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[Liliana Drăgoi \(Oniu\)](#) , [Marius Mihai Cazacu](#) ^{*} , [Iuliana Gabriela Breabăn](#) ^{*}

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Article

Evaluation of Scenarios for the Application of the Future PM_{2.5} and PM₁₀ Standards: A Case Study of Three Urban Areas in Romania and Implications for Public Policies

Liliana Drăgoi (Oniu) ¹, Marius-Mihai Cazacu ^{2,*} and Iuliana-Gabriela Breabăn ^{1,*}

¹ Faculty of Geography and Geology, Doctoral School of Geosciences, “Alexandru Ioan Cuza” University of Iasi, Carol I Boulevard, No. 11, 700506 Iasi, Romania

² Department of Physics, “Gheorghe Asachi” Technical University of Iasi, 700050 Iasi, Romania

* Correspondence: marius-mihai.cazacu@academic.tuiasi.ro; iulianab@uaic.ro;

Abstract

Directive (EU) 2024/2881 introduces stricter daily standards and alert thresholds for particulate matter, which will be applicable starting in 2030. Member States must transpose these standards by 2027. This study retrospectively applies the new framework to daily data from three urban areas in Romania from 2019 to 2024. The objective is to evaluate the risks of noncompliance and test additional, more sensitive indicators of pollution severity and source characteristics. The results show that the new standards would cause the daily and annual limits for PM_{2.5} and PM₁₀ to be exceeded in at least two of the three analyzed cities. Three indicators are proposed and applied: (i) Excess Concentration (EC), which quantifies the total amount of daily exceedances of the limit value; (ii) Toxic Load Index (TLI), which integrates the PM_{2.5}/PM₁₀ ratio as a proxy for toxicological potential; and (iii) Episode Index (EI), which captures the magnitude and duration of episodes that would trigger alert thresholds. The study includes a summary review of the air quality legislative framework and contributes to public policy literature by emphasizing risk-proportionate interventions. The proposed indicators support a smoother transition to forthcoming European requirements.

Keywords: particulate matter; PM₁₀; PM_{2.5}; Directive (EU) 2024/2881; air pollution; Romania; Excess Concentration; Toxic Load Index; Episode Index

1. Introduction

Air pollution is considered the greatest environmental health risk in Europe [1], contributing to a significant burden of cardiovascular, respiratory, and other chronic diseases. Worldwide, air pollution is estimated to cause millions of premature deaths and lost years of healthy life each year [2].

Particulate matter (PM) is among the most harmful atmospheric pollutants [1].

The EEA’s annual estimates for Romania for 2022 attribute 17900 deaths each year (or 185100 years of life lost) to fine particulate matter PM_{2.5} [3].

The toxic effects of particle pollution on humans depend on the particles’ size and chemical composition [4,5].

The two regulated sizes of particulates are PM₁₀ (particles with a diameter of 10 µm or less) and PM_{2.5} (particles with a diameter of 2.5 µm or less) [6,7]. Of these particles, fine particles (PM_{2.5}) are considered the most dangerous to human health. They penetrate deep into the lungs and can reach the alveolar region [1]. There is a strong causal relationship between PM_{2.5} exposure and increased

risk of all-cause mortality, acute respiratory infections, chronic obstructive pulmonary disease, ischemic heart disease [8,9], cancer [10] ischemic stroke [2,11].

The coarse fraction of particles, PM_{10-2.5}(coarse fraction, particles with an aerodynamic diameter between 2.5 and 10 mm) is mainly deposited in the upper respiratory tract (thoracic region) [12]. Exposure to this type of PM has been associated with adverse respiratory effects, including chronic obstructive pulmonary disease, asthma, and respiratory hospitalizations. Sometimes, the short-term effects are stronger than those associated with fine particles [13].

1.1. The Legislative Framework

The European Union updates its air quality directives regularly to reflect the latest scientific findings on the connection between pollution and human health.

Directive 96/62/EC on ambient air quality assessment and management, known as the “Framework Directive,” laid the foundations for the assessment and management of ambient air quality and was supplemented by daughter directives for specific pollutants: Directive 1999/30/EC (for sulfur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead), Directive 2000/69/EC (for benzene and carbon monoxide) and Directive 2002/3/EC (for ozone).

These directives were subsequently consolidated and simplified by Directive 2008/50/EC on ambient air quality and cleaner air for Europe, which became the main legislative act in this field. The World Health Organization’s (WHO) guidelines were used as a reference point for setting air quality standards. Directive 2008/50/EC was transposed into Romanian law by Law No. 104/2011 on ambient air quality.

In 2021, the WHO published new Global Air Quality Guidelines based on scientific evidence showing that air pollution has adverse effects even at exposure levels lower than previously considered safe. The document establishes significantly more restrictive guideline values for key air pollutants, including PM₁₀ and PM_{2.5}. These values correspond to concentrations at which the risk to health is minimal, according to the most recent scientific data [2].

In accordance with the 2021 WHO guidelines, the European Union adopted Directive (EU) 2024/2881 on ambient air quality and cleaner air for Europe. Member States shall transpose this Directive into national legislation by no later than 11 December 2026.

The directive reforms previous legislation, Directive 2008/50/EC, by introducing ambitious targets aimed at reducing the impact of pollution on health by 2030 and achieving “zero pollution” by 2050.

Directive (EU) 2024/2881 significantly reduces the limit values for PM₁₀ and PM_{2.5}, bringing them closer to WHO recommendations (Table 1). For example, the annual limit value for PM_{2.5} decreases from 25 µg/m³ to 10 µg/m³. Pentru PM₁₀, the daily limit value is reduced from 50 µg/m³ to 45 µg/m³, with a significant reduction in the number of permitted exceedances per year from 35 to just 18 exceedances per year. A new feature is the introduction of daily limit value for PM_{2.5} [6,7].

Table 1. Comparison of Limit Values for human health protection.

Pollutant	Averaging period	Directive 2008/50/EC*	Directive (EU) 2024/2881**	WHO, 2021 Recommended AQG level
		Limit value		
PM _{2.5} µg/m³	Calendar year	25	10	5
	1 day	-	25	15
			not to be exceeded more than 18 times per calendar year	not to be exceeded more than 3-4 times per calendar year
PM ₁₀ µg/m³	Calendar year	40	20	15
	1 day	50	45	45

	not to be exceeded more than 35 times per calendar year	not to be exceeded more than 18 times per calendar year	not to be exceeded more than 3-4 times per calendar year
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* to be attained by 11 December 2026. ** to be attained by 1 January 2030.

The new directive provides for the establishment of alert and information plans to manage episodes of intense pollution. It sets two types of thresholds: alert thresholds, which signal a risk to the health of the entire population in the context of short-term exposure and require immediate measures; and information thresholds, which indicate an increased risk to vulnerable groups and sensitive individuals and require the rapid and appropriate dissemination of relevant information. Alert thresholds for PM₁₀ and PM_{2.5} are assessed based on daily averages over a period of up to three consecutive days (or less), while information thresholds are determined based on a single day’s daily average. According to Directive (EU) 2024/2881, exceeding the alert threshold results in the activating of the short-term action plan for the protection of public health [6].

Table 2. Alert thresholds and Information thresholds - Directive UE 2024/2881.

Pollutant	Averaging period	Directive (EU) 2024/2881
PM _{2.5}	1 day	50 µg/m ³
PM ₁₀	1 day	90 µg/m ³

1.2. Need for Complementary Air Quality Indicators

Directive (EU) 2024/2881 establishes standard indicators for assessing air quality for PM₁₀ and PM_{2.5}, including annual limit values, daily limit values and the maximum number of daily exceedances, alert and information thresholds (Tables 1 and 2). These indicators do not always capture the magnitude of daily exceedances or pollution episodes. Assessments based only on the frequency of daily exceedances or the annual average concentration may underestimate acute exposures that have significant health impacts.

