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Monitoring Atmospheric Aerosol Pollution in Kyiv in 2024 under Natural and War-Related Impacts using Sentinel-5P and Public Sensor Networks

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SUMMARY

This study presents a comprehensive spatiotemporal assessment of aerosol air pollution in Kyiv during 2024, integrating data from ground-based public monitoring stations and Sentinel-5P satellite observations. The focus was on $PM_{2.5}$ and PM_{10} particle concentrations and their relationship with the Absorbing Aerosol Index (AAI), particularly in the context of both typical urban emissions and additional pollution episodes caused by wartime activities such as missile strikes, explosions, and fires. Aerosol air pollution data were collected from seven SaveEcoBot stations in Kyiv. Hourly measurements were aggregated into daily and monthly averages. The annual mean concentrations were 14.64 ± 9.05 µg/m³ for $PM_{2.5}$ and 23.06 ± 14.85 µg/m³ for PM_{10}, generally remaining within EU air quality limits. Nevertheless, several peak exceedances were observed, particularly in spring (March) and autumn (September). Satellite-derived AAI values over Kyiv in 2024 averaged -0.44 ± 0.51. Seasonal dynamics revealed the lowest (most negative) AAI values during summer, while higher (less negative) values occurred in late autumn and winter-indicating increased loads of UV-absorbing aerosols likely associated with combustion products. Statistically significant correlations were found between monthly AAI and ground-based concentrations of $PM_{2.5}$ and PM_{10}, supporting the complementary use of satellite data for assessing air pollution trends. Despite daily-scale discrepancies due to differences in measurement altitude and emission origin, the combined data revealed spatial pollution hotspots in densely built-up areas with high traffic and limited greenery. The findings emphasize the importance of integrating remote sensing and ground-based approaches for monitoring urban air quality under conditions of environmental and military stress.

Keywords: $PM_{2.5}$ and PM_{10} particulate matter; Public Sensor Networks; Absorbing Aerosol Index, Sentinel-5P satellite.

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Introduction

Atmospheric air in urban agglomerations is exposed to intense pollution, making it one of the most pressing environmental challenges of our time. Urban areas, particularly megacities, are characterized by high population density, dense transport networks, numerous industrial facilities, and extensive artificial surfaces. As a result of these impacts, the spatio-temporal characteristics of atmospheric air quality change, which in turn affect the stability and functioning of urban ecosystems and have serious consequences for public health and quality of life (Renard et al., 2023; Tomson et al., 2023). All these factors form an additional load on the atmosphere due to the constant influx of pollutants. Kyiv is a typical example of a megacity with a complex, multi-component environmental situation, complicated by a combination of traditional urban factors (transport emissions, reduction of green spaces, urban heat island effect) and new threats resulting from military actions (explosions, fires, shelling), as well as climate change (Boychenko & Maidanovych, 2024; Boychenko et al., 2025). The primary factor contributing to air quality deterioration is the presence of solid or liquid microparticles suspended in the atmosphere. The most hazardous are $PM_{2.5}$ and PM_{10} particles, which, according to the WHO classification, can penetrate deep into the lower respiratory tract and enter the bloodstream, leading to a broad spectrum of chronic diseases (WHO, 2010). Ukrainian legislation on atmospheric air protection is gradually aligning with European standards as part of the country's European integration course. In particular, Directive 2008/50/EC on Ambient Air Quality establishes annual average limits of 20 µg/m³ for $PM_{2.5}$ and 50 µg/m³ for PM_{10} (Exceedance of air quality…, 2024). An important satellite-based parameter for aerosol monitoring is the Absorbing Aerosol Index (AAI), also known as the UV Aerosol Index. It is derived from satellite measurements of ultraviolet reflectance and enables the detection and quantification of UV-absorbing aerosols, including dust, biomass-burning smoke, and volcanic ash (Seinfeld & Pandis, 2016; Park et al., 2023).

This study aims to perform a spatiotemporal analysis of aerosol pollution in a modern metropolis, focusing on $PM_{2.5}$ and PM_{10} concentrations obtained from ground-based monitoring, alongside the AAI derived from 2024 satellite observations.

Materials and Methods

$PM_{2.5}$ and PM_{10} concentration data were obtained from the Public Sensor Networks via the SaveEcoBot platform (https://www.saveecobot.com/maps), which aggregates air quality measurements from a nationwide network of monitoring stations in Ukraine. Seven monitoring sites in Kyiv with the most reliable records were selected for analysis: 28 Turivska St.; 22 Kytaivska St.; 26 Verbytskoho St.; 7/1 Kharkiv Highway; 64 European Union Ave.; 21 Shchuseva St.; 97 Beresteiskyi Ave. Hourly data from 2024 were averaged to daily means for consistency. Maximum Permissible Concentrations (MPC) for $PM_{2.5}$ and PM_{10} were determined in accordance with Directive 2008/50/EC (Exceedance of air quality…, 2024).

