UNVEILING THE DYNAMICS OF $PM_{2.5}$: A SYNERGISTIC APPROACH COMBINING LOW-VOLUME SAMPLING AND METEOROLOGICAL MONITORING

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ABSTRACT

There is a pressing environmental and public health issue regarding air quality in the urban areas of our country. Air pollution levels exhibit strong variability and are influenced by major emission sources such as biomass burning. This study presents an ongoing experimental investigation employing a low-volume sampler for 24-hour $PM_{2.5}$ collection, conducted concurrently with a meteorological monitoring station that records key atmospheric parameters. In densely populated areas of Tirana, elevated $PM_{2.5}$ concentrations present a complex pattern. During the winter, high levels are primarily attributed to increased combustion activities, whereas in the summer, photochemical reactions become the dominant factor in pollution formation. Additional contributors include both anthropogenic and natural sources—urban traffic, waste processing, construction activities, recycling, dust, and meteorological dynamics—all of which influence the chemical composition of particulate matter. To gain a more comprehensive understanding of the factors influencing air pollution and the chemical pathways of atmospheric particles, we integrated meteorological data with $PM_{2.5}$ sampling. Notably, half of the measurements conducted in April 2024 exceeded twice the established limit values. $PM_{2.5}$ concentrations during this period displayed substantial variability, ranging from a minimum of 13.949 µg/m³ to a maximum of 61.957 µg/m³. Backward trajectory analysis using the NOAA HYSPLIT model revealed that air parcels arriving in Tirana on April 23, 2024, originated from the Sahara Desert. This synergistic approach to air quality monitoring is expected to support the future re-evaluation of realistic limit values, thereby contributing to improved environmental management and public health policy.

Keywords: meteorological data, $PM_{2.5}$, air pollution

1. INTRODUCTION

Ambient air pollution is a major global health concern, contributing to an estimated 4.2 million premature deaths annually (WHO, 2021). Approximately 91% of the world's population lives in areas where air pollution levels exceed the safety thresholds established by the World Health Organization. Among all pollutants, fine particulate matter ($PM_{2.5}$) poses the greatest health risk due to its ability to penetrate deep into the lungs and enter the bloodstream. Prolonged exposure to $PM_{2.5}$ is linked to a wide range of serious health conditions, including lower respiratory infections, lung cancer, ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), and increased overall mortality. The risk of exposure to air pollution is significantly heightened by urbanization, which is associated with increased emissions from residential heating, traffic congestion, and industrial activities. Urban areas typically exhibit concentrated emissions due to inefficient heating systems during winter, a higher density of vehicles, and more extensive industrial operations. Currently, approximately 55% of the global population resides in urban areas—a figure that rises to 72% in Europe and Central Asia.

In Eastern Europe and the Western Balkans, air pollution levels consistently exceed internationally recognized safety thresholds, particularly during the winter months. In countries such as Bosnia and Herzegovina, Kosovo, and the Republic of North Macedonia, $PM_{2.5}$ concentrations in urban centres often surpass the World Health Organization (WHO) guidelines by a factor of three to four. The WHO has identified air pollution as the leading environmental risk factor contributing to mortality and disability in the Western Balkans. It is estimated that exposure to $PM_{2.5}$ results in approximately 1,600 premature deaths annually in North Macedonia and 760 in Kosovo, with 80–90% of these deaths attributed to cardiovascular diseases. Furthermore, long-term exposure to air pollution has been linked to increased susceptibility to respiratory infections, including COVID-19. Individuals with pre-existing cardiovascular or pulmonary conditions face significantly elevated risks of severe health outcomes and mortality, due to their reduced capacity to combat respiratory infections.