In this context, we propose developing and applying complementary indicators that consider the number of exceedances, their magnitude, and the characterization of pollution sources.

This study proposes three indicators: 1) Excess Concentration (EC), which sums the excess concentration relative to the daily limit value over a calendar year, 2) Episode Index (EI), which integrates the magnitude of pollution episodes throughout each episode, and 3) Toxic Load Index, which considers both the PM_{2.5}/PM₁₀ ratio necessary to identify potential dominant sources of pollution and the excess relative to the limit value.

Abbey et al. [14] previously used EC in the analysis of total suspended particles and other pollutants, which highlighted the importance of including the magnitude of limit value exceedances in air quality assessments. EC also reflects exposure epidemiology principles, which state that the „cumulative dose” of a pollutant determines long-term health risks [14,15].

Epidemiological studies have shown that the adverse effects of particulate matter (PM₁₀ and PM_{2.5}) depend not only on the concentration level on a given day, but also on the number of consecutive days with high exposure. This justifies the need for indicators that integrate this type of data [2,15].

In this context, an additional indicator, such as the pollution episode index (EI), can provide a more precise assessment of health risks by quantifying the excess PM accumulated during the entire pollution episode when the alert threshold is exceeded.

The third indicator proposed and applied in the study is the Toxic Load Index (TLI). The TLI was designed to quantify the potential toxicological impact of fine particle PM_{2.5} by integrating the magnitude of exposure and the nature of the particles. This allows us to highlight the degree of risk depending on the particles’ origin or composition. Sometimes, PM₁₀ levels are high, but the composition is dominated by coarse dust with low toxicity, such as mineral particles or Saharan dust. In other cases, the PM₁₀ level is moderate but dominated by fine particles from combustion.

Park et al. (2018) demonstrated that the toxicity of PM_{2.5} particles depends on their source. They proposed a differentiated toxicity score [16], which supports the idea that an indicator combining PM_{2.5} excess with the PM_{2.5}/PM₁₀ ratio is necessary for a more accurate assessment of health risks.

A study of 4.47 million deaths in 75 U.S. cities found that the chemical composition of PM_{2.5} matters for health, not just its total mass. An increase of 10 µg/m³ in the two-day average of PM_{2.5} is linked to an overall increase in mortality of 1.18%, especially in the spring. Sulfur, silicon, and calcium amplify the risk, with sulfur correlating with a respiratory mortality increase of up to 8.96% [17]. In these situations, the TLI provides a more relevant assessment of the risk to public health.

1.3. Research Objectives and Contributions

In preparation for compliance with the new European air quality standards, this study compares the concentrations of PM₁₀ and PM_{2.5} to the current and future limit values established in Directives 2008/50/EC and (EU) 2024/2881, respectively. The future limit values will be mandatory starting January 1, 2030. The analysis includes three urban background air quality monitoring stations, one industrial station in an urban area, and one rural background station to provide a representative comparison point of areas with lower anthropogenic influence. The aim is to assess compliance and identify gaps in relation to future legislative requirements to support public policy formulation.

This paper expands on two previous studies [18,19] which analyzed trends in PM₁₀ and PM_{2.5} concentrations in Suceava, Botoşani, and Iaşi, as well as spatial differences in these three northeastern Romanian urban areas. One of these studies examined the PM_{2.5}/PM₁₀ ratio as an indicator of particle origin and composition.

This study makes new contributions by integrating data from 2024 and including a rural background station as a baseline pollution level reference. It also uses three complementary indicators, which are described in Section 1.2. These improvements enable a more accurate characterization of air quality, population exposure, and proximity to the new limit values that will be mandatory starting in 2030, as outlined in Directive (EU) 2024/2881. The ultimate objective is to propose measures and recommendations to reduce PM concentrations below the future limit values and manage situations where alert thresholds are exceeded, adapted to each area.

2. Materials and Methods

2.1. Study Area

The study was conducted in three urban areas in northeastern Romania: Suceava, Iaşi, and Botoşani. These areas were previously studied by Dragoi et al. [18,19].

2.2. Air Quality Data

This study uses data on daily concentrations of PM₁₀ and PM_{2.5}. These concentrations were determined using the gravimetric reference method at air quality monitoring stations within the National Air Quality Monitoring Network from 2019 to 2024. The data are available to the public on the website <https://www.calitateaer.ro> (accessed on 04 June 2025).

Daily data were not collected in years when the fixed measurement data collection requirement was not met, nor when the legal requirements for data quality and aggregation, as set out in Annex 4 to Law 104/2011, were not fulfilled.

Table 3 shows the locations of the stations in the study.

Table 3. Locations of the monitoring stations.

Station		Latitude	Longitude	Altitude
Suceava	SV-1	47.649259°N	26.249009°E	376 m
	SV-2 ¹	47.668825°N	26.281403°E	289 m
Botosani	BT-1	47.739945°N	26.658999°E	167 m

Iasi	IS-2	47.150951°N	27.581920°E	42 m
	IS-4 ¹	47.213306°N	27.611074°E	186 m

¹ The SV-2 and SV-4 stations only provide daily PM10 concentration data.

The city of Suceava is implementing an Air Quality Plan for the PM₁₀ parameter, with the period of application of the measures being 2023–2027 [20]. An integrated plan for NO₂/NO_x and PM₁₀/PM_{2.5} is currently being developed in Iași, with measures to be implemented between 2024 and 2028 [21].

2.3. Definition and Calculation of the Proposed Indicators

All of the proposed indicators relate to the future limit values established in Directive (EU) 2024/2881.

2.2.1. Excess Concentration (EC)

The EC is an additional indicator that complements the annual number of daily exceedances. It provides more information about the magnitude of daily limit value exceedances. The EC indicator for a calendar year is calculated by adding the differences between the daily concentrations of particles matter and the daily limit value. This calculation only considers days on which the limit was exceeded.

The formula for EC is given by

$$EC = \sum_{i=1}^n (C_i - LV)$$

(1)

where

- C_i = daily concentration of PM (µg/m³)
- LV= daily limit value (45 µg/m³ for PM₁₀ and 25 µg/m³ for PM_{2.5})
- n = the duration in days when C_i > LV.

The annual EC is calculated by adding together all the daily EC values obtained from a station throughout the calendar year.

Classification thresholds for the EC indicator were established to assess the population’s exposure to particulate matter (Table 4).

These thresholds were set based on the daily limit values of 45 µg/m³ for PM₁₀ and 25 µg/m³ for PM_{2.5}, the maximum of 18 daily exceedances per year, as specified in Directive (EU) 2024/2881, and the daily exceedance values recorded at all air quality monitoring stations during the study period.

Based on data from all stations included in the study, the mean daily exceedance above the limit value in the future directive would be 13.1 µg/m³ for PM₁₀. Assuming 18 permitted annual exceedances, the average annual EC would be 236 µg/m³. Rounding this value down, the lower threshold of 250 µg/m³ is chosen for PM₁₀, which corresponds to low but frequent exposure in areas that comply with the directive.

For PM_{2.5}, the daily excess average calculated over the entire study period was not used because the data set is more limited. Only three stations monitor PM_{2.5}, and the available data do not fully cover all the analyzed years (Table 8). Therefore, the lower threshold for EC for PM_{2.5} was determined by adjusting the reference EC value for PM₁₀ using the ratio of the corresponding daily limit values (25 µg/m³ for PM_{2.5} and 45 µg/m³ for PM₁₀). This results in an adjustment factor of 0.56, corresponding to a reference EC of approximately 140 µg/m³.

However, the data analysis shows that the EC of 142 µg/m³ was reached at the SV-1 station in 2022 with only 15 values above 25 µg/m³. This suggests that a threshold of 140 µg/m³ may underestimate exposure in real-life scenarios, even when the number of exceedances is below the legal limit. The threshold for the low PM_{2.5} exposure category is 150 µg/m³, a value that considers the ratio to the thresholds set for PM₁₀ and the actual situations observed in the available data.