Spatial analyses were conducted using QGIS 3.28, integrating OpenStreetMap cartographic layers and Sentinel-2 satellite imagery processed through the Google Earth Engine platform (https://earthengine.google.com). Vector layers delineating Kyiv's residential districts, major transport corridors, water bodies, and green infrastructure supported spatial contextualization. Georeferenced monitoring data enabled a detailed assessment of pollution distribution across urban districts. To complement ground-based measurements, the Absorbing Aerosol Index derived from Sentinel-5P ultraviolet reflectance data accessed via the Earth Engine Data Catalog was utilized. The AAI detects and quantifies UV-absorbing aerosols such as mineral dust, biomass-burning emissions, and volcanic ash. Positive AAI values typically indicate elevated combustion-related aerosol loads, including wildfires and explosions. To assess correlations between aerosol peaks and potential emission sources, open-source media reports and meteorological data were reviewed to reconstruct the timing of dust storms, wildfires, and missile attacks throughout 2024. These events were cross-referenced with elevated $PM_{2.5}$/PM_{10} concentrations and positive AAI anomalies to identify spatiotemporal patterns and probable causal links.

Results

Spatiotemporal Analysis of $PM_{2.5}$ and PM_{10} Concentrations in Kyiv, Ukraine, Using Data from Seven Monitoring Stations (2024). In 2024, the mean annual concentrations of aerosol particles in Kyiv were 14.64 ± 9.05 µg/m³ for $PM_{2.5}$ and 23.06 ± 14.85 µg/m³ for PM_{10}, with notable spatial variability across the monitoring sites (see Fig. 1). Throughout the year, $PM_{2.5}$ concentrations exhibited two distinct peaks – in March (21.4 ± 3.3 μg/m^3) and September (21.6 ± 3.1 μg/m^3). During the cold season (October-February), mean monthly concentrations averaged 15.5 ± 1.3 μg/m^3, with the highest value observed in January (18.4 ± 2.0 μg/m^3). In the warm season (April-August), concentrations averaged 10.1 ± 1.3 μg/m^3. The annual distribution of PM_{10} concentrations followed a pattern similar to that of $PM_{2.5}$, but with certain differences: two pronounced peaks – in March (30.0 ± 3.3 μg/m^3) and September (42.0 ± 5.2 μg/m^3) – and two minima – in June (15.9 ± 1.3 μg/m^3) and December (15.9 ± 1.5 μg/m^3). During the cold season (October-February) and the warm season (April-August), mean PM_{10} concentrations averaged approximately 21.5 ± 2.5 μg/m^3. The highest daily PM_{10} concentrations were recorded on April 1-2 (83.5 ± 3.5 μg/m^3) and October 3-4 (101.9 ± 9.4 μg/m^3), exceeding the MPC by a factor of about two. For $PM_{2.5}$, the highest daily values occurred on September 20 (63.7 ± 9.0 μg/m^3) and on January 4 and April 1 (43.9 ± 7.7 μg/m^3), representing a two- to threefold exceedance of the MPC. The highest average annual concentrations of both PM fractions were recorded at 26 Verbytskoho St.: 18.13 μg/m^3 for $PM_{2.5}$ and 25.96 μg/m^3 for PM_{10}. Elevated levels were also observed at the monitoring station located on Kharkiv Highway, 7/1, with 16.16 μg/m^3 for $PM_{2.5}$ and 25.53 μg/m^3 for PM_{10}. Moderate $PM_{2.5}$ concentrations were measured at stations at 22 Kytaivska St. (13.9 μg/m^3), 97 Beresteyskyi Ave. (13.8 μg/m^3), 28 Turivska St. (13.61 μg/m^3), and 21 Shchuseva St. (13.4 μg/m^3). For PM_{10}, moderate concentrations were found at 26 Shchuseva St. (22.59 μg/m^3) and 22 Kytaivska St. (22.49 μg/m^3). The lowest $PM_{2.5}$ concentration was recorded at 64 European Union Avenue (13.24 μg/m^3), while the lowest PM_{10} concentrations were registered at 28 Turivska St. (22.33 μg/m^3), 97 Beresteyskyi Ave. (21.34 μg/m^3), and 67 European Union Avenue (21.06 μg/m^3). Overall, average aerosol particle concentrations on the left bank of the Dnipro River were slightly higher than those on the right bank.

