

Article

Elemental Characterization and Source Apportionment of Particulate Matter in Campania (Italy) During a Summer Period Using PIXE

Giuseppe Caso ¹, Fabio Marzaioli ¹, Mauro Rubino ¹, Miguel A. Hernández-Ceballos ², Francesca Barone ³, Enikő Papp ⁴, Zsófia Kertész ⁴ and Anikó Angyal ^{4,*}

¹ Department of Mathematics and Physics, University of Campania “Luigi Vanvitelli”, 81100 Caserta, Italy; giuseppe.caso@unicampania.it (G.C.); fabio.marzaioli@unicampania.it (F.M.); mauro.rubino@unicampania.it (M.R.)

² Department of Physics, University of Córdoba, 14071 Córdoba, Spain; f92hecem@uco.es

³ ARPAC–Campania Regional Agency for Environmental Protection, 80143 Naples, Italy; f.barone@arpacampania.it

⁴ Laboratory for Heritage Science, Institute for Nuclear Research, HUN-REN ATOMKI, H-4026 Debrecen, Hungary; papp.eniko.ivett@atomki.hu (E.P.); kerteszs.zsofia@atomki.hu (Z.K.)

* Correspondence: angyal.aniko@atomki.hu; Tel.: +36-52-509-200

Abstract

Atmospheric PM₁₀ was investigated across Campania, southern Italy, during August 2024 to assess its elemental composition and probable sources. In total, 132 daily samples were collected at six ARPAC sites representing harbor, traffic, industrial, school, and regional-background conditions. PM₁₀ concentrations ranged from 2 to 72 µg m^{−3}, with the highest and lowest values recorded at the traffic and background sites, respectively. Elemental composition was determined by particle-induced X-ray emission and complemented by SEM–EDS. Elemental-based Positive Matrix Factorization (PMF) resolved six profiles, tentatively assigned to S-rich secondary aerosol, Cl-rich marine aerosol, mixed combustion/industrial emissions, Cu-rich traffic emissions, Ca–Sr-rich road dust, and Pb–Zn-rich waste combustion. At the industrial site, the three anthropogenic profiles together represented 74% of the apportioned mass. Traffic-related, marine, and S-rich secondary aerosol represented 49%, 65%, and 30% at the traffic, harbor, and background sites, respectively. SEM–EDS identified representative irregular S–K-rich and Ca-rich particles, crystalline Na–Cl-rich particles, and fine spherical metal-rich particles. Conditional probability function and trajectory analyses indicated local and regional influences, including a possible secondary sulfate contribution from the Mount Etna region. As the PMF analysis relied exclusively on elemental data, these source assignments should be regarded as indicative rather than definitive.

Keywords: urban PM₁₀; elemental composition; element-based positive matrix factorization; secondary aerosol; marine aerosol; traffic emissions; road dust; regional atmospheric transport; Campania



Academic Editor: Qin’geng Wang

Received: 19 June 2026

Revised: 8 August 2026

Accepted: 10 August 2026

Published: 13 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Atmospheric particulate matter (APM or PM) plays a crucial role in the Earth’s climate system and in air quality, with effects extending to weather processes, visibility, ecosystems, human health, and both the natural and built environment. By scattering and absorbing solar radiation and acting as cloud condensation nuclei, aerosols influence the atmospheric

radiative balance and can contribute substantially to climate forcing. They are also responsible for haze formation and reduced visibility in many urban and industrialized regions. Beyond these environmental effects, particulate matter represents a major public health concern. Ambient air pollution is estimated to cause approximately 4.2 million premature deaths per year worldwide, mainly through exposure to fine particulate matter associated with cardiovascular and respiratory diseases and cancer [1]. Exposure to PM has been linked to severe health outcomes, including lung cancer, chronic obstructive pulmonary disease, cardiovascular disease, and stroke [2].

Urban air quality is controlled by emissions, meteorology, topography, and regional transport. While pollutant levels depend on source intensity and distribution, meteorological factors such as wind, stability, boundary-layer height, and precipitation regulate dispersion, transformation, and removal. Local geography can further enhance accumulation or recirculation, especially in valleys and coastal areas. Thus, urban air pollution reflects both local emissions and atmospheric transport processes.