Air quality management is governed by a legal framework aimed at protecting human health and preserving environmental quality. This framework is implemented through national legislation harmonized with European Union directives. Notably, Law No. 10431/2011 on environmental protection and Law No. 162/2014 on ambient air quality incorporate key provisions of EU Directive 2008/50/EC on ambient air quality and cleaner air for Europe. An important component of this framework is Decision No. 412, dated 19 June 2019 (VKM No. 412/2019), issued under Article 100 of the Constitution, which approves the National Plan for Air Quality Management. The primary objectives of this plan are to establish limit values for key pollutants such as $PM_{2.5}$, to initiate action plans when these limits are exceeded, and to maintain air quality where standards are already met. However, despite the existence of these policy instruments, they remain insufficient in effectively reducing emissions. There is an urgent need to strengthen regulations concerning cleaner fuel standards and to promote the adoption of more efficient and sustainable heating technologies.

Urban areas throughout the Western Balkans are among the primary sources of harmful air pollutants. This is largely due to the extensive use of wood burning for residential heating, combined with increasing traffic volumes. Transport-related emissions are a major contributor to localized air pollution in urban environments. Contributing factors include traffic congestion, outdated transport infrastructure, and aging vehicle fleets, all of which exacerbate pollutant levels. According to World Health Organization (WHO 2021) estimates, road transport accounts for up to 30% of particulate matter emissions in European cities.

Understanding the dynamics of air pollution in densely populated urban areas is essential for effective environmental and public health management. One promising approach involves integrating low-volume $PM_{2.5}$ sampling with continuous meteorological monitoring. The objective of this experimental setup is to assess the interaction between emission sources and atmospheric conditions. This integrated methodology has the potential to generate actionable insights for mitigating $PM_{2.5}$ pollution and informing the development of effective public health and environmental policies.

2. MATERIALS AND METHODS

Air pollution in urban environments is driven by a complex interplay of seasonal variability, anthropogenic activities, and meteorological conditions. Previous studies have emphasized the significant impact of domestic heating and regional pollutant transport on elevated $PM_{2.5}$ concentrations. For instance, Belis *et al*. (2019) identified biomass combustion as a major contributor to $PM_{2.5}$ levels, underscoring the need for policy interventions that extend beyond urban centers. Similarly, Todorović *et al*. (2020) reported that local heating is a dominant source of $PM_{2.5}$ during winter, while regional pollution transport also plays a critical role. Tasić *et al*., (2012) observed increased PM_{10} and $PM_{2.5}$ concentrations during colder months, largely due to domestic heating. Evagelopoulos *et al*., (2022) identified biomass burning and mining activities as key contributors to particulate matter pollution, although they noted a declining trend in $PM_{2.5}$ and PM_{10} concentrations over a 12-year period. Almeida *et al*., (2020) provided one of the most comprehensive assessments for the region, reinforcing that biomass burning—particularly for residential heating during winter—is a primary emission source. Furthermore, Wang *et al*., (2023) demonstrated that indoor $PM_{2.5}$ concentrations are strongly influenced by outdoor sources, especially secondary sulfate aerosols. These findings, summarized in Tables 1 and 2, collectively underscore the importance of understanding both the temporal and spatial dynamics of air pollution in Albania. Managing air quality in highly urbanized areas such as Tirana presents particular challenges due to a combination of geographic, socio-economic, and regulatory factors. The city's topography and frequent winter temperature inversions often trap pollutants near the surface. Major sources of emissions include outdated residential heating systems, traffic congestion involving a large number of aging diesel vehicles, and continuous construction activity. Economic constraints further limit the population's ability to adopt cleaner technologies, resulting in the continued reliance on polluting fuels and vehicles.

$PM_{2.5}$ concentrations in Tirana frequently exceed the World Health Organization (WHO) air quality guidelines, particularly during the winter months, leading to significant public health impacts, including increased incidence of respiratory and cardiovascular diseases (Çaushaj *et al*., 2024). The economic burden associated with these health outcomes is considerable and mirrors trends observed in other Western Balkan cities, such as Sarajevo and Skopje, where $PM_{2.5}$ levels are similarly critical (WHO 2021). To effectively address air pollution, Albania must adopt a multifaceted strategy grounded in realistic and context-sensitive standards. Key interventions include the modernization of residential heating systems, enhancement of public transportation infrastructure, stricter enforcement of air quality regulations, expansion of monitoring networks, and improved public awareness initiatives. For example, the introduction of cleaner heating technologies in other European regions has led to reductions of up to 50% in wintertime $PM_{2.5}$ concentrations. A comprehensive and integrated approach—aligned with European Union standards—is essential to tackling the complex and multifactorial nature of urban air pollution in Albania.