The annual analysis of EC values for monitored stations (Section 3.3.1), shows that the upper threshold of 750 µg/m³ for PM₁₀ in the Moderate EC category indicates situations in which exposure

is moderate, though frequent, and not persistently severe. The PM_{2.5} equivalent was set at 500 µg/m³, considering the PM_{2.5}/PM₁₀ ratio, which aligns with the average values observed in the study areas [19].

EC values become chronic and fall into the High or Very High EC category above values of 750 µg/m³ for PM₁₀ and 500 µg/m³ for PM_{2.5}.

Annual EC values above 1000 µg/m³ for PM₁₀ and above 800 µg/m³ for PM_{2.5} coincide with years in which extremely high daily concentrations are not just occasional. Further details can be found in Section 3. Results.

Table 4. Exposure categories for annual excess concentrations.

Categorie	EC annual (µg/m ³)		Interpretation criteria.
	PM ₁₀	PM _{2.5}	
Low	<250	<150	Less than 18 daily exceedances or low-magnitude daily exceedances
Moderate	251–750	151–500	Frequent moderate daily exceedances, slightly above the value limit and/or occasional high exceedances
High	751–1000	501–800	Frequent daily exceedances and/or high daily concentration levels
Very high	>1000	>800	Severe pollution or extreme episodes

These thresholds were proposed as guidelines for assessing pollution levels at different stations and in different years. They were not regulated by any normative act.

2.2.2. Episode Index (EI)

The pollution episode index (EI) was used to characterize PM₁₀ and/or PM_{2.5} pollution episodes. The EI integrates the magnitude of the excess above the alert threshold over the entire duration of the episode, thus providing a better estimate of the potential health risk.

They are calculated as the sum of the daily differences between the recorded daily concentrations and the alert threshold set by the directive, for each day on which the threshold is exceeded. An episode of pollution is defined as a succession of at least three consecutive days (or two days with very high values) during which the alert threshold is exceeded.

The formula for EI is given by

$$EI = \sum_{i=1}^n (C_i - P_{alert})$$

(2)

where

- C_i = the concentration on day i (µg/m³)
- P_{alert} = alert threshold (Directive (EU) 2024/2881: ≥ 50 µg/m³ for PM_{2.5} and ≥ 90 µg/m³ for PM₁₀).
- n = number of consecutive days in episodul de poluare where C_i > P_{alert}

The classification of PM₁₀ and PM_{2.5} pollution magnitude starts at a high level because the identification of these episodes begins with the alert thresholds of 90 µg/m³ and 45 µg/m³, respectively, as specified in Directive (EU) 2024/2881. Exceeding these thresholds requires the implementation of urgent measures, which will be included in short-term action plans aimed at reducing the immediate risk or duration of exceeding the alert thresholds. Since these values are double the daily limit values (45 µg/m³ and 25 µg/m³, respectively), any episode reaching or exceeding the alert threshold is considered a high-risk health event.

The thresholds for separating classes were established by considering the concentrations recorded during the study period and the references used in international practice. These references include the daily classifications applied in the United Kingdom, in accordance with air quality assessment guidelines [11].

For PM₁₀, data from the study period showed that the EI values tended to be concentrated around 25 µg/m³ and 100 µg/m³ (Section 3.3.2). These values were used to classify the data in Table 5, which reflects both the magnitude of the exceedance and the duration of exposure.

The limit values and alert thresholds for PM_{2.5} differ from those for PM₁₀. However, similar classification intervals were used (Table 5). This is because the EI is calculated relative to the alert threshold specific to each pollutant. This approach allows for comparison of the magnitude of episodes between the two particle fractions based on total exposure above the threshold, regardless of the concentration value.

Table 5. Classification of Pollution Episode Index.

Categorie	EI (µg/m ³)		Interpretation criteria.	
	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}
High	1-25	1-25	2–3 days with µg/m ³	90–100 2–3 days, with values slightly above 50 µg/m ³
Very high	26–100	26–100	3–4 days with µg/m ³	100–115 3–4 days with 60–70 µg/m ³
Extremely high	>101	>101	Long episodes and/or episodes with high peaks (>115 µg/m ³).	Long episodes and/or episodes with high peaks (>75-90 µg/m ³).

The threshold ranges used to classify the magnitude of pollution episodes were based on data from the literature on the health effects of exposure to PM [15,22].

2.2.3. Toxic Load Index (TLI)

The TLI aims to supplement traditional quantitative indicators, such as the daily average, the maximum number of daily exceedances, and the annual average, as well as the other two indicators proposed in this study, EC and EI, by integrating qualitative characteristics related to the toxic potential of suspended particles. TLI takes into account the excess of PM_{2.5} concentration above the daily limit value as well as the proportion of PM_{2.5} in total PM₁₀, expressed as the PM_{2.5}/PM₁₀ ratio.

The daily calculation of the TLI indicator enables the quick and precise evaluation of the health risks posed by fine particle pollution on a given day. It captures the fluctuating variations in PM_{2.5} and PM₁₀ levels, which differ significantly from day to day depending on weather conditions and emission sources. Thus, this indicator identifies acute pollution episodes.

The TLI can be integrated into air quality warning systems to provide summary information on pollution episode risk. This supports rapid decision-making by authorities.

The formula for TLI is given by:

$$TLI_i = \left(\frac{PM_{2.5,i}}{PM_{10,i}}\right) \times (C_i - 25)$$

(3)

where

- TLI_i = TLI daily
- C_i = the PM_{2.5} concentration on day i, when the LV is exceeded (µg/m³)
- $PM_{2.5,i}/PM_{10,i}$ = the ratio of concentrations on day i
- 25 (µg/m³) = daily limit value for PM_{2.5}

On days when the PM_{2.5} concentration does not exceed the daily limit value, the TLI value will be zero, indicating an absence of significant toxicity.

Conversely, as the PM_{2.5}/PM₁₀ ratio increases, so does the TLI, reflecting a higher proportion of PM_{2.5} in the total mass of PM, which is associated with increased toxicological potential [19].

While there is no indicator identical to the TLI in the literature, the TLI is based on principles used by other authors in environmental risk assessment, such as quantifying excess over limit values associated with acute adverse health effects [14], using the PM_{2.5}/PM₁₀ ratio to indicate the source and nature of the particles [19,23], and integrating these principles into a single indicator. Combining

quantity and relative toxicity is a common approach in environmental risk assessment. For instance, cumulative risk assessment uses products of exposure and toxicity coefficients [22].

Table 6. Classification of daily TLI for PM_{2.5}.

Categorie	TLI (µg/m ³)	Interpretation criteria
No risk	0	PM _{2.5} below LV, insignificant toxic load
Low	0.1 – 5	Slightly exceeded or lower PM _{2.5} /PM ₁₀
Moderate	5.1 – 12	Significant exceedance and high proportion of PM _{2.5}
High	12.1 – 20	Severe pollution with toxic composition
Very high	> 20	Critical episode, major toxicological risk

The classification thresholds for daily TLI values were established based on methodological and toxicological considerations. For the excess component, the daily limit value of 25 µg/m³ for PM_{2.5} was used. Thus, the zero reference value for TLI directly corresponds to an absence of exceedances and an insignificant toxic load. Subsequent thresholds were set according to the severity levels of PM_{2.5} excess, weighted by the PM_{2.5}/PM₁₀ ratio.

This ratio varies from approximately 0.3 (in episodes with coarse dust) to 0.9–1.0 (in cases of combustion-source pollution with increased toxic potential) [23].