PM composition and source apportionment are investigated worldwide through long-term monitoring networks and targeted field campaigns. In the United States, the Interagency Monitoring of Protected Visual Environments (IMPROVE) network and the Chemical Speciation Network complement PM_{2.5} mass measurements with elemental analysis, major inorganic ions, organic carbon, and elemental carbon. These chemically resolved datasets support the evaluation of long-term trends, regional transport, visibility impairment, health effects, and emission sources [3]. In Europe, the European Monitoring and Evaluation Programme (EMEP) combines measurements of particulate mass and chemical composition with emission inventories and atmospheric-transport modelling to assess regional air quality and the transboundary movement of atmospheric pollutants [4]. Comparable monitoring and research programmes have been established in China and Australia, while targeted composition and source-apportionment studies have been conducted in Russia, Africa, Latin America, and the Middle East.

Elemental measurements combined with receptor modelling have been applied in a wide range of environments. In Beijing, year-long PIXE measurements and Positive Matrix Factorization distinguished secondary sulfur, vehicle emissions, fossil-fuel combustion, biomass burning, road and soil dust, and metal-processing profiles [5]. PIXE-based analysis in Mexico City identified elemental associations representing industrial emissions, wind-blown soil, biomass burning, and heavy-oil combustion [6]. In Jeddah, XRF measurements of PM_{2.5} and PM₁₀ differentiated marine aerosol, resuspended soil, oil combustion, traffic, and industrial contributions [7]. Studies in Dakar and Bamako combined elemental, ionic, and carbonaceous measurements to identify traffic, mineral dust, sea salt, industrial emissions, and solid-fuel combustion [8]. Elemental characterization of PM_{2.5} and PM₁₀ in industrial areas of Russia has similarly been used to evaluate crustal components and potentially toxic metals [9]. These international studies demonstrate the value of elemental analysis for source discrimination.

Air pollution in the Campania region of southern Italy is a significant environmental and public-health concern. The region is affected by a combination of anthropogenic and natural sources contributing to elevated concentrations of PM, heavy metals, nitrogen dioxide (NO₂), and ozone (O₃) [10,11]. Major emission sources include road traffic, especially in the densely populated urban areas of Naples and Salerno, where high traffic intensity and vehicle emissions contribute substantially to air-quality degradation [10]. Industrial activities, including energy production, manufacturing, and waste-management-related processes, may also release fine particulate matter and potentially toxic trace elements. Agricultural activities, open burning, and illegal or uncontrolled waste combustion have

additionally been identified as relevant regional concerns, particularly because they can contribute to both primary particulate emissions and secondary aerosol precursor gases [11].

In response to these challenges, the Campania Region has implemented air-quality mitigation measures, including regional air-quality plans aligned with European legislation and improvements to environmental monitoring networks [11]. Air-quality measurements are made publicly available to inform citizens and support public-health protection. At the national level, Italy implements European air-quality legislation through Legislative Decree No. 155/2010, which transposes Directive 2008/50/EC and establishes the regulatory framework for air-quality monitoring and management [10]. The Italian Institute for Environmental Protection and Research (ISPRA) and the Regional Environmental Protection Agencies (ARPAs) play a central role in collecting, processing, and disseminating air-quality data. Nevertheless, standard monitoring data alone are often insufficient to identify the relative importance of individual emission sources. Therefore, additional chemical and receptor-based approaches are needed to better understand how PM sources vary in space and time and to support more effective air-pollution control strategies.

Several previous studies have investigated particulate matter in Naples and the surrounding Campania region. Di Vaio et al. [12] examined the chemical composition of PM₁₀ at urban background and traffic sites in Naples and identified contributions from crustal material, sea salt, secondary inorganic aerosol, and anthropogenic trace elements. PM₁₀-bound polycyclic aromatic hydrocarbons were also investigated in Naples, highlighting the influence of traffic and combustion-related sources and their potential health relevance [13]. Chianese et al. [14] studied PM_{2.5} and PM₁₀ in the urban area of Naples and showed that aerosol chemical properties and metal solubility vary according to air-mass origin. Carbonaceous aerosol has also been examined in southern Italy and Naples. Dinoi et al. [15] compared organic and elemental carbon in PM_{2.5} and PM₁₀ at several southern Italian sites, while Sirignano et al. [16] used radiocarbon analysis to demonstrate a substantial biomass-burning contribution to PM_{2.5} carbonaceous aerosol in the city centre of Naples. More recently, Rubino et al. [17] investigated the usefulness of stable carbon and nitrogen isotope ratios ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) for PM source apportionment under different meteorological conditions.

Traffic and maritime emissions are particularly relevant in Naples because of the city's dense road network and major port activity. Tunnel and road-traffic studies have provided emission factors and chemical profiles for traffic-related particulate matter and associated compounds [18,19]. In parallel, cruise-ship and maritime emissions have been assessed using emission inventories, modelling approaches, and direct chemical characterization of PM₁₀ emitted from hydrofoil exhaust stacks [20,21]. These studies confirm that port-related emissions may contribute to the atmospheric pollutant burden in coastal urban areas. Meteorological effects have also been investigated in Naples, where stagnant atmospheric conditions, weak ventilation, thermal inversions, absence of precipitation, and specific synoptic patterns have been associated with elevated PM₁₀ episodes [22].