Table 1. Major sources of $PM_{2.5}$ and PM_{10} in Western Europe

Study	Main Source	$PM_{2.5}$ and PM_{10} Concentrations	Conclusion
Belis *et al.* (2019)	Energy production, agriculture, residential combustion	Influenced by inefficient coal plants and biomass burning	Biomass combustion significantly impacts $PM_{2.5}$ levels; policies should address emissions beyond city limits
Todorović *et al.*, (2020)	Biomass burning, traffic,	$PM_{2.5}$ with 14.5% from biomass burning	Local heating is a major contributor; regional pollution

	regional combustion		significantly affects $PM_{2.5}$ levels
Tasić *et al.*, (2012)	Copper smelter, domestic heating	Higher in cold periods	Domestic heating significantly increases PM levels in cold seasons
Evagelopoulos *et al.*, (2022)	Lignite mining, biomass burning	Decreased over 12 years	Biomass burning and mining activities are key sources of PM pollution
Almeida *et al.*, (2020)	Biomass burning, secondary sulfates	$PM_{2.5}$ with 16% from biomass burning	Biomass burning is a major source, especially in winter due to heating
Wang *et al.*, (2023)	Biomass burning, traffic	Indoor $PM_{2.5}$ mainly from secondary sulfate pollution	Indoor PM levels heavily influenced by outdoor sources

During winter, biomass burning is a major influence on the chemical composition of atmospheric particles. Organic compounds released from biomass combustion undergo atmospheric oxidation, forming secondary organic aerosols (SOAs) that significantly contribute to $PM_{2.5}$ concentrations (Srivastava *et al*., 2020). Additionally, sulphur compounds emitted from biomass burning, along with emissions from numerous vehicles using poorly refined fuels, promote the formation of sulphate aerosols, particularly under conditions of high humidity and low temperatures. Nitrogen oxides (NO_x) also react with ammonia to form ammonium nitrate, a process that is especially pronounced in winter due to concurrent agricultural activities and enhanced biomass burning. In contrast, summer air pollution dynamics are driven by different mechanisms. Increased solar radiation accelerates photochemical reactions, leading to the formation of ozone and SOAs from volatile organic compounds (VOCs). Although biomass burning decreases during the warmer months, episodic increases in $PM_{2.5}$ concentrations may still occur due to agricultural activities. Furthermore, elevated temperatures facilitate the conversion of sulphur dioxide into sulphate, which then combines with ammonia to form ammonium sulphate (Aksoyoglu *et al*., 2020).

Comparative data from European urban centres reveal varying levels of $PM_{2.5}$ pollution. In Athens, Theodosi *et al.*, (2018) reported an average $PM_{2.5}$ concentration of 16.811 µg/m³ (SD = 10.576) based on 850 samples collected between December 2013 and March 2016. This value is slightly lower than the average observed in Tirana, indicating marginally better air quality in Athens during the referenced period.

Milan, a more industrialized and densely urbanized area, was characterized by higher pollution levels, with an average $PM_{2.5}$ concentration of 30.129 µg/m³. In Sarno, Italy, Cesari *et al.*, (2019) recorded a notably lower $PM_{2.5}$ level of 14.2 µg/m³ (SD = 6.8) from data collected between May 2011 and April 2012, possibly due to reduced industrial activity and effective pollution control strategies. Further comparisons show $PM_{2.5}$ concentrations of of 19.1 µg/m³ (SD = 7.1) in Athens (Grivas *et al*., 2018; Jan 2013 - Jan 2014, 16.26 µg/m³ (SD = 9.53) in Zagreb (2013), and 21.9 µg/m³ (SD = 18.2) in Budapest (Perrone *et al*., 2018; early 2015). These values align with Tirana's pollution levels, though peaks of maximum values are much higher in Tirana. Sofia also reported an average $PM_{2.5}$ concentration of 17.4 µg/m³ (SD = 11.1), slightly lower than Tirana but within the same general range.

