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Original scientific paper

ASSESSMENT OF AIR QUALITY MANAGEMENT STRATEGIES IN SKOPJE: LONG-TERM PM TRENDS AND REGULATORY COMPLIANCE 2016–2025

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Abstract: Air quality remains a persistent challenge in urban environments, particularly in cities with complex emission structures and seasonal variability. This paper investigates air quality management strategies in Skopje from 2016 to 2025, emphasizing particulate matter (PM) concentrations and long-term pollution trends. The methodology integrates multi-year monitoring data with statistical processing, graphical interpretation, and an assessment of dominant emission sources. A significant portion of the study evaluates the relationship between national regulatory practices and the European Union framework to determine practical alignment. By synthesizing technical observations with the regulatory context, this paper offers a grounded perspective on the evolution of air quality management over the analyzed decade.

Key words: air quality; particulate matte;, urban pollution; regulatory alignment

ПРОЦЕНА НА СТРАТЕГИИТЕ ЗА УПРАВУВАЊЕ СО КВАЛИТЕТОТ НА ВОЗДУХОТ ВО СКОПЈЕ: ДОЛГОРОЧНИ ТРЕНДОВИ НА PM ЧЕСТИЧКИТЕ И УСОГЛАСЕНОСТ СО РЕГУЛАТИВАТА 2016–2025

Апстракт: Квалитетот на воздухот претставува постојан предизвик во урбаните средини, особено во градовите со комплексни емисиони структури и сезонска варијабилност. Овој труд ги истражува стратегиите за управување со квалитетот на воздухот во Скопје во периодот 2016–2025 година, со акцент на концентрациите на суспендираните честички (PM) и долгорочните трендови на загадување. Методологијата интегрира повеќегодишни податоци од мониторинг со статистичка обработка, графичка интерпретација и процена на доминантните извори на емисија.Значителен дел од студијата го оценува односот помеѓу националните регулаторни практики и рамката на Европската Унија за да се утврди практичната усогласеност. Преку синтеза на техничките набљудувања со регулаторниот контекст, трудот нуди перспектива за еволуцијата на управувањето со квалитетот на воздухот втемелена во анализираниот период.

Клучни зборови: квалитет на воздух; суспендирани честички; урбано загадување; регулаторна усогласеност

INTRODUCTION

Ambient air pollution is a major environmental and public health concern [1]. Across European urban centers, it remains one of the most critical challenges, driving urgent regulatory reforms [2]. Specifically, Skopje has historically experienced severe exceedances of particulate matter limit values, generating substantial socio-economic and health implications [3]. Alongside anthropogenic emissions from heating and traffic, the city's specific urban morphology and continuous spatial expansion further complicate the effective dispersion of pollutants [4]. The primary objective of this work is to systematically evaluate the evolution of air quality management strategies over a decade. Driven by the complex interaction of these emission sources and meteorological conditions, Skopje serves as a representative urban case study.

The city's valley topography severely limits horizontal airflow. During winter, frequent temperature inversions reduce vertical exchange, causing the Planetary Boundary Layer (PBL) altitude to frequently drop below 200 m [5]. This fundamentally dictates the volume available for pollutant dispersion and drastically increases PM concentrations. Furthermore, radiational cooling at night forms a highly stable, shallow nocturnal boundary layer that traps ground-level emissions. Morning solar radiation then increases the PBL height, improving vertical mixing. These diurnal PBL oscillations are a key mechanism driving the daily variability of pollution.

To address these severe physical limitations on pollutant dispersion, robust regulatory frameworks are essential. While the national "Ambient Air Quality Act" [6] mandates institutional air quality planning, it lacks specific legal instruments for individual protection. In contrast, the new EU Directive 2024/2881 [7] introduces legal liability and the right to compensation for health damages caused by non-compliance with air quality standards (Article 28), transforming regulation from mere governance into strict accountability.

While existing studies extensively document the localized health impacts and meteorological drivers of pollution in Skopje, there is a notable gap in synthesizing long-term technical monitoring data with the evolving legal frameworks. Previous literature lacks a comprehensive, decade-long analysis of pollution trends across different urban zones, evaluated directly against the stringent new European standards. To address this, the present study provides a combined long-term statistical and regulatory assessment of air quality in the city in the period of 2016–2025. The scientific added value of this research lies in integrating advanced heatmap visualizations of a ten-year continuous dataset with a direct comparative analysis between national legislation and the newly introduced EU Directive 2024/2881, offering a practical perspective on urban air quality management.

METHODOLOGY

The research methodology is structured into four distinct phases: data collection, data preprocessing, data processing, and data visualization and analysis, as illustrated in the flowchart in Figure 1.