During summer, increased tourism in Mediterranean cities can modify emission patterns and increase population exposure to urban air pollution. Naples is a major tourist destination and experiences high visitor pressure, intense road traffic, port activity, and elevated temperatures during July and August. Under these conditions, source apportionment of PM is critical for identifying and quantifying the major contributing sources and for distinguishing natural contributions, such as sea salt or mineral dust, from anthropogenic emissions. Chemical characterization of particles, combined with receptor-based statistical modelling and atmospheric transport analysis, provides essential evidence for interpreting elevated aerosol levels, supporting air-quality management, and assessing the contribution of specific local and regional sources.

Although previous studies have examined PM chemical composition, carbonaceous aerosols, PAHs, traffic and maritime emissions, and meteorological controls in Naples, most have focused on individual sites, particular source categories, or seasons other than summer. Consequently, knowledge remains limited regarding how PM₁₀ elemental composition and element-based source profiles vary simultaneously across contrasting environments within Campania during the summer period. In particular, few studies have integrated multi-site elemental measurements with receptor modelling, single-particle characterization, directional analysis, and regional transport assessment. This limits the ability to distinguish spatially widespread regional influences from site-specific contributions associated with harbor, traffic, industrial, and other urban activities.

To address this knowledge gap, the present study employed a multi-site design to compare PM₁₀ mass and elemental concentrations among harbor, traffic, industrial, school, and regional-background sites. Selected particles were characterized using SEM–EDS, element-based profiles were resolved using Positive Matrix Factorization, and potential source directions and regional transport pathways were evaluated using Conditional Probability Function and Potential Source Contribution Function analyses. This integrated approach provides a spatially resolved assessment of both local and regional influences on summertime PM₁₀ across Campania. As the receptor model was based exclusively on elemental data, the resolved factors were interpreted cautiously as indicative profiles.

2. Materials and Methods

2.1. Studied Area and Sampling Sites

This study was conducted in Campania (Figure 1), a region in southern Italy covering approximately 13,590 km² with a population of about 5.8 million inhabitants [23]. Campania faces significant air quality and environmental management challenges, with PM₁₀ and PM_{2.5} concentrations frequently exceeding European regulatory limits [23]. The region is also burdened by waste management problems, particularly in industrialized areas, posing risks to public health and the environment [24,25].

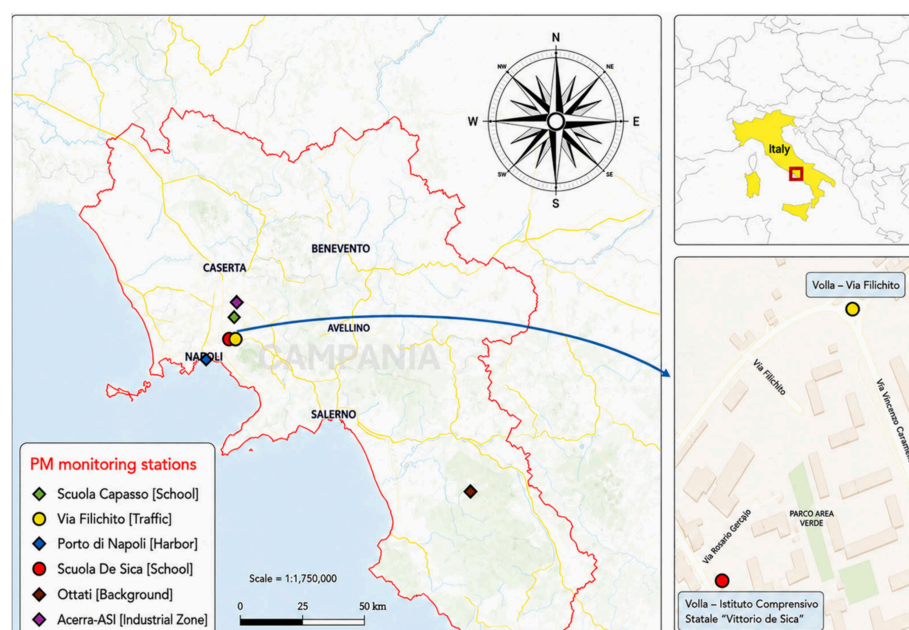


Figure 1. Spatial distribution of the particulate matter (PM) monitoring stations considered in this study across the Campania region (southern Italy). Sites represent multiple station typologies—school, traffic, harbor, background, and industrial—classified according to Legislative Decree No. 155/2010. The inset map indicates the position of Campania within Italy.