Thus, with an excess of 10 µg/m³ and a high PM_{2.5} proportion (e.g., 0.8), the TLI reaches 8, corresponding to a moderate–high risk zone. Threshold values of 5, 12, and 20 were selected as progressive benchmarks to distinguish between different exposure types (e.g., occasional or hazardous). These thresholds were derived mathematically.

3. Results

3.1. Measured Annual Mean Concentrations Compared with Current and Future Limit Value

3.1.1. Annual Mean Concentrations of PM₁₀

Between 2019 and 2024, annual mean PM₁₀ concentrations were below the limit value in force. Applying the new limit from Directive (EU) 2024/2881, compliance was observed only at SV-1 and IS-4 in 2022–2023. For SV-2 (2022–2024) and IS-4 (2024), compliance could not be assessed due to insufficient data. (Table 7).

Table 7. Annual mean concentrations of PM₁₀ compared to current and future annual limit value.

Year	BT-1	IS-2	IS-4	SV-1	SV-2	Directive 2008/50/EC	Directive (EU) 2024/2881
	µg/m ³	µg/m ³	PM ₁₀ µg/m ³	µg/m ³	µg/m ³	LV	LV
2019	27.30	32.10	20.22	22.60	32.87	40 µg/m ³	20 µg/m ³
2020	25.15	30.43	20.68	20.75	30.51		
2021	23.27	30.73	20.47	22.29	28.54		
2022	21.70	29.60	18.34	17.88	-		
2023	20.72	27.18	18.62	18.53	-		
2024	26.23	27.53	-	21.39	-		

3.1.2. Annual Mean Concentrations of PM_{2.5}

For the years in the analysed period for which the data quality objective was met, it can be concluded that the annual mean concentrations of PM_{2.5} were below the annual limit value in force. However, if the annual limit value set in Directive (EU) 2024/2881 had been applied, the concentrations recorded at the stations in Suceava and Iaşi would have exceeded the future limit value (Table 8).

Table 8. Annual mean concentrations of PM_{2.5} compared to current and future annual limit.

Year	BT-1	IS-2	SV-1	Directive	Directive (UE)
	PM _{2.5}	PM _{2.5}		2008/50/EC	2024/2881
	µg/m ³	µg/m ³	µg/m ³	LV	LV
2019	13.34	-	-	25 µg/m ³	10 µg/m ³
2020	-	-	14.47		
2021	13.74	20.21	15.14		
2022	-	18.02	12.12		
2023	-	14.91	11.23		
2024	-	15.50	13.75		

3.2. Daily Exceedances Relative to Current and Future Daily Limit Values for PM₁₀ and PM_{2.5}

3.2.1. Analysis of Daily Exceedances for PM₁₀

During the analyzed period, the maximum number of 35 daily exceedances permitted by Law 104/2011 (which transposes Directive 2008/50/EC) was not exceeded at any station except in 2019 at IS-2, where 36 values were above 50 µg/m³. This threshold was also reached in 2019 at SV-2 and in 2020 at IS-2.

For IS-4 in 2024 and for SV-2 in 2022, the 90.4th percentile is used to verify compliance with regard to the number of exceedances of the daily limit value since the annual PM₁₀ data capture did not meet the target for fixed measurements. This value must be less than or equal to the limit value of 50 µg/m³. In 2024, the 90.4 percentile at IS-4 was 30.93 µg/m³, and at SV-2 in 2022 was 39.82 µg/m³ (In 2023 and 2024, the data coverage at SV-2 was 0% and 8%, respectively).

Applying the future daily limit value of 45 µg/m³ (not to be exceeded more than 18 times a calendar year), as set out in Directive (EU) 2024/2881, results in a substantial increase in hypothetical exceedances at all analysed stations. This suggests that, under the stricter standard, the assessment framework for population exposure to PM₁₀ pollution would flag exceedances more frequently, reflecting higher sensitivity in evaluating air quality impacts.

Stations IS-2 and SV-2 would be the most affected by the application of the new directive. For example, in 2019, SV-2 registered 35 exceedances, but would record 73 hypothetical exceedances when applying the future daily limit value of 45 µg/m³ (not to be exceeded more than 18 times a calendar year). Similarly, IS-2 recorded 36 exceedances in 2019, but would reach 52 hypothetical exceedances under the new directive, almost three times the future permitted maximum.

Stations IS-4 and SV-1, which typically record lower PM₁₀ levels, are less affected by the future daily limit value. Regardless of the legislative requirements applied, a decrease in the number of exceedances at all stations between 2019 and 2023. In 2024, however, a partial increase was noted at several locations (e.g., BT-1, IS-2 and SV-1), although the number of exceedances remained below the maximum values recorded in 2019. This trend may suggest a general improvement in air quality, potentially due to measures implemented to reduce PM₁₀ pollution[20,21], but it is also influenced by meteorological conditions.

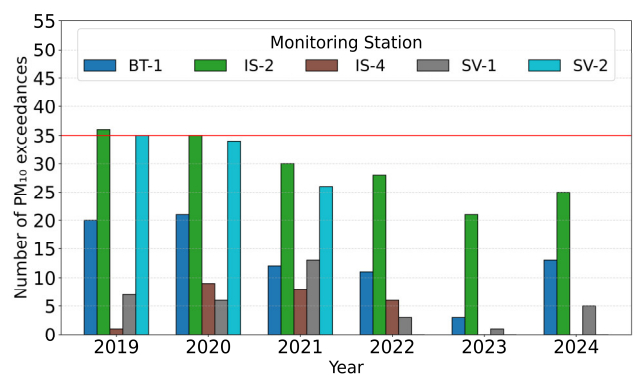


Figure 1. Annual number of PM₁₀ exceedance days (Directive 2008/50/CE) — not to be exceeded more than 35 times a calendar year.

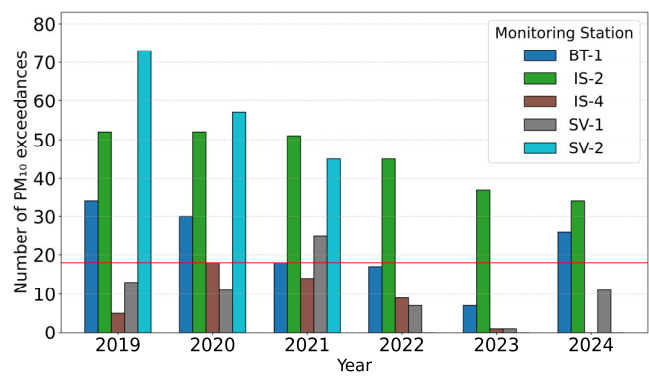


Figure 2. Annual number of PM₁₀ exceedance days (Directive (EU) 2024/2881) — not to be exceeded more than 18 times a calendar year. Values for years prior to the directive’s entry into force represent a hypothetical comparison.

3.2.2. Analysis of Daily Exceedances for PM_{2.5}

Current legislation does not specify a daily limit for PM_{2.5}. Based on the data from the study period and the future daily limit value (25 µg/m³, not to be exceeded more than 18 times a calendar year) established in Directive (EU) 2024/2881, the limit value would have been exceeded at all stations except SV-1 in 2022 and 2023 (Figure 3).

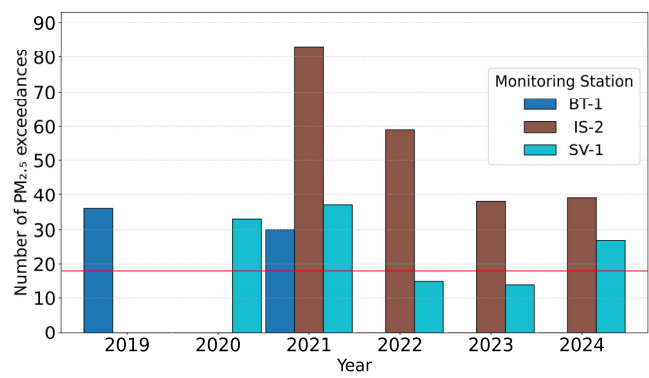


Figure 3. Annual number of PM_{2.5} exceedance days (Directive (EU) 2024/2881) — not to be exceeded more than 18 times a calendar year. Values for years prior to the directive’s entry into force represent a hypothetical comparison to the future limit value set in Directive (EU) 2024/2881.