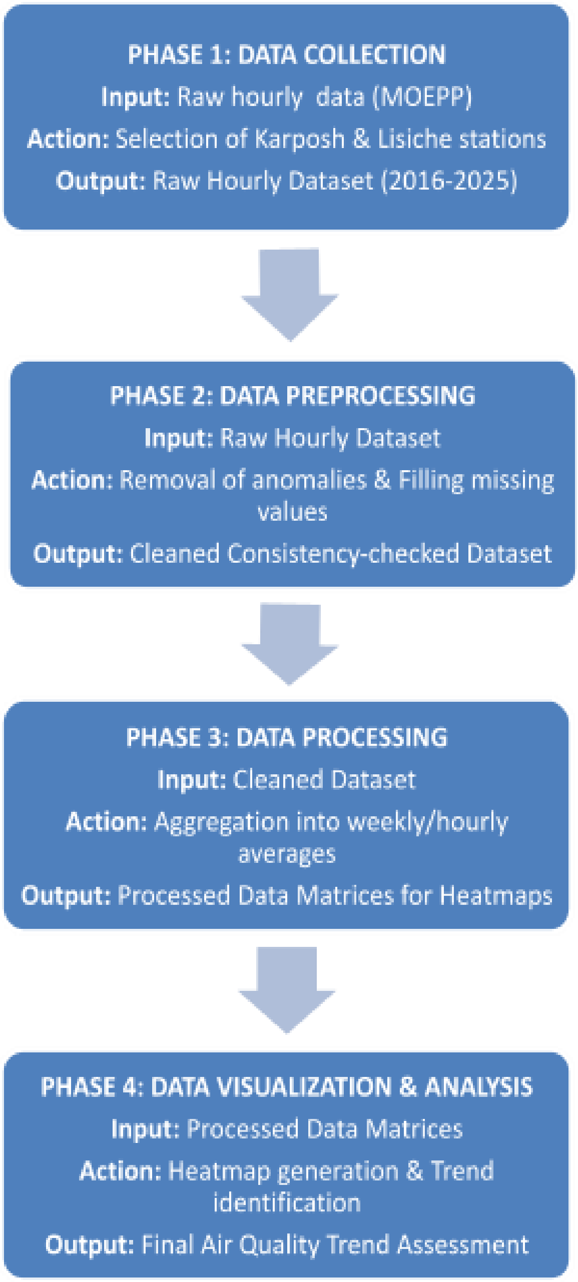

Fig. 1 Flowchart of the four-phase air quality assessment methodology

Phase 1: Data collection: The initial phase involved the acquisition of raw hourly data for particulate matter (PM$_{2.5}$ and PM$_{10}$) from the authorized State Automatic Air Quality Monitoring System (SAAQMS), governed by the Ministry of Environment and Physical Planning (MOEPP). The analyzed dataset spans a comprehensive 10-year period, from January 2016 to December 2025. To capture the spatial distribution of pollutants and the diverse urban microenvironments within the Skopje agglomeration, two specific monitoring stations were selected: Karposh and Lisiche. This selection was not random but based on their distinct geographical positioning (Karposh in the western part, and Lisiche in the eastern part of the city) and their varying proximity to major emission sources. Together, these locations provide a representative overview of the three primary types of polluters: industrial facilities, urban traffic, and residential households. The exact geographical coordinates of the stations were provided by MOEPP. Furthermore, all measurements were recorded at a standard height of 1.5 meters above ground level, which accurately represents the average human inhalation height for ambient air.

Phase 2: Data preprocessing: Following data retrieval, the raw hourly datasets were integrated into Microsoft Excel for preprocessing. This phase included systematic data sampling and the rigorous removal of measurement anomalies. Specifically, negative values resulting from instrument calibration errors and extreme outliers exceeding three standard deviations (the 3-sigma rule) from the weekly mean were excluded. To ensure temporal continuity without distorting the statistical baseline, isolated data gaps of one to two hours were addressed using linear interpolation. Larger missing intervals were reconstructed utilizing mean diurnal profile imputation for the respective month, thereby preserving the natural seasonal variance of the dataset prior to further analysis.

Phase 3: Data processing: The cleaned dataset was subsequently processed to extract meaningful temporal trends. Using time-series aggregation and arithmetic averaging in Excel, the data matrices were structured. This involved the precise calculation and adoption of values to generate average weekly profiles and average hourly profiles, allowing for the isolation of specific pollution peaks related to time of day or day of the week.

Phase 4: Data visualization and analysis: In the final phase, the processed data matrices were utilized to construct heatmaps for trend identification. The heatmaps were developed entirely within Microsoft Excel using custom formulas and conditional logic. A continuous color gradient was applied to visually represent pollution intensity: green indicates minimal pollution values (clean air), progressively transitioning through darker shades as concentrations increase, culminating in dark red, which signifies the maximum recorded pollution values (heavily polluted ambient air). This visualization method directly correlates temporal patterns with the exact intensity of the aerosol pollution.