PM sampling was conducted using the air-quality monitoring network operated by the Regional Environmental Protection Agency of Campania (ARPAC). Monitoring stations are strategically located in sensitive areas, including high-density urban areas with heavy traffic, urban and suburban backgrounds near schools and hospitals, and emission-influenced zones such as industrial facilities, waste treatment plants, and port areas. According to recent ARPAC assessments, particulate matter remains a relevant air-quality concern in the Naples–Campania area. In 2025, annual mean PM₁₀ concentrations were below the Italian/EU annual limit value of 40 µg m^{−3} at all regional monitoring stations; however, eleven stations exceeded the daily PM₁₀ limit value of 50 µg m^{−3} on more than 35 days [26]. These data indicate that particulate pollution remains spatially variable and locally critical, particularly in densely urbanized and traffic-influenced sectors of the study area.

In this study, six stations were used:

Via Filichito is a primary road in Volla and functions as a high-capacity urban transport corridor. Due to recurring traffic congestion, especially during peak hours, and the significant proportion of heavy goods vehicle traffic, the location represents traffic-dominated conditions. In this environment, primary exhaust emissions and non-exhaust sources (brakes, tyres and road wear) are expected to contribute to the formation of PM.

The Vittorio De Sica Comprehensive School is located in the urban area of Volla within a predominantly residential and densely built-up setting. The surrounding area is characterized by consolidated urban land use, with residential functions prevailing. As a school attended by children, the site represents a sensitive urban-residential receptor for assessing community-relevant PM₁₀ and PM_{2.5} exposure. Air quality at this location is expected to reflect the contribution of local urban emissions, including nearby road traffic, together with broader background influences.

The Acerra ASI area is an industrial development zone located in the northern part of the city, approximately 30 km northeast of Naples, and is used for mixed industrial and logistics activities (e.g., metal processing, energy production, cargo handling). Industrial activities and related freight transport generate increased heavy vehicle traffic and increased local road traffic.

The Port of Naples is one of the most important maritime transport hubs in the Mediterranean, characterized by intense passenger and freight traffic and daily ship movements (e.g., ferries, hydrofoils, cruise ships, and cargo ships).

The Nicola Capasso High School is located in a residential area close to the city center, with local commercial and professional activities in the surrounding area. It is suitable as a sensitive receptor site for assessing air quality relevant to the community in the case of mixed urban impacts and potential impacts from the wider area (e.g., transport corridors and, depending on meteorological conditions, nearby industrial zones).

Ottati is a small town in the Campania region, located at an altitude of ~526 m above sea level, with low population density and limited local industrial activity. Due to the scarcity of direct local sources, this site is suitable as a regional background/reference station, providing baseline concentrations for comparison with urban/industrial sites and supporting the assessment of the contribution of regional traffic.

2.2. PM Sampling

PM₁₀ was collected on 47 mm quartz microfibre filters (Whatman™ grade QM-A; Whatman International Ltd., Maidstone, UK), selected for their low hygroscopicity, high filtration efficiency (≥99.5% for 0.3 µm particles), and mechanical robustness, which helps minimize fibre loss during subsequent laboratory handling and analyses. These filters comply with established standards, including UNI EN 12341:2023 [27], for gravimetric determination of PM in ambient air [28]. PM₁₀ was collected using low-volume automatic

samplers (Skypost PM FX; TCR Tecora®, Cogiate, Italy) operating at a flow rate of approximately 2.3 m³/h over 24 h periods. This sampling method adheres to UNI EN 12341:2023 standards, ensuring accurate and reliable air quality measurements for environmental assessment and public health monitoring.

2.3. Gravimetric Measurement

The determination of PM mass concentration was performed gravimetrically, following the procedures outlined in UNI EN 12341:2023. Filters were conditioned for 48 h in a climatic chamber maintained at 20 °C and 50% relative humidity, and were subsequently weighed using an ME36S microbalance (Sartorius AG, Göttingen, Germany) in a dedicated weighing room. Conditioned, pre-weighed filters were then mounted in appropriate holders and stored in sealed containers prior to sampling. Following sample collection, filters underwent another 48 h conditioning period under the same controlled conditions before being reweighed to obtain the final mass.