Table 2: Major Sources of $PM_{2.5}$ and PM_{10} in Albania

STUDY	Main source	Measurements	Conclusion
Kuci & Neziri (2012)	Urban activity, industrial emissions	PM_{10}: 53.38-238 µg/m³	High PM_{10} values indicate significant risk to public health in urban areas.
Hysenaj (2019)	Traffic, residential heating	-	Suggests upgrading vehicle fleets to reduce air pollution.
Jevtić & Matkovic (2022)	General urban pollution	$PM_{2.5}$ caused 4,000 premature deaths in Albania	Highlights the need for improved air quality standards and policies.
Nanushi *et al*., (2015)	Traffic, residential heating	PM_{10} > 50 µg/m³	High PM_{10} levels

			significantly increase emergency hospital visits for COPD and asthma.
Hysenaj & Duraj (2021)	Traffic, industrial emissions	-	High positive correlation between PM_{10} and pollutants like O_3 and SO_2.
Belis *et al.*, (2022)	General urban pollution	-	Air pollution significantly impacts health, leading to increased mortality and morbidity.
Mankolli *et al.*, (2011)	Industrial emissions, traffic	Lead in air increased from 0.19 to 0.29 µg/m³	The persistent increase in lead pollution highlights ongoing air quality issues.
Liti and Cara (2022)	Urban traffic, industrial emissions	CO_2: 350-1000 ppm	High NO_2 values exceed Albanian and EU standards.
Allajbeu *et al.*, (2017)	Industrial emissions, traffic	-	High ecological risk from trace metals, indicating significant air pollution.

The studies summarized in the table highlight the significant impact of air pollution on public health in Albania and the diversity of pollution sources. Based on the extensive data collected over different periods, it is practical to implement a range of management strategies to achieve effective pollution mitigation.

3. RESULTS AND DISCUSSIONS

We established an experimental setup that integrates low-volume $PM_{2.5}$ sampling with continuous meteorological monitoring. This methodology is crucial, as 24-hour particulate matter sampling, complemented by real-time meteorological data, allows for a comprehensive understanding of the factors driving pollution levels and the seasonal chemical transformations of atmospheric aerosols.

For this study, filters were collected at an urban monitoring site in Tirana, specifically at the Faculty of Natural Sciences, University of Tirana (Figure 1), using a Low Volume Sampler (LVS) between 27 March and 27 April 2024. The equipment was positioned 17 meters above ground level in an open environment to ensure representative sampling of ambient air. Alongside $PM_{2.5}$ concentrations, concurrent measurements of temperature and atmospheric pressure were recorded. The LVS device used in this study (Figure 2) operates under a wide range of environmental conditions, from approximately –30°C to over 50°C. The sampler maintains a consistent flow rate of 2.3 m^3/h. Both flow rates and sampled air volumes are recorded as operating m^3/h and operating m^3 (based on ambient temperature and pressure) as well as standard m^3/h and standard m^3 (normalized to 0°C and 1013 mbar), enabling accurate standardization and comparison of data.