RESULTS AND DISCUSSION

Temporal distribution and heatmap analysis

The long-term temporal dynamics of PM_{10} concentrations in Skopje are visualized through heatmap diagrams for the Karposh (Table 1) and Lisiche (Table 2) monitoring stations. These diagrams map average weekly values over a ten-year period. The numerical values presented within these specific heatmaps represent the average weekly concentrations of PM_{10}. These weekly arithmetic means were derived by aggregating the preprocessed base dataset of continuous hourly measurements over the ten-year period (2016–2025). This level of temporal aggregation was selected to smooth out short-term daily anomalies while effectively highlighting broader intra-annual pollution patterns.

The analysis indicates a clearly expressed seasonal variability, with high-concentration zones consistently localized in the winter months (weeks 1–8 and 46–52). This specific winter period corresponds to the peak heating season and is characterized by stable atmospheric conditions and a reduced Planetary Boundary Layer (PBL) height.

- Karposh station analysis: The patterns in Karposh show a more uniform distribution during transitional periods, likely due to the continuous influence of traffic emissions. However, even here, a noticeable cooling of colors (reduction in intensity) is observed in the middle section of the heatmap (weeks 15–35) across the years.
- Lisiche station analysis: The Lisiche heatmap shows significantly higher intensities compared to Karposh, particularly during the winter months. The "winter blocks" in Lisiche are more persistent, confirming the heavy impact of domestic heating with solid fuels in this residential area.
- Station comparison and trends: A comparison of the two locations reveals that Lisiche consistently exhibits 20–30% higher peak concentrations than Karposh during winter episodes. Quantitatively, the analysis between 2016 and 2025 indicates a significant improvement. In Karposh, annual average PM_{10} levels decreased by 48.3% (from 60.1 to 31.1 $\mu g/m^3$), while Lisiche showed a 36.7% reduction (from 79.1 to 50.1 $\mu g/m^3$). While summer concentrations remain relatively constant, the most significant reductions are observed during the transitional and winter heating periods.

Table 1

Heatmap diagram of PM$_{10}$ concentrations at the Karposh monitoring station (2016–2025), illustrating seasonal variability and recurring high-concentration periods