2.4. Elemental Analysis

The elemental composition of collected samples was determined using particle-induced X-ray emission (PIXE) spectroscopy [29]. Analyses were conducted at the HUNREN ATOMKI Tandetron accelerator [30] using the in-air millibeam PIXE facility [31]. Samples were irradiated with a 2.5 MeV proton beam with 2 mm × 2 mm dimensions, at a current of 20–30 nA, accumulating a charge of 10 µC per sample. The quartz filters were analyzed under normal atmospheric conditions, since the high Si content of the filter material prevents accurate analysis of light elements such as Na, Mg and Al. During irradiation, a 10 × 10 mm² area of each filter was raster-scanned to minimize beam-induced damage and improve the representativeness of the analysis. The emitted characteristic X-rays were detected using a detector cluster comprising three 65 mm² Be-windowed silicon drift detectors (SDDs) and one 30 mm² ultra-thin-window (UTW) SDD. Kapton absorbers (125 µm thick; DuPont de Nemours, Inc., Wilmington, DE, USA) were placed in front of the Be-windowed detectors, while a pair of permanent magnets shielded the UTW detector from scattered protons. Detailed instrumental parameters, detection limits, and analytical performance characteristics are reported elsewhere [31]. Spectra acquired by the three Be-windowed detectors were summed to enhance sensitivity. Spectral deconvolution and quantification were performed using the GUPIXWIN software (version 3.0.3) [32]. Concentrations of the following elements were obtained after blank correction: S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Rb, Sr, Ba, and Pb. For S, Cl, K and Ca, the self-absorption effects of quartz filters were corrected [33].

Blank filters were analysed using the same PIXE protocol as the aerosol samples, and the mean elemental surface concentration measured on the blanks was subtracted from the corresponding sample concentrations. Replicate precision was expressed as the relative standard deviation (RSD). Method accuracy was evaluated using NIST SRM 2783 (particulate matter on filter media), and the certified and PIXE-measured elemental surface concentrations are also compared.

The combined standard uncertainty of each PIXE concentration included contributions from X-ray counting statistics and spectral fitting, calibration, integrated beam charge, blank correction, effective deposit area, and sampled-air volume. Assuming that these uncertainty components were independent, the combined standard uncertainty was calculated by propagation in quadrature:

$$U_{\text{tot}} = \sqrt{\sum_i U_i^2} \quad (1)$$

where u_i represents the individual standard uncertainty components associated with the sampling and analytical procedures. The analytical uncertainty typically ranged from 5–15%, depending on the element and concentration.

2.5. Determination of Particle Morphology by Electron Microscopy

To complement the bulk elemental data, particle morphology and composition were examined using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDS). Six filters were selected based on elevated elemental concentrations measured by PIXE. Filter sections were mounted on aluminium stubs using double-sided adhesive tape and examined at HSLab, HUN-REN ATOMKI, using a JEOL JSM-IT500HR (JEOL Ltd., Tokyo, Japan) scanning electron microscope equipped with a JEOL EX-74232U1L4Q EDS detector. Secondary-electron (SE) and backscattered-electron (BSE) images and EDS spectra were acquired under low-vacuum conditions (50 Pa), using an accelerating voltage of 15 kV, a probe-current setting of 35, a working distance of 10 mm, and an EDS acquisition time of 40 s per spectrum. The samples were examined without conductive coating. Approximately 20 individual particles were analysed across multiple fields of view. The SEM–EDS results were considered qualitative to semi-quantitative examples rather than statistically representative measurements of the entire filters. They were used to support the interpretation of the bulk PIXE measurements and the probable source types identified by element-based PMF.

2.6. Statistical Analysis and Model Calculations

2.6.1. Positive Matrix Factorization (PMF)

Source apportionment was conducted using the widely applied Positive Matrix Factorization (PMF) method [34,35]. A summary of the PMF input data, modelling parameters, factor contributions, and model diagnostics is provided in Supplementary Table S1.

Variables with more than 80% of values below detection limits were excluded. To minimize the influence of data points with high residuals, the robust mode of the EPA PMF 5.0 model was utilized. Values below the limit of detection (LOD) were replaced with $0.5 \times \text{LOD}$, and corresponding uncertainties were set to 5/6 of the LOD. Missing values were imputed using the mean concentration of the respective species, with uncertainties assigned as four times the imputed values. To improve model robustness and convergence, an additional 5% modeling uncertainty was added. Based on signal-to-noise (S/N) ratios and scaled residuals, chromium (Cr), nickel (Ni), and rubidium (Rb) were identified as weak tracers for the PM_{10} fraction.