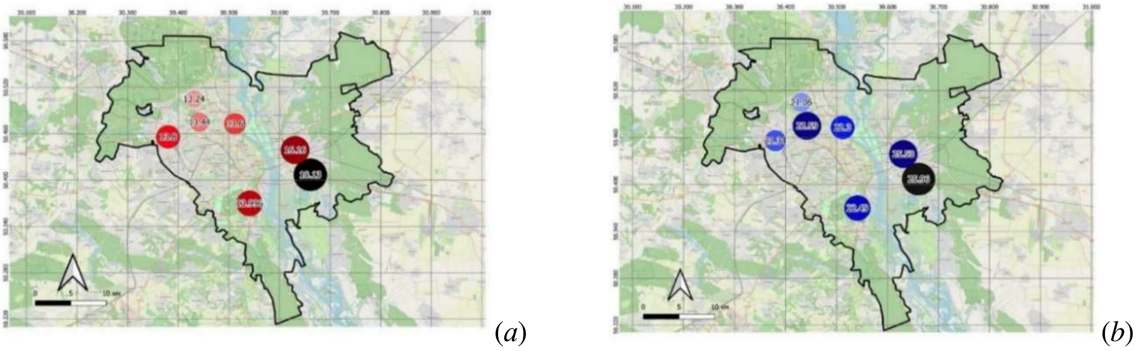

(*a*) (*b*)

Figure 1. *Spatial distribution of mean annual $PM_{2.5}$ (a) and PM_{10} (b) concentrations in Kyiv in 2024, based on data from seven automated monitoring stations.*

Elevated atmospheric aerosol concentrations result from the combined effect of persistent background levels and superimposed local influences, including dense vehicular traffic, industrial emissions, topographic constraints, and prevailing meteorological and microclimatic conditions. Episodic enhancements are further driven by adverse natural phenomena, such as dust storms, prolonged droughts, and forest or peatland fires, which introduce substantial short-term variability. In addition, the ongoing armed conflict has emerged as a novel and critical factor, with missile strikes and unmanned aerial vehicle attacks producing episodic surges in near-surface particulate loading. Figure 2 synthesizes daily PM_{10} and $PM_{2.5}$ concentrations recorded in 2024 and juxtaposes them against the timing of major missile strikes, forest and peatland fires, and dust storms (as reconstructed from open-source media and meteorological portals), with values averaged across seven ground-based monitoring stations to reveal spatiotemporal concordance and potential causal linkages.

Application of Sentinel-5P Absorbing Aerosol Index for Evaluating UV-Absorbing Pollution in Kyiv during 2024. Analysis of Sentinel-5P data for 2024 indicates that the mean Absorbing Aerosol Index over Kyiv was –0.44 ± 0.51. Figure 3 compares normalized daily atmospheric concentrations of PM_{10} and $PM_{2.5}$ with corresponding AAI values for Kyiv. Monthly averages of $PM_{2.5}$ and PM_{10} show a relatively strong correlation with satellite-derived AAI, yielding correlation coefficients of 0.72 and 0.77, respectively, which reflects a high degree of consistency in overall temporal trends. However, daily-scale analysis reveals notable discrepancies between satellite and ground-based measurements. These differences likely arise from the distinct sensitivities of the two observation methods: AAI primarily responds to ultraviolet-absorbing aerosols generated by combustion processes (e.g., smoke, ash), whereas ground-based instruments measure total particulate mass in the near-surface atmosphere, integrating both local and regional sources of pollution.

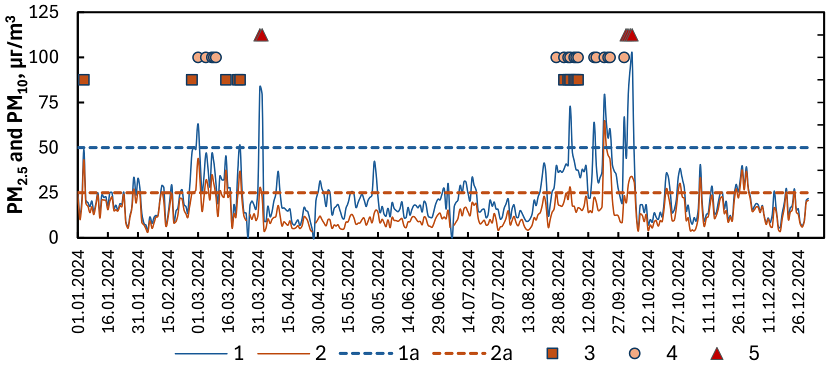


***Figure 2**. Dynamics of daily atmospheric concentrations of PM_{10} (1) and $PM_{2.5}$ (2) in Kyiv during 2024: 1a and 2a – Maximum Permissible Concentrations for the respective particle fractions; 3 – periods of the most intense unmanned aerial vehicle and missile attacks; 4 – forest and peatland fires; 5 – dust storms and severe wind events.*