Karposh PM10 (weekly)	Average weekly value expres sed in μg/m^3									
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	182.56120	91.44872	123.31770	56.62316	95.97423	43.57508	79.47143	112.71770	103.61530	75.82043
2	74.31954	202.67620	99.48969	88.50186	93.37574	32.25149	53.18730	54.66958	54.51989	49.17936
3	75.52323	149.36090	61.08989	184.2088	58.63337	113.67340	46.77842	47.56213	65.60342	45.28156
4	171.37460	177.80170	111.65490	71.64726	122.80550	40.47786	61.92285	20.24847	40.10242	75.52399
5	80.12107	268.34070	115.56090	115.5683	95.29230	74.77736	71.57192	37.46883	66.24348	52.81936
6	61.78221	73.74274	67.63859	54.84367	48.10064	43.14440	52.18345	51.89683	102.71700	47.51001
7	56.44329	101.12320	60.49661	38.4974	67.35926	85.69476	63.25355	67.04438	45.09261	55.67441
8	56.57347	87.56284	37.11607	75.83544	55.70456	73.52352	35.77959	50.87795	46.37467	42.73810
9	37.22364	66.19157	62.81000	49.56776	48.38952	50.21358	49.85753	38.92049	39.85993	47.33244
10	35.53433	35.89087	48.96774	66.58307	32.39596	53.52090	33.81413	37.60614	26.82423	43.10547
11	34.78659	48.49297	45.19760	46.6313	35.17288	28.89199	47.98573	29.72197	26.00280	39.48523
12	38.57724	58.52119	38.57076	38.96651	40.84826	38.62813	39.36827	39.20333	28.99315	27.03661
13	50.79199	38.75446	39.61183	42.87281	44.37941	31.33099	42.80673	22.37894	29.25106	19.99217
14	44.20056	28.10580	34.41134	47.68231	33.11706	27.81780	28.55027	22.86277	33.57013	13.09713
15	40.07163	34.01651	53.61620	20.85083	27.12182	26.93147	30.53695	20.46636	36.21519	22.17650
16	37.50890	21.20526	39.60990	26.85436	28.24887	25.33556	26.95451	21.30057	23.60881	17.61566
17	21.78841	40.52203	46.22379	49.43697	24.22082	38.97549	22.42846	23.71989	15.37174	16.16186
18	18.74104	38.64804	44.35433	24.86283	22.16746	27.05174	25.02911	20.52822	15.46366	20.01056
19	26.65869	28.69169	29.06564	25.19376	21.90993	22.49387	32.84791	17.31142	14.72059	18.85910
20	22.36131	26.31447	22.29460	24.18371	45.94420	24.36598	26.49547	26.60126	19.81221	13.25547
21	27.23349	23.41117	27.05357	22.16750	31.65895	31.77810	39.49049	22.80884	21.65453	15.45376
22	26.97460	27.55042	34.18114	–	15.52020	26.22417	34.52614	22.40078	23.57344	14.75524
23	24.25271	28.37833	29.72357	–	21.63581	29.30227	27.33287	26.38415	29.89156	24.23007
24	24.60370	30.63860	31.40862	46.00077	23.49700	28.18472	24.48960	18.55170	37.85811	22.03135
25	42.88807	34.99176	25.45899	33.50267	15.44317	52.71544	36.53592	31.76894	52.13440	19.81240
26	30.22557	48.26363	21.84719	–	20.48651	40.25627	31.45673	21.22618	28.23030	22.37524
27	24.48416	31.18580	33.97461	32.17873	27.95412	36.83772	29.17820	23.11870	22.83049	19.73321
28	30.89600	33.73711	27.63574	30.38013	27.36991	34.97265	–	34.00774	34.00709	19.75684
29	28.20360	36.09125	30.93781	–	22.83910	28.06892	31.26793	37.25939	34.89667	18.71853
30	35.33226	31.11299	24.57169	27.67323	19.01017	47.47722	29.19150	20.51528	22.99174	34.79323
31	32.57830	38.62851	31.06987	26.59503	22.15887	47.14270	25.24438	24.82698	27.95010	13.93669
32	26.92590	44.65187	35.95551	–	24.74570	33.02322	20.52926	18.37960	19.85799	17.09317
33	44.48154	35.87954	32.03443	27.78287	–	28.43257	29.14734	33.31627	37.57757	26.80184
34	28.66051	31.80164	34.27459	42.70190	–	37.62453	31.72647	38.69202	24.52940	18.24733
35	42.73030	39.19270	32.72446	39.86597	–	25.46464	25.19068	25.22642	34.28607	24.48689
36	42.52754	32.77221	31.75764	39.51707	–	28.74853	21.30820	27.59800	51.79239	18.66869
37	61.83666	36.94603	34.30400	33.96176	–	40.39662	22.82322	35.34971	13.25363	23.36657
38	37.26067	29.59374	46.23320	32.36835	–	26.65276	15.78434	44.05665	15.42695	19.33077
39	67.13931	28.94846	34.43549	30.92547	–	33.97154	25.09577	31.65312	24.00619	21.12807
40	47.79514	37.86460	46.57454	29.52047	31.06047	25.98606	28.05421	34.31919	17.96864	10.30657
41	66.91759	53.97864	43.58766	38.00127	32.52072	14.26250	31.94263	50.79380	17.18819	12.51896
42	33.84209	87.94297	62.34853	55.13636	21.99789	48.19015	36.26293	35.28338	26.03383	22.66496
43	68.92306	34.75450	49.05707	74.64382	55.27790	66.10764	37.76416	37.91788	43.99203	26.36680
44	82.11958	70.37434	73.30069	44.76658	47.07670	56.03758	55.58927	28.99420	39.55801	28.29567
45	54.15353	89.05047	101.72560	33.86322	64.48902	52.46002	46.47875	28.80036	60.07709	24.55001
46	122.08500	44.52933	85.56866	48.34937	114.6545	69.98255	56.55923	30.66173	29.79906	36.74447
47	141.0769	120.08740	60.19500	46.43100	68.51273	54.24000	28.76502	29.86216	40.30739	24.04859
48	83.16847	56.22856	70.28774	42.88383	141.56340	56.13800	59.25830	45.44793	47.60940	22.35417
49	216.3018	97.88880	138.19740	81.63167	96.85448	37.63568	47.72418	59.60908	29.35347	42.42966
50	121.8411	185.63180	74.48090	56.17770	61.04939	26.22426	34.08209	43.14992	39.84603	53.46763
51	221.87980	40.81356	102.15040	52.59775	47.27292	112.46102	114.01230	93.16704	52.61041	145.29510
52	46.05465	107.51610	92.19563	16.73401	84.03221	66.00155	123.14260	157.12230	24.26330	42.70976
Annually	60.13769	63.42649	53.60008	48.89023	48.96683	41.75828	39.17898	37.21285	34.97302	31.07103

Table 2

Heatmap diagram of PM_{10} concentrations at the Lisiche monitoring station (2016–2025), illustrating seasonal variability and recurring high–concentration periods