The PMF model was run with a six-factor solution. Diagnostic evaluation included assessing scaled residuals, Q-values, and source profiles. The selected solution was considered optimal, providing a physically interpretable result and a good fit to the original data, as indicated by a $Q_{\text{true}}/Q_{\text{expected}}$ value of 1.53 (Brown et al., 2015b [34]) and high correlation coefficients ($R^2 = 0.86\text{--}0.98$) between modeled and observed concentrations for most species. Weakly represented variables exhibited lower correlations ($R^2 = 0.37\text{--}0.70$).

All model runs converged, and scaled residuals were normally distributed within the range of -3 to $+3$, indicating a well-behaved model fit. Various values of FPEAK (a rotational control parameter in PMF) were tested; however, no tested value resulted in demonstrably improved or more interpretable source profiles.

To assess the robustness and uncertainty of the solution, three error estimation techniques were applied: bootstrap (BS), displacement of factor elements (DISP), and bootstrap enhanced by displacement (BS-DISP). These diagnostics confirmed that the solution was robust and exhibited minimal rotational ambiguity. Bootstrap analysis indicated that factors

were reproduced in at least 80% of resampled solutions, and DISP analysis revealed no factor swaps at the minimum dQ level, confirming stable and well-defined factors.

2.6.2. Conditional Probability Function (CPF)

CPF analysis was applied to the element-based PMF profile contributions to identify probable source directions and transport pathways at the monitoring sites [36]. For each wind-direction sector θ and wind-speed interval j , CPF was calculated as:

$$CPF(\theta) = \frac{m_{\theta,j}}{n_{\theta,j}} \quad (2)$$

where $n_{\theta,j}$ is the total number of observations within a given wind-direction and wind-speed category, and $m_{\theta,j}$ is the number for which the corresponding profile contribution exceeded its 75th percentile. Calm conditions ($<1 \text{ m s}^{-1}$) were excluded because wind-direction measurements are unreliable at low wind speeds. Meteorological data for Naples were obtained from the ERA5 reanalysis dataset through the Copernicus Climate Data Store [37]. CPF polar plots were generated using the openair package in R [38]. High CPF values were interpreted as indicating probable source directions or transport pathways rather than confirming individual emission sources.

2.6.3. Backward Trajectories Calculation

Backward trajectories were generated using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPPLIT) [39], which is widely used for backward trajectory simulations. Meteorological data from the NOAA Global Data Assimilation System (GDAS) were used as input, which offers a spatial resolution of 0.25° latitude/longitude at 6 h intervals. These trajectories were computed at each monitoring station on an hourly basis for a 96 h period, releasing air parcels at a terminal height of 500 m above ground level (AGL). The calculations relied on time integration of parcel positions derived from three-dimensional wind fields. This set of trajectories was then used as input in the Potential Source Contribution Function (PSCF).

2.6.4. Potential Source Contribution Function (PSCF)

The Potential Source Contribution Function (PSCF) generates a probability map surrounding a receptor site by allocating air mass residence time, thereby identifying potential source regions influencing air quality [40]. Each back trajectory is classified as either “polluted” or “clean” based on a predefined concentration threshold. The study domain is discretized into $0.25^\circ \times 0.25^\circ$ grid cells, and the PSCF for cell (i, j) is defined as:

$$PSCFi,j = \frac{m_{i,j}}{n_{i,j}} \quad (3)$$

where $n_{i,j}$ is the number of trajectories passing through cell (i, j) , and $m_{i,j}$ is the number of trajectories with high source concentrations passing through the same cell [41].

3. Results and Discussion

3.1. Sampling Coverage and Dataset Composition

Simultaneous PM_{10} sampling at the six monitoring stations produced 132 valid samples during August 2024 (Table 1). The resulting dataset comprised contrasting industrial, traffic, harbor, school, and regional-background environments and therefore provided the basis for evaluating spatial differences in PM_{10} mass and elemental composition across Campania.

Table 1. Summary of PM₁₀ sampling periods and sample numbers across six monitoring stations in Campania during August 2024.

Monitoring Station	Site Type	Sampling Period	Samples (n)
Acerra	Industrial	2–27 August 2024	24
Volla Via Filichito	Traffic	2–28 August 2024	26
Porto	Harbor	9–28 August 2024	18
Volla Succursale de Sica	School 1	9–28 August 2024	20
Scuola Capasso	School 2	9–28 August 2024	19
Ottati	Regional background	3–28 August 2024	25
Total			132

All 132 PM₁₀ samples were analysed by PIXE. The resulting 132 × 18 data matrix, consisting of PM₁₀ mass and 17 elemental variables, was used in the PMF analysis. Selected samples were additionally examined by SEM–EDS to provide complementary information on particle morphology and elemental associations.