3.3. Proposed Supplementary Indicators for PM₁₀ and PM_{2.5}

In order for the daily and annual mean PM values to fall below the limit values set by the new directive, additional measures to reduce emissions are necessary. When identifying and prioritising the most effective measures, the meteorological characteristics of the area and the following additional indicators can be taken into account: Excess Concentration, Episode Index and Toxic Load Index.

3.3.1. Excess Concentration

The EC indicator, as defined in point 2.2.1, was correlated with the number of daily exceedances of the future daily limit values for PM₁₀ and PM_{2.5} for the purposes of interpretation.

Figures 2 and 4 show that assessing exposure to PM₁₀ involves quantifying both the frequency and magnitude of hypothetical exceedances of the daily limit value. A similar pattern is observed for PM_{2.5}, as illustrated in Figures 3 and 5.

Therefore, correlating the number of hypothetical daily exceedances with the annual excess concentration enables differentiation between situations characterised by frequent, low-magnitude exceedances, and situations with fewer, but significantly higher, exceedances.

The highest cumulative excess (1165 µg/m³) would have been recorded in 2019 at station SV-2, corresponding to 73 hypothetical daily exceedances, if the future PM₁₀ limit values had been applied. In 2020, a cumulative excess of 1064 µg/m³ would have been recorded with 57 hypothetical exceedances.

At station IS-2, a cumulative PM₁₀ excess of 677 µg/m³ would have been recorded in 2019, increasing to 1202 µg/m³ in 2020. However, there were only 52 hypothetical exceedances in both years (Figures 2 and 4). According to the classification in section 2.1 of the annual PM concentration excess magnitude, stations SV-2 and IS-2 fell into the Very High EC category in 2019 and 2020, indicating severe pollution.

From 2021 to 2023, the number of hypothetical daily exceedances of the future daily limit value for PM₁₀ decreased, as did excess magnitude at all stations. Most stations fell into the Low EC category, with IS-2 and SV-2 in the Moderate EC category.

EC increased in 2024 compared to 2023. BT-1 returned to the Moderate EC category, but values remained below 2019–2020 levels. The trend for station SV-2 from 2022 to 2024 cannot be interpreted due to a lack of data.

IS-4 and SV-1 stations were in the Low EC category in all years for which data was available, with fewer exceedances and lower magnitude (Figures 2 and 4).

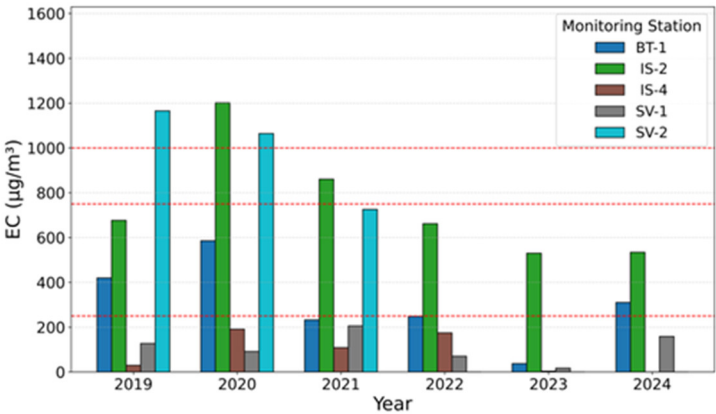


Figure 4. Annual Excess Concentration PM₁₀ (— EC thresholds according to Table 4).

Based on the classification of annual PM excess magnitude (Table 4), the results show significant variations in PM_{2.5} levels between years and locations. In 2021, station IS-2 was in the Very High EC category, with an annual excess of 973 µg/m³ and 83 hypothetical exceedances of the daily limit value. This indicates severe, sustained PM_{2.5} pollution levels. During the same period, the BT-1 and SV-1

stations recorded 30 and 37 hypothetical exceedances, respectively, reflecting their Moderate EC classification. At IS-2, the cumulative excess decreased from high EC in 2022 to Low EC in 2024, with fewer and less intense exceedances. At SV-1, cumulative exceedances remained low in 2022 and 2023, but in 2024 they returned to Moderate EC, below 2021 levels (Figure 5).

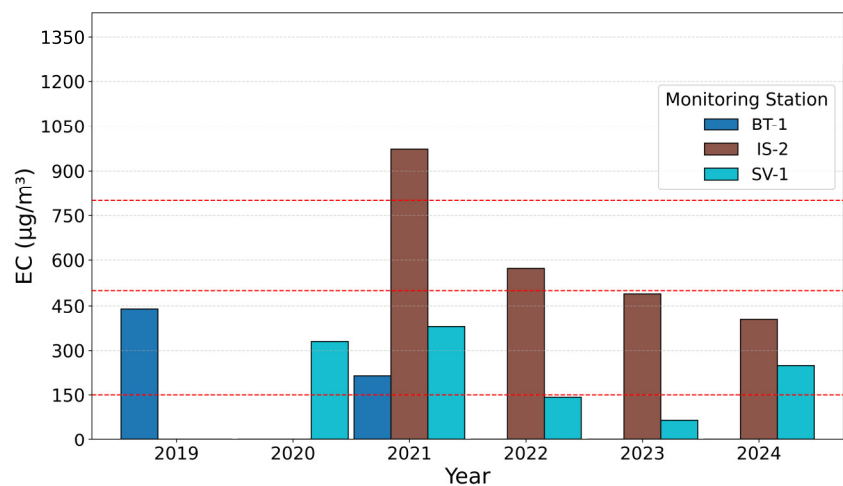


Figure 5. Annual Excess Concentration PM_{2.5} (— EC thresholds according to Table 4).

3.3.2. Episode Index (EI)

To characterise the magnitude of PM pollution episodes, the EI indicator was applied, which takes into account both the duration and the average excess concentration above the alert threshold. Of the data analysed for the period 2019–2024, the highest EI values for PM₁₀ were recorded at stations IS-2 and SV-2, where short episodes of very high concentrations occurred. For instance, IS-2 recorded an episode in February 2021 with an average excess of 23.34 µg/m³ over three days, resulting in an EI of 70.03 µg/m³, which was the highest value during the analysed period. Similar values were also identified at SV-2 in 2020 (Table 9).

Table 9. Episodes of PM₁₀ pollution > 90 µg/m³, 2019 - 2024.

Station	Period		Duration (days)	Average exceedance (µg/m ³)	EI (µg/m ³)
SV-2	08-01-2020	10-01-2020	3	22.11	66.33
IS-2	09-01-2020	10-01-2020	2	6.56	13.11
SV-2	25-01-2020	28-01-2020	4	8.89	35.56
IS-2	25-01-2020	28-01-2020	4	6.42	25.68
BT-1	26-11-2020	27-11-2020	2	7.69	15.37
IS-2	26-11-2020	28-11-2020	3	8.61	25.83
IS-2	24-02-2021	26-02-2021	3	23.34	70.03

The longest PM_{2.5} episode above 50 µg/m³, with the highest mean daily excess, was recorded in Iaşi in 2021 (Table 10). In the same 4-day interval, Suceava recorded one value above 50 µg/m³ on 22.02.2021, one day earlier, while no significant increases were observed in Botoşani. In Iaşi, PM₁₀ also exceeded the future directive’s alert threshold during this period (Table 9), while no significant increases were observed in Suceava and Botoşani.

Table 10. Episodes of PM_{2.5} pollution PM_{2.5}> 50 µg/m³, 2019 - 2024.