Lisiche **PM10** (weekly)	Average weekly value expressed in μg/m³									
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	258.7	138.8	207.5	–	171.1	44.4	109.7	147.9	130.9	150.2
2	102.9	225.9	144.7	–	133.5	40.9	67.5	73.6	66.7	116.2
3	110.0	162.4	83.8	–	79.4	130.2	75.0	70.2	116.8	72.1
4	252.9	207.5	151.8	–	183.8	61.9	71.8	29.7	35.5	100.3
5	128.6	331.5	150.0	–	158.2	147.1	94.6	56.7	109.7	102.5
6	91.6	109.7	92.8	–	70.0	53.4	66.0	89.4	138.8	73.9
7	68.2	116.5	92.1	–	107.0	131.3	79.0	127.0	69.9	76.4
8	68.7	110.8	44.1	–	74.4	130.2	43.4	91.7	60.2	58.6
9	41.4	69.0	80.7	–	63.4	79.9	51.3	42.1	46.6	65.5
10	37.7	35.3	58.9	–	40.5	65.0	34.7	48.4	34.1	78.7
11	43.9	58.8	44.1	–	55.5	29.5	55.0	41.5	33.0	47.4
12	38.0	54.7	43.8	–	66.5	47.0	48.5	59.7	41.0	38.9
13	54.8	40.1	42.3	–	49.0	37.0	41.8	29.3	29.8	30.9
14	41.2	25.0	35.0	–	38.1	36.8	26.3	26.9	37.9	22.7
15	33.9	29.8	43.1	–	41.9	29.0	35.0	25.9	39.8	35.9
16	34.2	20.6	34.5	–	35.2	29.9	29.1	27.2	25.4	25.0
17	27.2	34.8	38.6	–	24.7	38.9	25.0	25.2	23.2	25.8
18	21.8	34.6	37.6	–	24.8	27.4	26.8	21.6	20.2	25.8
19	30.7	25.7	32.0	–	26.0	22.4	31.2	17.7	20.3	24.0
20	24.7	25.3	24.7	–	54.4	23.4	28.3	27.3	26.5	20.0
21	30.6	24.8	33.4	–	34.1	29.5	33.4	26.1	28.7	25.5
22	28.0	29.0	36.6	–	16.1	26.3	33.7	20.9	23.5	24.2
23	22.9	28.5	40.0	–	19.8	27.3	20.7	24.3	28.9	35.0
24	25.8	38.8	42.4	–	26.9	26.9	25.6	19.7	32.7	33.9
25	39.3	40.1	39.4	–	19.8	60.6	29.9	33.3	54.0	32.4
26	38.8	43.0	28.9	–	21.9	37.8	28.8	23.5	27.5	33.3
27	56.2	31.4	45.5	–	28.9	32.9	22.3	22.7	23.7	32.3
28	60.7	33.0	32.5	–	31.5	35.4	26.4	32.9	31.8	33.5
29	60.2	34.4	33.8	–	21.3	26.9	30.0	39.7	33.2	30.5
30	63.2	25.3	31.1	–	23.8	56.0	29.3	27.1	24.0	40.5
31	68.5	30.6	34.5	–	31.3	42.3	25.4	22.9	29.1	21.3
32	42.2	42.5	35.4	–	20.7	35.2	21.2	16.1	21.9	23.9
33	46.9	37.0	34.6	–	34.3	33.9	32.1	29.6	35.5	30.8
34	33.6	32.6	40.6	–	26.4	32.4	34.4	35.4	27.4	26.0
35	48.0	38.9	44.0	–	36.1	28.4	24.5	26.0	32.3	29.3
36	26.8	33.7	36.2	–	34.1	29.4	26.4	22.0	45.1	28.4
37	53.6	39.9	35.1	–	44.4	46.6	30.3	37.8	16.9	44.6
38	33.2	31.2	40.8	–	47.9	31.1	25.0	44.4	24.3	26.6
39	68.5	39.4	29.9	–	32.7	32.2	32.1	32.3	30.7	31.7
40	–	55.1	41.2	–	28.4	23.9	42.0	37.9	25.0	18.9
41	–	51.2	–	–	36.9	16.6	39.0	40.8	30.1	21.9
42	37.8	73.6	–	–	28.1	57.4	59.2	30.7	35.5	35.7
43	67.5	48.5	–	–	74.1	82.2	71.4	42.5	62.4	39.8
44	108.4	93.1	–	–	70.5	63.7	79.3	35.8	62.1	64.0
45	67.1	104.0	–	–	79.6	80.9	74.7	36.8	89.7	44.7
46	182.9	50.7	–	–	158.0	70.6	78.1	45.3	42.6	79.5
47	185.5	177.1	–	–	95.0	61.0	53.1	61.9	73.6	42.1
48	114.2	79.7	–	–	198.2	67.4	74.2	63.7	109.6	34.4
49	302.9	140.2	–	–	109.7	40.7	64.9	73.5	55.5	85.8
50	169.9	226.6	–	–	87.6	31.2	44.2	94.1	69.8	106.8
51	296.3	68.1	–	75.4	61.6	148.7	179.9	163.9	120.3	199.8
52	63.0	156.3	–	35.1	107.1	93.5	171.0	215.8	49.0	57.2
Annually	79.1	73.8	55.5	55.2	61.2	52.2	50.0	49.2	48.1	50.1

