faulty datalogger.

The PM_1, $PM_{2.5}$ and PM_{10} data was collected with high temporal resolution (1 minute), and then averaged on an hourly basis for analysis. During the data processing stage, moving averages were applied to smooth out short-term fluctuations, ensuring a consistent dataset for trend analysis. Data filtration was based on a moving-average filter over a 3-data-point window to remove measurement data higher or lower 1.5 times than the window mean. Hourly, monthly and yearly mean values represent arithmetic averages. Additionally, 95% confidence intervals were estimated using the openair R package [37], providing a reliable estimate of data variability. These intervals represent the level of uncertainty associated with the calculated averages.

4. Temporal Analysis of PM Concentrations

The first part of the results focuses on the temporal variability of PM_1, $PM_{2.5}$ and PM_{10} concentrations over the study period, including monthly, diurnal, weekly, and seasonal variations.

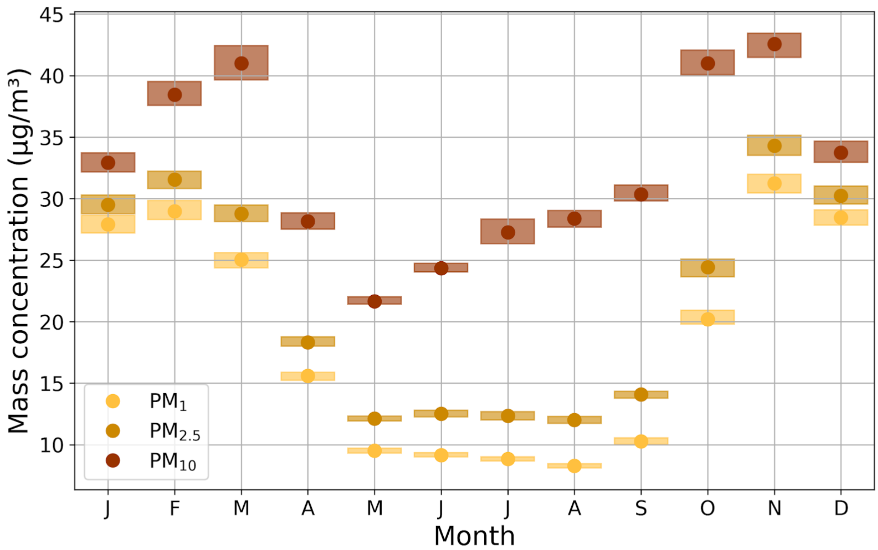

Fig. 2. Averaged monthly variation of PM_1 (yellow), $PM_{2.5}$(light brown) and PM_{10}(dark brown) mass concentration, 2020 – 2024 (95% confidence interval)

Averaged monthly variation of PM concentrations between 2020-2024 (Fig. 2) reveals a clear seasonal trend, with a higher PM loading during the colder months. This increase is primarily driven by enhanced emissions from residential heating, including biomass and fossil fuel combustion, which contribute heavily to PM levels. The elevated wintertime concentrations are further intensified by atmospheric stability conditions, such as temperature inversions, which limit vertical mixing and trap pollutants near the surface, as emphasized also by [38][39].