Station	Period		Duration (days)	Average exceedance (µg/m ³)	EI (µg/m ³)
BT-1	06-12-2019	08-12-2019	3	28.12	84.36
SV-1	26-01-2020	27-01-2020	2	4.85	9.7
BT-1	26-11-2020	27-11-2020	2	17.45	34.9
SV-1	26-11-2020	27-11-2020	2	5.07	10.14
SV-1	19-01-2021	20-01-2021	2	7.15	14.3
IS-2	23-02-2021	26-02-2021	4	26.46	105.82
BT-1	13-11-2021	14-11-2021	2	16.64	33.28
IS-2	15-03-2022	16-03-2022	2	8.97	17.94
IS-2	09-02-2023	11-02-2023	3	22.58	67.74
IS-2	29-12-2023	30-12-2023	2	7.61	15.22
IS-2	06-11-2024	08-11-2024	3	15.22	45.66

3.3.3. Toxic Load Index (TLI)

Figure 6 illustrates the annual TLI totals that met PM_{2.5} data quality objectives, classified according to the criteria in Table 6.

The TLI distribution shows large inter-annual and inter-urban variability. The most pronounced toxic episodes were recorded at IS-2 in 2021, which had the highest proportion of High and Very High days. In contrast, BT-1 showed mostly Low toxicity, while SV-1 showed intermediate values with peaks in 2021–2022.

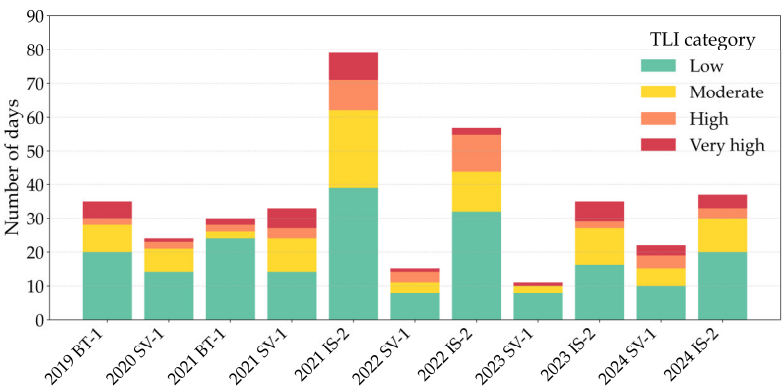


Figure 6. Distribution of TLI Levels by station and year.

4. Discussion

The retrospective analysis shows compliance with the current Air Quality Directive for both PM fractions, except for daily PM₁₀ exceedances at IS-2 in 2019 and at SV-2 in 2019 and IS-2 in 2020, when the maximum number of exceedances was reached (Table 7, Table 8, Figure 2, Figure 3).

Stricter standards set out in the Directive (EU) 2024/2881, highlight probable non-compliance, raising questions about these areas’ ability to comply with future limit values.

This misalignment underscores the importance of assessment indicators that can capture risks before future limits take effect. The study’s three indicators represent a step towards a more detailed and proactive assessment of air quality, supporting trend analysis and developing concrete measures to improve air quality.

The discussion then focuses on compliance with future standards, the relevance of the proposed indicators, interpreting the results in a local context, and the implications for public policy.

4.1. Compliance with Future Standards

The application of Directive (EU) 2024/2881 leads to a stricter reassessment of air quality, in which previously acceptable values become relevant in terms of exposure.

The new annual limit value established by Directive (EU) 2024/2881 indicates that only the annual mean concentrations measured in 2022 and 2023 at SV-1 and IS-4 would comply with the future standard. Since the data collection requirement was not met between 2022 and 2024 at SV-2 and in 2024 at IS-2, it is not possible to assess compliance for these stations in the respective years (Table 9).

Applying the daily limit values for PM₁₀ and PM_{2.5}, which will be in effect starting in 2030, provides a useful estimate of current exposure in relation to future standards. Retrospective analysis shows that, in almost all years analyzed, most stations would have exceeded the threshold of 18 daily exceedances per year. The exceptions for PM₁₀ include stations IS-4 (2019–2023; no data available for 2024), SV-1 (2019–2020; 2023–2024), and BT-1 (2021–2023). The only exception for PM_{2.5} is station SV-1 in 2022 and 2023.

The downward trend observed between 2021 and 2023 regarding the number of days exceeding the future daily limit value and cumulative excess for PM₁₀ and PM_{2.5} suggests an improvement in air quality at most monitored stations. This development may reflect the implementation of emission reduction measures [18,19] or more favorable weather conditions for pollutant dispersion. In 2024, there was a slight increase in the number of daily PM₁₀ exceedances at SV-1 and BT-1 compared to the previous year due to unfavorable meteorological conditions for pollutant dispersion. However, this increase remains considerably lower than in 2019, indicating a possible stabilization of pollution at a lower level than in previous years. At IS-2, the number of daily PM₁₀ exceedances decreased in 2024. The lack of a similar increase at IS-2 may be due to these developments not always reflecting a general regional trend but rather local factors.

This conclusion indicates that achieving the targets set for 2030 will require sustained efforts to reduce emissions in the absence of additional measures. Specific exceptions, such as station SV-1 in 2022 and 2023, demonstrate that compliance with the daily limit value is possible but depends on favorable local conditions and/or effective measures. The lack of PM₁₀ data for station SV-2 from 2022 to 2024 prevents an assessment of compliance or noncompliance with future PM₁₀ limit values.

4.2. Analysis and Relevance of the Proposed Additional Indicators

Analyzing the excess concentration and the number of hypothetical daily exceedances under the conditions of applying future limit values for PM₁₀ and PM_{2.5}, the results show that SV-2 station would face the highest exposure levels in terms of the frequency and magnitude of exceedances. The high number of daily PM₁₀ hypothetical exceedances in 2019 and 2020 (73 and 57, respectively) and the annual excess of over 1000 µg/m³ indicate a significant and sustained PM₁₀ load.

The high pollution levels recorded at the SV-2 station in 2019 and 2020 can be attributed to unfavorable weather conditions that limited pollutant dispersion, as well as residential and industrial emission sources [18]. These causes also explain why the cumulative annual PM₁₀ excess values are high, despite a slight decrease in the number of exceedances between the two years.

In contrast, if the future limit value of 45 µg/m³ had been applied at the IS-2 station, there would have been 52 concentrations above this limit in both 2019 and 2020. Assuming the same number of hypothetical exceedances, the cumulative excess of PM₁₀ relative to the limit value of 45 µg/m³ increased from 676.83 µg/m³ in 2019 to 1201.67 µg/m³ in 2020. This suggests an increase in daily PM₁₀ concentrations during pollution episodes, possibly due to sporadic local sources and specific meteorological variations. This shows that the excess concentration does not always follow the same trend as the number of exceedances.

A comparison of the two stations underscores the importance of incorporating both the number of exceedances and the cumulative excess into the analysis of PM pollution. A low number of exceedances may correspond to a low excess if the exceedances are mild. Conversely, a high excess may result from a few severe exceedances, even if the number of days is low. For instance, frequent,

moderate PM₁₀ exceedances at SV-2 generated sustained exposure, whereas rare, intense PM₁₀ pollution episodes at IS-2 may acutely impact the population's health.

The results regarding annual PM_{2.5} excess highlight spatial differences and significant temporal variations between analyzed stations. The most severe situation occurred in 2021 at station IS-2, where 83 hypothetical exceedances of the future daily limit value and an annual PM_{2.5} excess of over 970 µg/m³ were recorded. These values indicate high exposure to fine particles and significant potential to affect population health. Values recorded between 2022 and 2024 mainly fall into the Moderate or Low EC categories, suggesting an improved air quality trend, likely due to favorable weather conditions for dispersion and PM reduction measures currently being implemented or completed as part of air quality plans [20,21]. However, the persistence of moderate values at stations IS-2 and SV-1 indicates that PM_{2.5} pollution episodes have not been completely eliminated and could reoccur in contexts of unfavorable atmospheric conditions or intensified human activities. For BT-1 station, only data from 2018 and 2021 are available.