Comparative analysis of daily concentration trends (2016 vs. 2025)

To further evaluate the long–term trends, a direct comparative analysis of daily PM_{10} concentrations was performed. While the heatmap analysis focuses on weekly aggregations, Figure 2 provides a higher–resolution comparison between the initial year of the study (2016) and the final year (2025) across a full 365–day cycle.

The daily time–series analysis confirms a substantial reduction in both the frequency and the magnitude of extreme pollution episodes. In 2016 (represented by the orange/red line), peak daily concentrations frequently exceeded 300 μg/m³. In contrast, the 2025 profile (blue line) exhibits a significant downward shift. Although the characteristic seasonal variability remains, the winter peaks in 2025 are approximately 40% lower than those recorded in 2016, indicating a significant decrease in the most severe pollution events over the analyzed decade.

A similar evaluation was conducted for the Karposh station, as shown in Figure 3. Although Karposh generally exhibits lower absolute PM_{10} concentrations compared to Lisiche, the relative improvement over the decade is even more pronounced. This station represents an urban environment with heavy traffic influence, making it a critical indicator for assessing urban mobility and general air quality management.

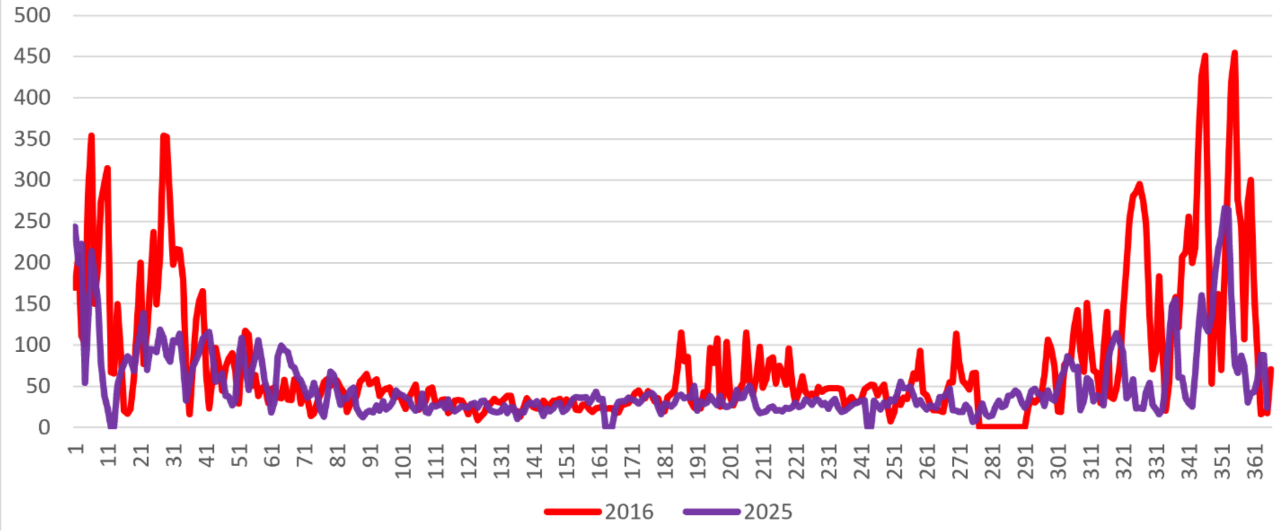

Fig. 2. Comparison of daily PM_{10} concentrations (μg/m³) at the Lisiche monitoring station for the years 2016 and 2025