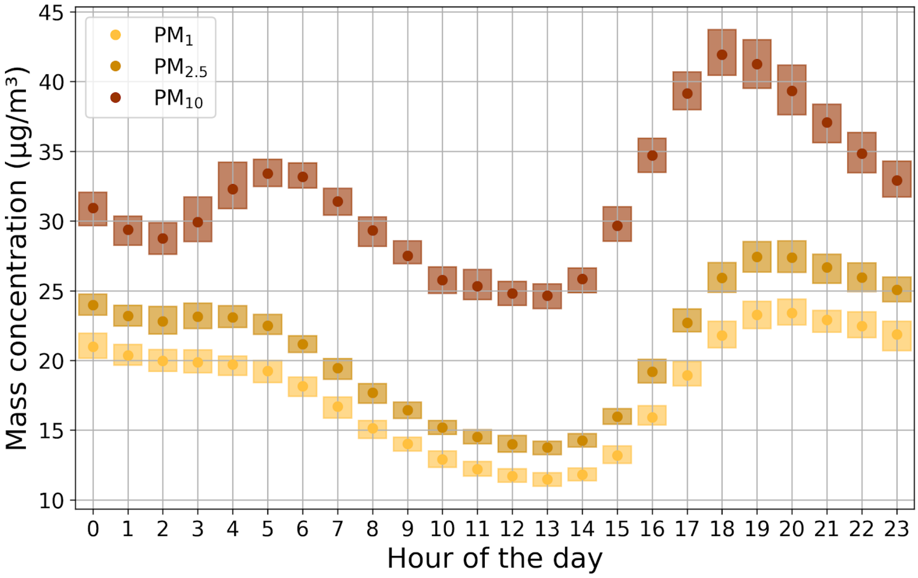

Fig. 3: Diurnal profile (UTC time) of PM_1 (yellow), $PM_{2.5}$ (light brown) and PM_{10} (dark brown) mass concentration, 2020 – 2024 (95% confidence interval)

In contrast, lower PM_1 and $PM_{2.5}$ concentrations are observed during late spring and early summer (May–June), when heating-related emissions decline, and meteorological factors such as increased precipitation and stronger atmospheric turbulence enhance pollutant dispersion. However, PM_{10} shows notable fluctuations during the warmer months, likely influenced by factors such as increased atmospheric dust resuspension, agricultural activities, and potential contributions from pollen and other biogenic aerosols [40].

Diurnal variations in PM concentrations (Fig. 3) show distinct peak periods in the morning (5:00 – 6:00 UTC) and in the evening (18:00 – 19:00 UTC). These peaks are correlated with temperature changes and the height of the planetary boundary layer [41]. PM_{10} exhibits a more pronounced diurnal variation than fine particles ($PM_{2.5}$), suggesting that coarser particles are more influenced by daily atmospheric conditions.

Analysis of weekly trends highlights a gradual increase in aerosol concentration from Monday to Friday, with concentrations typically lower on weekends. This pattern is attributed to the correlation between PM and traffic intensity, with higher pollutant emissions on weekdays when vehicular traffic is more frequent. The analysis of the $PM_{2.5}/PM_{10}$ ratio (Fig. 4) reveals distinct temporal patterns, with higher ratios observed during colder months, particularly in winter, indicating a greater contribution of fine particles, most probably from heating-related emissions.

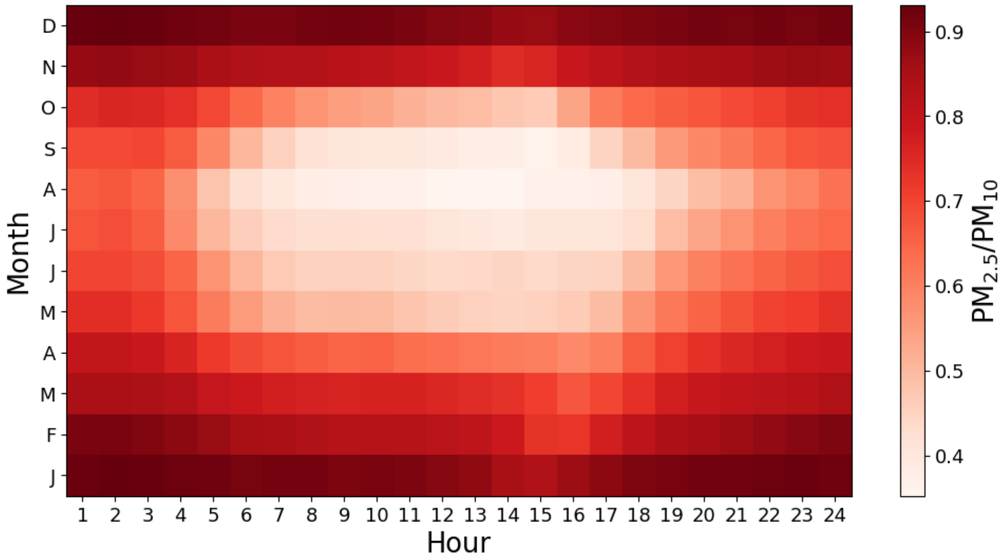

Fig. 4: Monthly-hourly contour plot of the $PM_{2.5}/PM_{10}$ ratio, 2020 – 2024

Diurnal variations in the $PM_{2.5}/PM_{10}$ ratio follow the same pattern as PM_{10} and $PM_{2.5}$ diurnal variations, showing elevated ratios during morning and evening traffic peaks, as expected. However, the lower ratios during warmer months and midday hours reflect a higher proportion of coarse particles. This variation can be influenced not only by factors like dust resuspension and atmospheric mixing, but also by other atmospheric conditions, such as temperature changes and the height of the planetary boundary layer, as identified in [42].