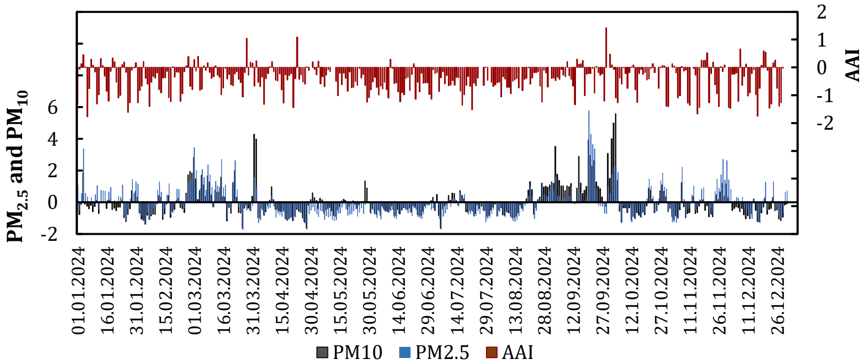
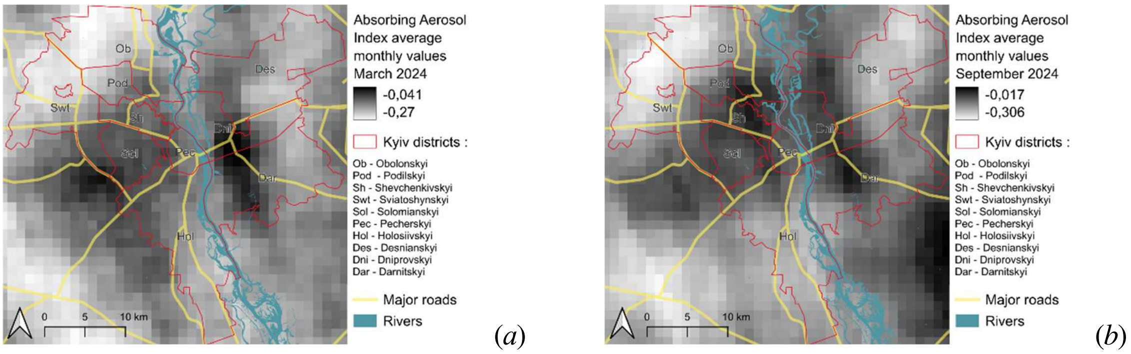


***Figure 3.** Comparison of the normalized value of daily atmospheric concentrations of PM_{10} and $PM_{2,5}$ aerosol particles and Absorbing Aerosol Index (AAI) in Kyiv (2024).*

The seasonal AAI dynamics in 2024 exhibit moderate variability, with consistently negative values indicating generally low concentrations of UV-absorbing aerosols in the atmosphere. The most negative values were observed in June (–0.610) and July (–0.569), likely reflecting reduced fire activity and specific meteorological conditions. During winter and early spring (January-March), less negative AAI values (–0.24 to –0.52) point to higher concentrations of combustion-related aerosols, possibly associated with heating and other anthropogenic sources. A comparable pattern appears in autumn (September–November), coinciding with the onset of the heating season.

Figure 4 shows the spatial distribution of AAI over Kyiv for March and September 2024 – the months with the highest recorded levels of aerosol pollution. The maps highlight localized areas of elevated UV-absorbing aerosol concentrations, which may result from diverse emission sources, including combustion products from shelling, fires, and dust storms.



(*a*) (*b*)

***Figure 4.** Spatial distribution of the Absorbing Aerosol Index (AAI) in Kyiv based on Sentinel-5P satellite data for March (a) and September (b), 2024.*

Conclusions

The study provides a detailed spatiotemporal analysis of aerosol pollution in Kyiv in 2024 using ground-based and satellite data. Annual mean PM$_{2.5}$ (14.64 ± 9.05 μg/m^3) and PM$_{10}$ (23.06 ± 14.85 μg/m^3) concentrations were mostly within EU limits, but peak exceedances occurred in March and September. Highest annual levels were recorded on the left bank of the Dnipro River (26 Verbytskoho St.; 7/1 Kharkiv Highway), indicating pollution hotspots. Sentinel-5P Absorbing Aerosol Index (AAI, –0.44 ± 0.51) showed seasonal increases in late autumn and winter and correlated significantly with ground PM$_{2.5}$ ($r = 0.72$) and PM$_{10}$ ($r = 0.77$). Short-term PM surges were linked to missile attacks, dust storms, and fires. Combining remote sensing with ground monitoring proved effective for identifying pollution dynamics, highlighting the need for multi-source approaches to manage urban air quality under both environmental and military stress.

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