The data show that not all exceedances are the same, so differentiated emission reduction measures tailored to local source profiles and area characteristics are needed. Authorities can include the EC indicator in air quality plans or roadmaps to identify high-risk areas, even when exceedances appear low.

EI is used to analyze pollution episodes. It helps to more accurately characterize the intensity and duration of these events. This indicator was selected based on epidemiological evidence linking each 10 µg/m³ increase in PM₁₀ and PM_{2.5} concentrations with adverse health effects. A meta-analysis of 59 studies in China showed that a 10 µg/m³ increase in the average daily concentration of PM₁₀ is associated with a 0.36% increase in non-accidental mortality, a 0.36% increase in cardiovascular mortality, and a 0.42% increase in respiratory mortality. For PM_{2.5}, the same increase was correlated with greater effects: a 0.40% increase in non-accidental mortality, 0.63% in cardiovascular mortality, and 0.75% in respiratory mortality [19]. Another study in Brescia, Italy, showed that a 10 µg/m³ increase in the average daily concentration of PM₁₀ leads to a 5.7% increase in emergency room visits and a 6.5% increase in hospitalizations for patients with chronic lung disease, both one day after exposure and after five consecutive days. For PM_{2.5}, the effects were more pronounced: a daily increase of 10 µg/m³ was associated with increased risks of 7.4% for emergency visits and 9.1% for hospitalizations one day after exposure, and 8.3% and 9.9% after five days of exposure [12]. The risk appears to be higher for PM_{2.5} exposure, due to PM_{2.5}'s ability to penetrate deeper into the respiratory tract [6].

The high PM₁₀ EI values observed at stations IS-2 and SV-2 in 2020 and 2021 reflect short, intense episodes lasting two to four days and characterized by concentrations above the alert threshold. The daily excess average ranged from 6.42 µg/m³ to 23.34 µg/m³.

The highest EI indicator value for the two particle fractions during the entire study period was recorded for PM_{2.5}: 105.82 µg/m³·day at station IS-2 compared to the 50 µg/m³ alert threshold. This episode lasted four days, with an average daily excess of 26.46 µg/m³. This value confirms the Extremely High classification and highlights a high level of sustained exposure with a potentially significant impact on public health.

In 2020, each PM₁₀ pollution episode occurred within the same time intervals at at least two monitoring stations, suggesting that these were not isolated local events but rather influenced by common meteorological conditions (e.g., thermal inversions, air stagnation) or regional pollution sources.

In the case of PM_{2.5}, a pollution episode was observed to occur simultaneously at two different stations in only one situation.

It is more difficult to compare episodes between the analyzed stations for PM_{2.5}, mainly due to the frequent lack of data from the Botoşani station. Even in the four episodes (Table 10), for which there were complete records at all stations, only one station exceeded the 50 µg/m³ threshold for at least two consecutive days, and this was not confirmed in the other two urban areas. Similar

situations were recorded when data were available at both SV-1 and IS-2, with the exceedance confirmed at only one station.

This difference can be attributed to the distinct characteristics of the two particle fractions. PM₁₀ is more influenced by common local or regional sources, such as road traffic and resuspension, while PM_{2.5} frequently originates from combustion and secondary formation processes in the atmosphere. PM_{2.5} is more influenced by short-term and local atmospheric variations.

Comparing EI between locations and periods allows for better prioritization of interventions and can guide the adoption of appropriate local measures, such as restricting traffic during periods of thermal inversion and closely monitoring emissions from industrial installations.

Analysis of the TLI indicator at the three monitoring stations reveals significant variability in air toxicity among years and stations, with frequent episodes of moderate to very high toxic load. Generally, stations BT-1 and SV-1 recorded the highest proportions of days with low toxicity (>50%) in 2021 and 2023, indicating periods of lower toxicity.

Analysis of the cumulative proportion of days with high and very high toxicity by station shows that no year at station BT-1 exceeded the 25% threshold, indicating a low incidence of episodes with a high toxic load. In contrast, episodes of more severe toxicity were recorded at station SV-1 in 2021 (27.3%), 2022 (26.7%), and 2024 (31.8%). Although the cumulative share did not exceed 25% at station IS-2 in any year (with maximum values of 23% in 2023 and 19% in 2022), the absolute number of days with high toxicity remains significant due to the higher number of daily PM_{2.5} exceedances. These results confirm the usefulness of the TLI indicator for identifying areas and periods where exposure to pollutants poses a higher risk, even when the number of daily exceedances or annual averages does not indicate noncompliance.

Integrating this indicator into current monitoring would allow for a more comprehensive assessment of health risks and support the development of intervention measures tailored to locally specific conditions.

4.2. Relevance to Public Policy Development

Proposing additional indicators, such as EC, EI, and TLI, could provide a stronger scientific foundation for creating differentiated public policies for urban areas and aligning them with future limit values.

These indicators offer supplementary information beyond that provided in current air quality directives, enabling a more detailed characterization of particulate matter and a clearer understanding of its sources and toxicity. This added value enables the differentiation of pollution reduction measures and facilitates the transition from general interventions based solely on the concentration and frequency of PM₁₀ and PM_{2.5} exceedances to public policies tailored to local specifics and aimed at reducing the actual impact on public health and the environment. These findings highlight the need for public policies that are adapted to local emission source characteristics and atmospheric dispersion conditions.

Specialist literature and recommendations from advisory bodies, such as COMEAP in the UK, emphasize the necessity of indicators beyond daily average concentrations[11].

One example is the method proposed by Cariolet et al. (2018), which applies the concept of urban resilience to outdoor air pollution. This method defines three “resilience capacities”: reducing emissions, reducing concentrations, and reducing population exposure. In the greater Paris area, the implementation of this GIS-based “quick scan” method, which uses a 500-meter grid, allowed for the precise identification of areas in urgent need of intervention. Combining similar approaches with the indicators proposed in this study could support proactive, tailored policies to reduce air pollution in urban environments[24].

Cazacu et al. (2024) propose a public policy emphasizing the importance of including the “cumulative effect of pollution” in national legislation. This refers to the interaction between multiple pollutants [25]. Although the proposed indicators (EC, EI, and TLI) are limited to particulate matter

(PM₁₀ and PM_{2.5}), they could partially fulfill this requirement by quantifying cumulative exceedances, episode duration, and toxicological potential.

4.3. Recommendations for Reducing Particulate Matter

Based on the existing information and results, as well as the analysis of the proposed indicators (EC, EI, and TLI), recommendations can be made to reduce the concentration of particulate matter (PM₁₀ and PM_{2.5}) and decrease population exposure.

According to the Integrated Air Quality Plan for Nitrogen Dioxide/Nitrogen Oxides (NO₂/NO_x) and PM₁₀ and PM_{2.5} in the city of Iași [21], in 2018, the main source of particulate emissions was the production of asphalt mixtures for road paving. This process generated 71.767 tonnes of PM₁₀ and 18.074 tonnes of PM_{2.5}. The second-most important source was the residential sector (heating homes and cooking), which emitted 57.97 tonnes of PM₁₀ and 56.61 tonnes of PM_{2.5}. Road transport ranked third, contributing 47.254 tonnes of PM₁₀ and 32.923 tonnes of PM_{2.5}.

Although road paving generated the highest emissions in 2018, the highest concentrations of PM₁₀ and PM_{2.5} were recorded during the cold season [19], not in the summer when most of the work takes place. Therefore, the direct impact of asphalt paving on air quality in winter is relatively low. Priority measures should target the dominant sources of pollution during the cold season: residential heating with wood in areas bordering the municipality, heavy road traffic, and polluting vehicles.