3.2. Analytical Performance and Data Quality

Element-specific limits of detection (LODs), limits of quantification (LOQs), mean blank-filter surface concentrations, and representative replicate precision data for the traffic site are reported in Table 2. Element-specific LODs ranged from 0.6 to 23.9 ng cm^{−2}, while LOQs ranged from 1.8 to 72.4 ng cm^{−2}. Replicate measurements of sample Volla6_66, collected at the traffic site, are presented as a representative example and generally yielded RSDs below 18%, indicating acceptable within-filter repeatability for the quantified elements. Comparison with NIST SRM 2783 showed close agreement between certified and PIXE-measured surface concentrations for most elements present at readily quantifiable levels, including S, K, Ca, Ti, Mn, Fe, Cu, Zn, and Pb. Overall, the blank correction, replicate precision, and reference-material comparison support the use of the PIXE dataset for the subsequent spatial and PMF analyses.

Table 2. Element-specific limits of detection (LODs), limits of quantification (LOQs), mean blank-filter surface concentrations, representative replicate results and relative standard deviations (RSDs) for the traffic site, and certified and PIXE-measured concentrations of NIST SRM 2783. All concentrations are expressed in ng cm^{−2}.

Element	LOD Conc. (ng cm ^{−2})	LOQ Conc. (ng cm ^{−2})	Blank Conc. (ng cm ^{−2})	Mean Conc. (ng cm ^{−2})	Volla6_66 SD (ng cm ^{−2})	RSD %	Certified Conc. (ng cm ^{−2})	SD Conc. (ng cm ^{−2})	Measured Conc. (ng cm ^{−2})	Fit Error (%)
S	23.9	72.4	111	2910	290	9.9	105.4	26.1	106	33.2
Cl	7.7	23.3	72	659	4	0.6	n.d.			
K	6.1	18.5	184	1100	110	10.3	530.1	52.2	569	2.9
Ca	1.9	5.8	1472	9400	980	10.5	1325.3	170.7	1312	0.9
Ti	1.2	3.6	17	96	10	10.9	149.6	24.1	151	1.4
V	1.1	3.3	<LOD	<LOD			4.9	0.6	2	18.2
Cr	0.8	2.4	12	20	3	15.4	13.6	2.5	17	4.8
Mn	0.8	2.4	4	31	3	10.1	32.1	1.2	32	2.6
Fe	0.7	2.1	112	1570	170	10.6	2660.6	160.6	2622	0.4
Co	0.9	2.7	1				0.8	0.1	1	10.1
Ni	0.7	2.1	30	11	1	6.3	6.8	1.2	9	5.7
Cu	0.7	2.1	9	78	3	3.2	40.6	4.2	38	2.1
Zn	0.6	1.8	11	57	7	12.6	179.7	13.1	171	0.9
Br	0.7	2.1	<LOD	69	1	11	n.d.			
Rb	0.7	2.1	1	<LOD			2.4	0.6	6	23.7
Sr	1.1	3.3	8	16.0	0.5	3.4	n.d.			
Pb	1.9	5.8	5	13.0	2.3	17.5	31.8	5.4	35	11.7

3.3. Spatial Variability of PM₁₀ Mass and Elemental Composition

Figure 2 shows spatial variability of PM₁₀ mass and selected elemental concentrations across the six sampling site types.