The trend analysis using the Theil-Sen estimator (Fig. 5) indicates a statistically significant decrease of -1.73% per year (95% confidence interval: [-3.4, -0.59] %/year) in the $PM_{2.5}/PM_{10}$ ratio. This suggests a relative reduction in fine PM ($PM_{2.5}$) compared to coarse particles (PM_{10}). The confidence interval does not include zero, reinforcing the reliability of the detected trend. The deseasonalization process ensures that the observed trend is not influenced by recurring seasonal variations, making the long-term decline more reliable.

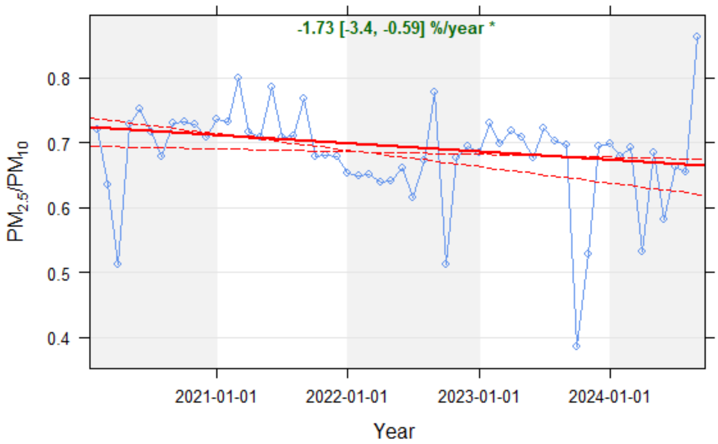

Fig. 5 Theil-Sen estimator for $PM_{2.5}/PM_{10}$ trends over the study period (95% confidence interval)

5. Compliance with the new Air Quality Standards

The second part of the results assesses how the measured $PM_{2.5}$ and PM_{10} concentrations align with the regulatory limits specified in Annex I, Section 1 of the EU Directive 2024/2881 of the European Parliament and Council, dated 23 October 2024, concerning ambient air quality and cleaner air for Europe (recast). This directive establishes limit values for the protection of human health, with specific targets to be attained by 11 December 2026 and 1 January 2030. The directive specifies that the daily PM_{10} concentration should not exceed 50 µg/m³ more than 35 times per year for the 2026 target, while a stricter limit of 45 µg/m³ applies with a maximum of 18 exceedances for the 2030 target. The analysis highlights annual exceedances and their implications for compliance with these regulatory thresholds, considering only days when full-day measurements were available.

Table 1

PM_{10} and $PM_{2.5}$ exceedances of daily limits

Year	Measured Days	PM_{10} (2026 exceedances)	PM_{10} (2030 exceedances)	PM_{10} compliance	$PM_{2.5}$ (2030 exceedances)	$PM_{2.5}$ compliance
2020	312	38	47	No (2026, 2030)	83	No
2021	271	41	57	No (2026, 2030)	108	No
2022	347	61	74	No (2026, 2030)	118	No
2023	264	30	44	Yes (2026) /No (2030)	62	No
2024	273	24	36	Yes (2026) /No (2030)	55	No