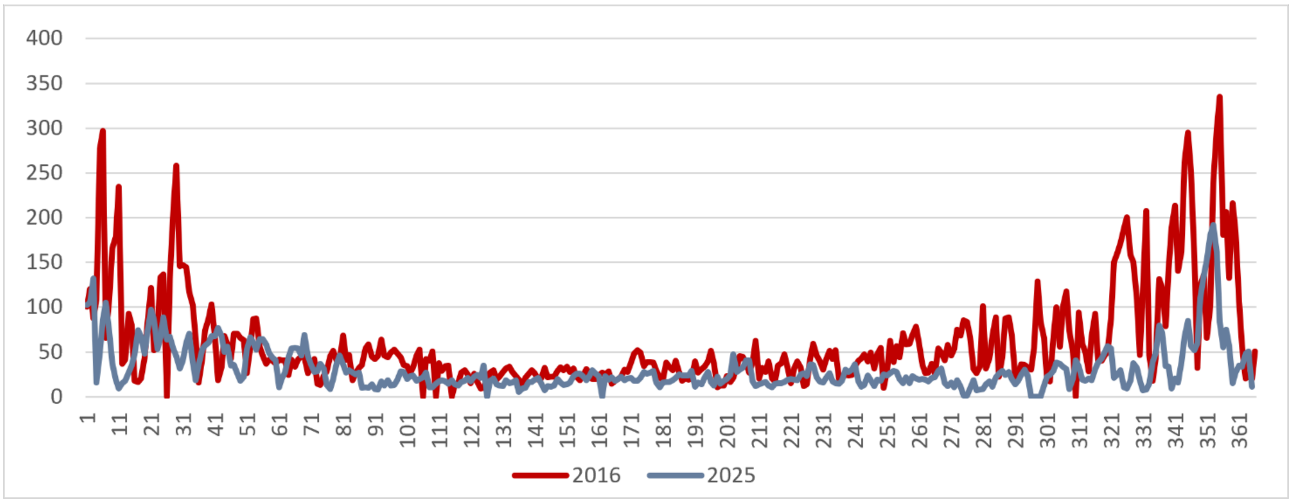

Fig. 3. Comparative analysis of daily PM_{10} concentrations at the Karposh monitoring station for the years 2016 and 2025

The daily trends for Karposh confirm a 48.3% reduction in annual average concentrations. As illustrated in the Figure, the extreme peaks that characterized the 2016 winter season are significantly flattened in the 2025 profile. The consistency of the summer concentrations across the decade suggests that baseline urban pollution remains stable, while the drastic winter reflect long–term changes in local emission dynamics. The fact that Karposh now stays more frequently within the regulatory daily limit of 50 µg/m³ compared to 2016 highlights the long–term evolution of air quality in this part of the city.

The overall progress in air quality management relative to statutory requirements is summarized in the annual trend analysis. Figure 4 illustrates the comparison of annual average PM_{10} concentrations for both the Karposh and Lisiche stations over the 2016–2025 period, measured against the European Union and national annual limit value.

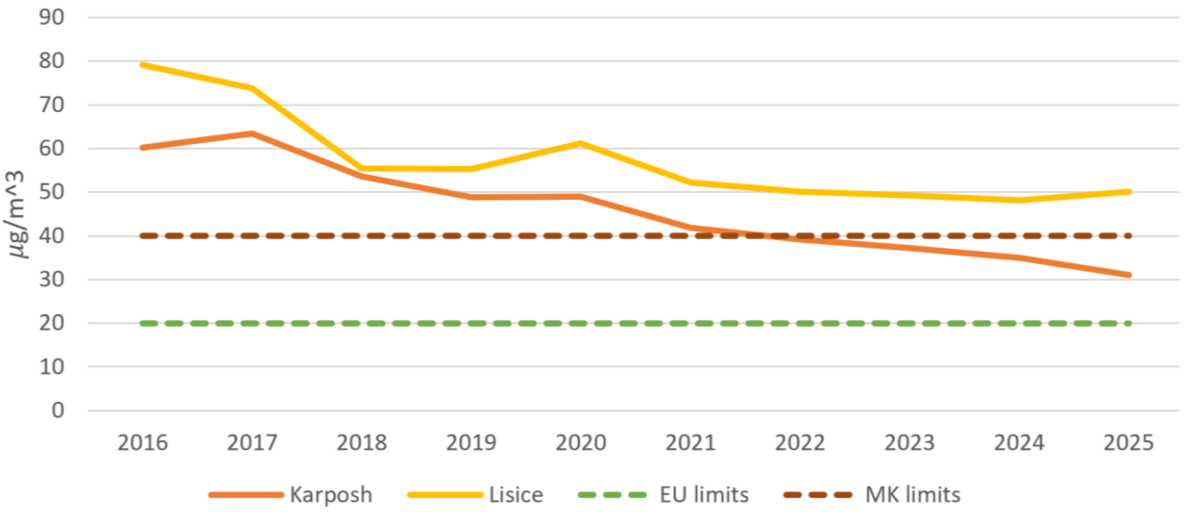

Fig . 4. Comparative analysis of annual average PM_{10} concentrations at Karposh and Lisiche stations (2016–2025)

As displayed in Figure 4, a consistent and measurable downward trend is evident for both monitoring locations. A significant milestone is reached at the Karposh station, where the annual average concentration successfully dropped below the regulatory threshold of 40 µg/m³ in the final stage of the analyzed decade.