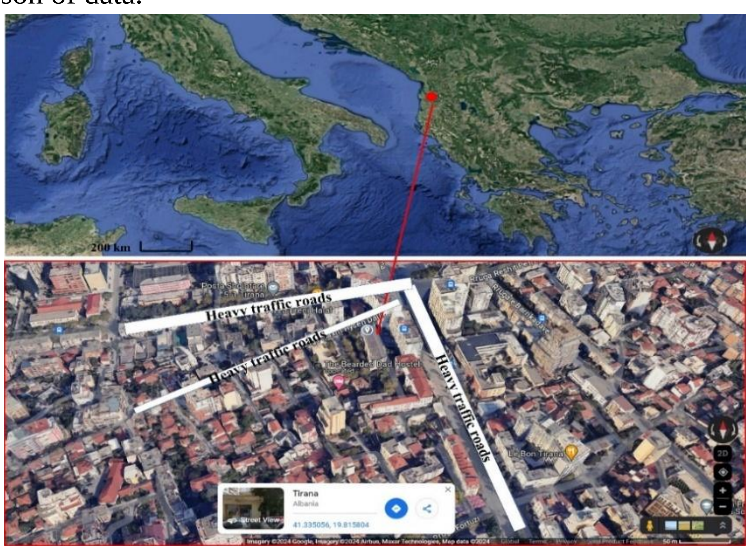


Fig. 1: Site location: The Faculty of Natural Sciences, University of Tirana, Albania (satellite images).

A Davis Vantage Pro 2 automatic weather station was installed on the terrace of the Faculty of Natural Sciences building (Figure 2), near the air sampling site. This station monitors localized meteorological conditions, creating an experimental database specific to the sampling location. Although the collected data are valuable for research purposes, they are not classified as official meteorological data. To ensure a reliable meteorological time series, the station was installed following established guidelines and standards. These include positioning temperature sensors at the standardized height of 2 meters above ground level and minimizing the influence of urban heat sources, among other criteria. The Davis Vantage Pro 2 is a calibrated, WMO-certified device widely used across Europe and the United States, with over 10,000 units installed in both public and private sectors. It provides accurate and consistent meteorological observations, ensuring high-quality data for each monitored parameter.

A **B**

Fig.2: Continuous monitoring devices placed at the Faculty of Natural Sciences, University of Tirana, Albania, a) Davis Vantage Pro 2 b) Low Volume Sampler.

The filters used for 24-hour PM2.5 sampling were weighed before and after collection to determine mass concentrations. Throughout the sampling period, continuous measurements of temperature and pressure were recorded using a data logger with USB storage capability. In the event of power loss, the system's data remain securely stored in internal memory and the microcontroller, supported by a high-capacity battery capable of preserving data for several years. Prior to weighing, filters were stored in a refrigerated environment and weighed using a high-precision microbalance. Sampling was conducted with an LVS6-RV standard reference sampler, following the CEN EN 12341 guidelines. The filters used were Whatman PTFE filters with polypropylene ring support, featuring a 2 µm pore size and 46.2 mm diameter. By integrating data from both air quality and meteorological monitoring systems, this study facilitates a more comprehensive understanding of air pollution dynamics and enables accurate source apportionment analysis.

The measured PM2.5 concentrations during this period exhibited substantial variability, ranging from a minimum of 13.949 µg/m³ to a maximum of 61.957 µg/m³ (Figure 3), with an average concentration of 38.8 µg/m³. On April 23, 25, and 27, 2024, PM2.5 levels reached or exceeded 50 µg/m³. Starting on April 22, a documented dust transport event contributed to significantly elevated PM2.5 levels, exceeding the World Health Organization's (WHO) recommended annual mean limit of 10 µg/m³ as well as the 24-hour mean threshold of 25 µg/m³.