Temporary traffic restriction measures have shown varying degrees of effectiveness in reducing concentrations of particulate matter.

In Beijing in 2007, restrictions that were in place for four days, from 6:00 a.m. to 11:00 p.m., led to a 6–15% decrease in hourly PM₁₀ concentrations in the urban area [26]. During international marathons in Lanzhou, implementing traffic restrictions for several hours led to significant reductions in submicron particles. Decreases of up to 67% were recorded for very fine particles in the 100–200 nm range, which are part of PM_{2.5}. This demonstrates that the restrictions are particularly effective in reducing the finest particles [27].

In areas with high cumulative PM levels and fewer exceedances (e.g., IS-2), the following measures are recommended to limit pollution peaks: restricting traffic during periods of thermal inversion, redirecting traffic flows, establishing systems to restrict vehicle access to cities, including low-emission and zero-emission zones, encouraging behavioral changes and protecting the health of children and other sensitive and vulnerable population groups [6].

A steady decline in annual PM concentrations is difficult to predict because weather conditions significantly influence these levels from year to year.

The mentioned plan, which has not yet been adopted [21], provides for measures for the period 2024–2028 to modernize traffic arteries, build a bypass around the municipality of Iași, encouraging the introduction of electric and hybrid vehicles in taxi services, banning cars with lower pollution standards in the municipality of Iași, encouraging the use of public transport by expanding the tram infrastructure, thermal rehabilitation of residential buildings, maintenance and expansion of green spaces, etc. By implementing these measures, IS-2 forecasts an average annual concentration of 32.163 µg/m³ for PM₁₀ and 20.204 µg/m³ for PM_{2.5} in the projection year 2024, values below the VL according to current legislation, but above the future directive limits. Also, according to this plan, it is expected that by the end of 2028, the current limit value of 50 µg/m³ will be exceeded on 32 days for PM₁₀.

According to the Air Quality Plan for the Municipality of Suceava, for PM₁₀ suspended particles [20], in 2018, the main source of PM₁₀ emissions in Suceava Municipality was road transport, which contributed 47.197 tons of PM₁₀, followed by electricity and heat production, which generated 24.656 tons of PM₁₀, and residential heating, with 19.358 tons of PM₁₀. Another significant source of emissions was the asphalt mixing process, which contributed 5.018 tons.

Long-term measures are recommended for areas with frequent exceedances and high cumulative excesses, such as the Suceava municipality. One measure is reducing emissions from small and medium-sized stationary combustion sources (including biomass) by replacing them.

Progiou et al. (2023) used a regression model to quantify the impact of biomass heating on PM₁₀ concentrations, highlighting that reducing emissions by 45% could eliminate daily exceedances of the limit value. Based on these results, the researchers proposed a cost-effective package of measures, including replacing biomass heating with natural gas systems, promoting heat pumps, taxing residential biomass, and modernizing the vehicle fleet. When these measures were applied in an air quality modeling simulation, there was a 67% reduction in exceedance episodes [28].

Therefore, similar measures, such as encouraging the transition to clean heating sources and implementing temporary bans during critical episodes, can significantly contribute to meeting the new thresholds established by Directive (EU) 2024/2881.

For coarse particulate matter in urban areas in the summer, street washing is recommended. A study in Krakow showed that sweeping and washing streets reduced PM₁₀ and PM_{2.5} concentrations by 17.3% and 15.4%, respectively, for up to three days. The greatest reduction was recorded in areas with heavy traffic. The effect was smaller in residential and industrial areas. Although temporary, street cleaning significantly improves air quality [17].

The plan includes measures to modernize the vehicle fleet from 2023 to 2027. These measures include replacing diesel buses with electric buses, modernizing traffic arteries, thermally rehabilitating residential buildings, expanding the natural gas network, and offering tax incentives for citizens to connect to the natural gas system[20]. The plan's developer predicted that implementing the measures would result in an average annual PM₁₀ concentration of 27.193 µg/m³ at SV-2 and 22.134 µg/m³ at SV-1. These values are below the current legislation's limit of 40 µg/m³, but above the limit of 20 µg/m³ according to future directives. According to the plan, it was also predicted that, by 2027, there would be 20 values above the limit value of 50 µg/m³ at SV-2 and 6 at SV-1 (below the maximum allowed 35 times).

The decrease in PM concentrations after 2020 suggests that effective measures have been implemented in IS and Suceava to reduce particle emissions. However, it is possible that the reduction observed from 2021 to 2023 will not be sufficient under less favorable atmospheric dispersion conditions.

To fall below the future limit value of 45 µg/m³ (not to be exceeded more than 18 times), it is proposed that additional measures continue to be implemented in both SV-2 and IS-2.

Other measures that may be considered include those set out in Annex VIII, point B of Directive 2024/2881, such as the introduction of low-emission zones (LEZ)

An LEZ is an area that only allows vehicles classified as low PM₁₀ emission vehicles to enter. All highly polluting vehicles are banned from LEZs. To date, LEZs have been implemented in 152 cities across nine EU countries. Germany, in particular, has been at the forefront of global LEZ efforts [29].

Since 2008, Germany has introduced LEZs in numerous cities to comply with air pollutant limit values. These zones have led to reductions of up to 10% in PM₁₀ concentrations [30,31].

In Munich, introducing LEZs and restricting heavy traffic (>3.5 tons) resulted in reductions of up to 19.6% in summer and 6.8% in winter at a traffic monitoring station, as well as reductions of up to 5.7% in summer and 3.2% in winter in urban background areas. The most pronounced effects occurred on Fridays and weekends during the summer [28]. In Berlin, traffic-related soot concentrations decreased by 52% between 2007 and 2010 [31]. Although the overall decrease in PM₁₀ was moderate, the reduction in toxic components, such as very fine particles and components of PM_{2.5} resulting from diesel combustion that may contain heavy metals and polycyclic aromatic hydrocarbons, indicates significant health benefits.

Classifying the EI indicator into different intervals ensures that the intensity of pollution episodes correlates with differentiated intervention measures. Episodes in the High categorie, for example, can be managed through awareness and prevention measures. In contrast, those in the Very High categorie and Extremely high categorie require restrictive interventions on local sources of pollution. This classification provides a practical tool for rapid decision-making at the local level.

In areas where recurrent or persistent episodes have been identified, such as IS-2 and SV-2 stations, EI can guide investments in local forecasting.

TLI assesses average pollution levels and the temporal and qualitative profile of toxic exposure, making it relevant for planning environmental measures according to each location’s characteristics.

5. Conclusions

A retrospective assessment of PM₁₀ and PM_{2.5} concentrations in three Romanian cities compared to the 2030 limit values provides an estimate of how close they are to the new European requirements.

The results indicate that Suceava and Iași are likely to exceed the limit values for both PM fractions without additional measures. To achieve this objective, specific measures must be taken at the local level that are adapted to the area’s topography, prevailing weather conditions, and local resources. In Botosani, there is not enough data to assess future limit values.

The study shows that the proposed indicators (EC, EI, and TLI) offer a more detailed characterization of suspended particles. They do so by capturing the magnitude of exceedances, the intensity of pollution episodes, and the toxic load.

Due to their practical nature, these indicators can be useful tools for authorities by facilitating real-time decision-making and the long-term evaluation of pollution reduction measures.

Additionally, the indicators can be correlated with epidemiological data to estimate health impacts and support communication with the population through more easily interpretable indices.

Further studies are needed to validate the proposed indicative thresholds for these indicators depending on dominant pollution sources and urban characteristics to ensure uniform applicability across different regions.

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Abbreviations

The following abbreviations are used in this manuscript:

AQG	Air Quality Guidelines
EC	Excess Concentration
EI	Episode Index
PM	Particulate matter
TLI	Toxic Load Index
WHO	World Health Organization
LEZ	Low emission zone

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