In 2020, PM_{10} concentrations exceeded the 2026 target on 38 days, accounting for 12.18% of the 312 days with data, therefore surpassing the allowable 35 exceedances. Additionally, there were 9 separate exceedances of the stricter 2030 limit, bringing the total exceedances for that standard to 47 (15.06% of measured days), indicating non-compliance with both targets. In 2021, there were 41 exceedances of the 2026 limit (15.13% of 271 available days), along with 16 additional exceedances of the 2030 limit alone, leading to 57 total exceedances (21.03% of measured days), showing a worsening trend. In 2022, the 2026 limit was breached in 61 days (17.58% of 347 measured days), and an additional 13 days exceeded only the 2030 threshold, leading to a total of 74 exceedances (21.33% of measured days), marking the most challenging year in terms of compliance. In 2023, PM_{10} concentrations exceeded the 2026 threshold in 30 days (11.36% of 264 available days), staying within the allowable limit. However, the 2030 limit was exceeded on 14 of these days, totalling 44 exceedances (16.67% of measured days), indicating that while compliance with the 2026 target was achieved, the stricter 2030 limit remained an issue. In 2024, there were 24 exceedances of the 2026 limit (8.79% of 273 measured days), and 12 of these also surpassed the 2030 threshold, leading to a total of 36 exceedances (13.19% of measured days). Although compliance with the 2026 target appears to be met, the stricter 2030 standard remains a challenge.

For $PM_{2.5}$, the directive does not set a daily limit for 2026, but for 2030, the threshold is 25 $\mu g/m^3$, with a maximum of 18 exceedances. In 2020, this limit was exceeded on 83 occasions (27.24% of available data days). In 2021, exceedances increased to 108 (39.85% of measured days). The highest number of exceedances was recorded in 2022, with 118 days (34.01% of available data). In contrast, 2023 saw a decline to 62 exceedances (23.48% of measured days), and in 2024, further improvement was observed with 55 exceedances (20.15% of available data). A summary of exceedances and compliance with daily limits is presented in Table 1.

The analysis also examines compliance with the annual mean concentration limits established by the directive. For PM_{10}, the 2026 target is 40 $\mu g/m^3$, which is reduced to 20 $\mu g/m^3$ for 2030. In 2020, the annual mean PM_{10} concentration was 31.59 $\mu g/m^3$, below the 2026 limit but exceeding the 2030 standard. A slight increase was observed in 2021 (33.57 $\mu g/m^3$), remaining within the 2026 threshold but further above the 2030 target. PM_{10} levels peaked in 2022 at 35.64 $\mu g/m^3$, approaching the 2026 limit and remaining well above the 2030 standard. However, improvements followed, with concentrations decreasing to 29.15 $\mu g/m^3$ in 2023 and 28.76 $\mu g/m^3$ in 2024, demonstrating progress toward cleaner air, although still exceeding the 2030 requirement.

For $PM_{2.5}$, the annual mean concentration limit is set at 25 $\mu g/m^3$ for 2026 and a stricter 10 $\mu g/m^3$ for 2030. In 2020, the annual mean $PM_{2.5}$ concentration was 20.29 µg/m³, meeting the 2026 target but exceeding the 2030 requirement. In 2021, levels increased slightly to 25.23 µg/m³, just surpassing the 2026 limit. A downward trend followed, with concentrations decreasing to 21.94 µg/m³ in 2022 and further down to 20.03 µg/m³ in 2023. By 2024, $PM_{2.5}$ levels had reached 17.71 µg/m³, confirming compliance with the 2026 limit. However, despite this progress, all recorded values remain significantly above the ambitious 2030 target, indicating the need for continued efforts to improve air quality.

Overall, while some progress has been made in reducing PM concentrations, the stricter 2030 limits remain difficult to achieve in this area, underscoring the necessity for sustained air quality measures.

6. Conclusions

This study highlights the seasonal, diurnal, and weekly variability of particulate matter (PM_1, $PM_{2.5}$, and PM_{10}) concentrations, near Bucharest. Higher PM levels were observed during the colder months, primarily due to heating activities, with lower concentrations in late spring and early summer. Diurnal peaks in the morning and evening were linked to temperature changes and planetary boundary layer height, with coarser particles (PM_{10}) showing more pronounced daily variations. The $PM_{2.5}/PM_{10}$ ratio indicated a greater contribution of fine particles in winter, associated with heating emissions, while coarse particles were more prevalent during warmer months. In terms of regulatory compliance, while annual PM concentrations showed gradual improvements, exceedances of the EU's 2026 and 2030 limits were observed. $PM_{2.5}$ levels in 2024 met the 2026 target but still exceeded the 2030 threshold, indicating the need for continued efforts to meet future air quality standards.

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