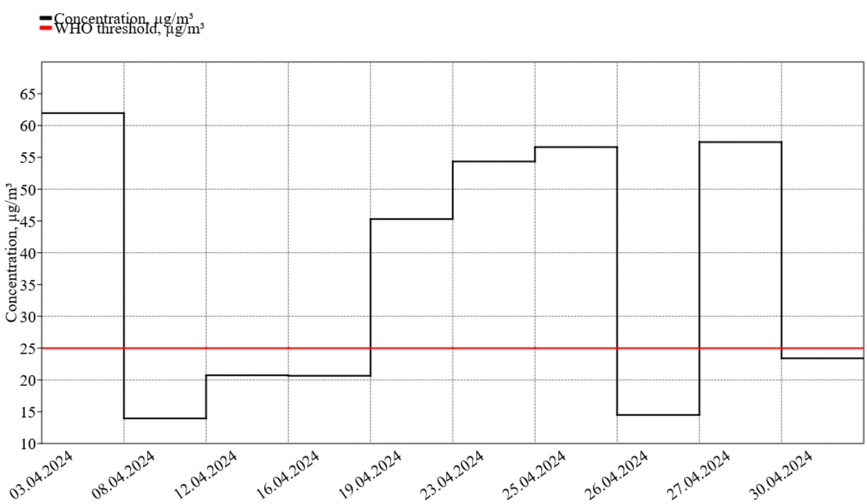
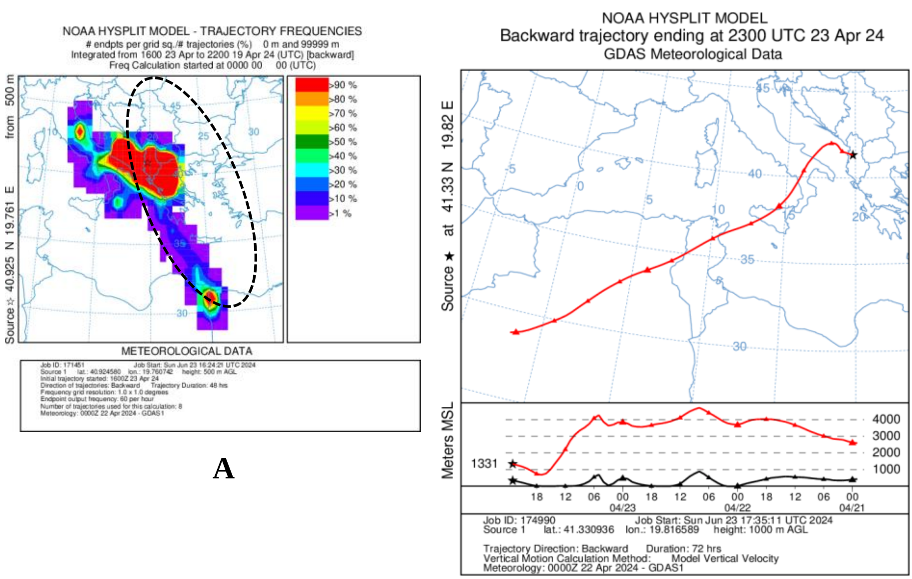


Fig. 3: Concentration of $PM_{2.5}$ measured for 24 hours during April 2024.

To investigate whether the elevated PM2.5 values originated from external sources, we employed the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, a key tool for simulating the movement of air parcels and tracking the transport of airborne pollutants. Using this approach, HYSPLIT calculates backward trajectories from the sampling site, enabling the identification of pollutant sources by distinguishing between local emissions and those transported from distant regions via atmospheric advection. The model incorporates detailed meteorological data to ensure simulations accurately reflect actual atmospheric conditions. Consequently, HYSPLIT is indispensable for source attribution and supports the development of effective air quality management strategies, particularly in urban areas affected by diverse emission sources.

Utilizing the NOAA HYSPLIT model, backward trajectory analysis revealed that air parcels reaching Tirana on April 23, 2024, originated from the Sahara Desert (Figure 4). This finding indicates that the elevated particulate matter concentrations were influenced by long-range transboundary dust transport from Northern Africa. These results emphasize the significant impact of regional and intercontinental dust events on urban air quality and underscore the necessity for integrated monitoring, forecasting, and mitigation strategies to protect public health.



A

B

Fig. 4. NOAA HYSPLIT model results. A) Trajectory frequencies during 22-23 April 2024 B) Backward trajectory durian 21-23 April 2024.

4. CONCLUSIONS

This study presents an experimental setup combining two devices: one for continuous $PM_{2.5}$ measurement and another for monitoring wind, temperature, and humidity. In April, we recorded an average PM2.5 concentration of 38.8 µg/m³, significantly exceeding the World Health Organization's safe limit. Application of the NOAA HYSPLIT model revealed that a substantial source of particulate matter is dust transported from the Sahara Desert, particularly during dust storms. These elevated PM2.5 levels highlight the need to extend this experimental approach across all seasons, enhance source tracking capabilities, and develop realistic strategies to improve air quality in our city.

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