The persistent gap between the two curves, despite the shared declining trend, highlights the localized impact of high–emission sources, particularly domestic heating in the Lisiche area. The alignment of both curves toward lower values suggests structural changes in emission profiles beyond seasonal meteorological variations.

Regulatory compliance: national legislation vs. EU frameworks

Despite the local improvements, the broader situation remains serious. According to the 2023 Global Air Quality Report [8] Macedonia still records significantly higher concentrations of PM2.5 compared to the average of the European Union countries. This data emphasizes the necessity of further systemic action. From a legal perspective, the results indicate that the existing air quality management system is limited in terms of its effectiveness. Although national legislation provides for obligations to prepare plans, their implementation does not always result in measurable improvements. In this context, the European approach, which introduces the right to compensation for health damages caused by illegal levels of air pollution, represents a significant step towards increasing the responsibility and protection of citizens.

To systematically contextualize these regulatory differences, Table 3 provides a comparative overview of the existing national legislative framework against the updated European Union directives regarding air quality standards and enforcement mechanisms.

Based on the parameters outlined in Table 3, this difference between the national and European approaches indicates a fundamental transformation in the concept of air quality management. While the national system is primarily based on planning and administrative obligations without strict enforcement mechanisms, the European regulation introduces direct legal protection for citizens. With the introduction of the right to compensation for health impacts, air pollution is no longer treated solely as an environmental problem, but also as a fundamental human rights issue, which significantly increases the legal pressure on institutions for the effective implementation of measures.

Summarizing the findings, it is evident that achieving air quality targets in Skopje is closely linked to the strictness and enforcement of the regulatory framework. The comparative analysis between the national legislation and the new EU Directive 2024/2881 indicates a systemic gap in three key pillars: standards, accountability and transparency. While the Macedonian Regulation on Limit Values is a static document, the new EU regulation is a progressive act that fully incorporates the strictest WHO recommendations from 2021. Table 3 quantitatively illustrates this systemic gap regarding the fundamental standard for fine particulate matter ($PM_{2.5}$). As analyzed in the table, achieving alignment with the EU's 2030 target of 10 μg/m³ will require Macedonia to mandate a drastic 60% reduction from its current legally permissible annual limit of 25 μg/m³.

Table 3

Comparative analysis of air quality management frameworks

Pollutants	Averaging period	MK decree (50/05, 04/13) μg/m³	Directive (EU) 2024/2881 (2030 Target) μg/m³	Percentage of reduction (EU ambition) %
$PM_{2.5}$ (Fine particles)	1 year	25	10	–60
PM_{10} (Suspended particles)	1 year	40	20	–50
PM_{10} (Suspended particles)	24 hours	50 (35 times a year)	45 (18 times a year)	Drastic reduction
NO_2 (Nitrogen dioxide)	1 year	40	20	–50
NO_2 (Nitrogen dioxide)	1 hour	200 (18 times a year)	200 (1 time per year)	Drastic reduction
NO_x (Nitrogen oxides)	1 year	30	30	0
SO_2 (Sulfur dioxide)	24 hours	125	50 μg/m³	–60
SO_2 (Sulfur dioxide)	1 hour	350 (24 times a year)	350 (1 time per year)	Drastic reduction

CONCLUSIONS

This study assessed long–term air quality management in Skopje by analyzing PM concentration trends over a ten–year period (2016–2025).

The analysis yields several specific conclusions:

- Significant decadal improvement: The Karposh station achieved a major milestone by successfully bringing the area into compliance with the EU annual limit value of 40 μg/m³, reflecting a nearly 50% reduction over the decade.
- Persistent residential hotspots: While Lisiche showed substantial reduction, it remains above the statutory threshold, confirming that residential areas heavily reliant on solid–fuel heating require more aggressive, localized interventions.
- Reduction in peak intensity: The comparative analysis of daily profiles between 2016 and 2025 indicates that the "pollution ceiling" has been lowered. Extreme winter peaks have decreased by approximately 40%, highlighting a significant shift in long–term pollution episodes, even though seasonal variability remains high.
- Methodological efficacy: Heatmap visualizations proved to be an indispensable tool for identifying spatiotemporal patterns that are often obscured in standard time–series graphs, specifically highlighting the interaction between emission cycles and the dynamics of the planetary boundary layer (PBL).

In conclusion, the integration of technical monitoring and legal analysis is a key step toward improving air quality management. The study indicates that while Skopje is on a trajectory toward regulatory compliance, the winter months remain a challenge due to the complex interplay between emissions and stable atmospheric conditions. Future research should prioritize the integration of high–resolution meteorological models and urban parameters to enhance forecasting capabilities and refine the targeting of emission–reduction policies.

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