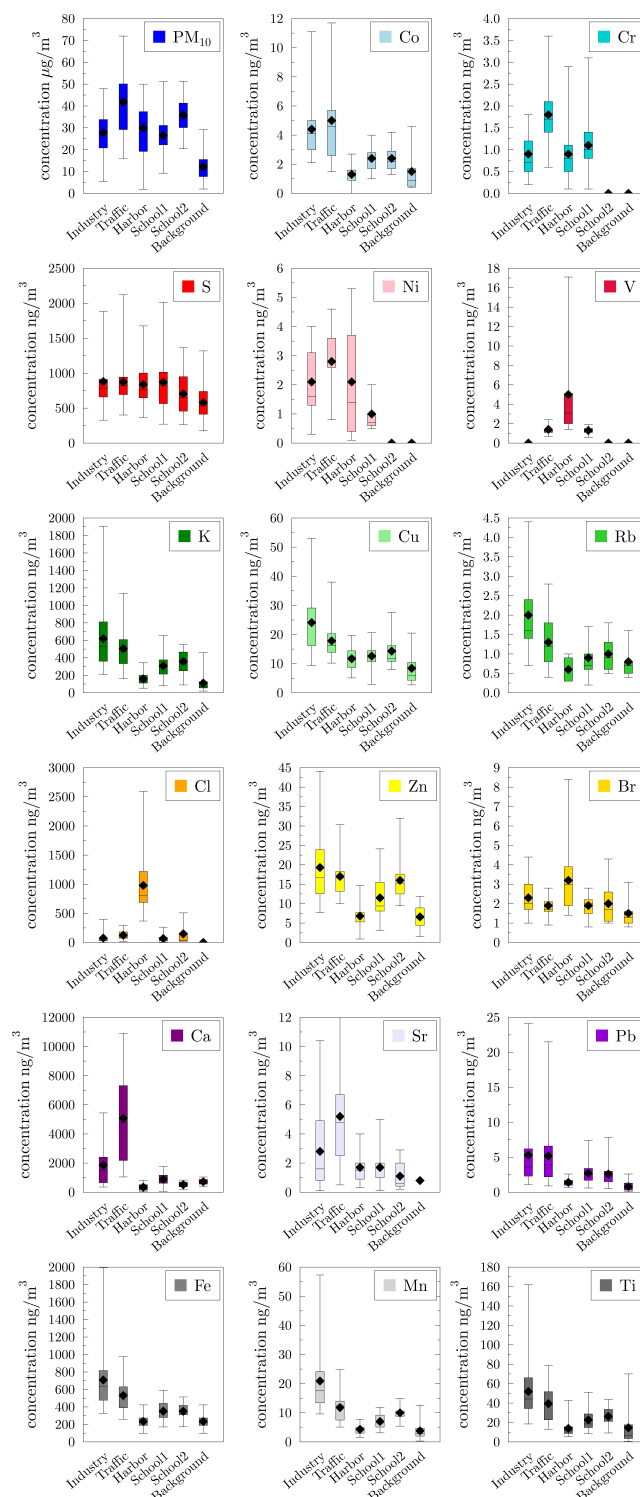


Figure 2. Spatial variability of PM₁₀ mass and selected elemental concentrations at the six sampling sites. Boxes represent the interquartile range (IQR), extending from the first quartile (Q1, 25th percentile) to the third quartile (Q3, 75th percentile). The horizontal line inside each box indicates the median (50th percentile), while the filled black square marker represents the arithmetic mean. The interval indicates the range between the lowest and highest values. PM₁₀ concentrations are reported in μg/m³, whereas elemental concentrations are expressed in ng/m³.

PM₁₀ mass and elemental concentrations are presented using medians and interquartile ranges because several distributions were skewed and contained relatively high observations. These statistics provide a robust descriptive comparison among sites but do not, by themselves, establish statistically significant differences. Accordingly, the following interpretation focuses on differences in median values, concentration ranges, and multielement patterns.

PM₁₀ mass concentrations showed moderate spatial variation among the six monitoring environments. The traffic site and School 2 exhibited higher median concentrations than the regional background station, while the industrial and harbor sites also showed relatively elevated values. However, the distributions overlapped considerably, and the differences should therefore be regarded as descriptive rather than statistically significant. The broad interquartile ranges and extended upper ranges at several sites suggest episodic high-concentration events rather than uniformly elevated pollution. Therefore, the observed spatial pattern is consistent with a combination of regional aerosol loading and site-specific primary emissions, including road dust resuspension, non-exhaust traffic emissions, industrial activities, and marine aerosol input [42–44].

Sulfur concentrations were relatively high at all sites and showed less spatial contrast than several crustal and metal-related elements. This comparatively uniform distribution is consistent with a regional contribution from secondary sulfur-containing aerosol formed through the atmospheric oxidation of SO₂. Nevertheless, local or near-regional combustion emissions may also have contributed to the measured S concentrations. Because PIXE measures total elemental S and cannot directly distinguish sulfate from other sulfur-containing compounds, S is interpreted cautiously as a mixed indicator of regional secondary aerosol formation and possible combustion-related inputs [42,43].

The clearest spatial contrast was observed for Cl, for which the harbor site displayed a substantially higher median concentration and greater variability than the inland stations. This distribution is consistent with a strong contribution from marine aerosol and coastal or port-related air masses. The lower Cl concentrations observed inland may reflect dilution, deposition, and chemical aging during transport. Br and Sr displayed less distinct spatial patterns and cannot be assigned to a single source based on Figure 2 alone. Br may be associated with marine aerosol, combustion, or waste-related emissions, whereas Sr may originate from marine aerosol, crustal material, or resuspended dust.

At the traffic site, Ca showed a comparatively high median concentration and broad distribution, consistent with possible contributions from road-dust resuspension, construction-derived material, and disturbed mineral surfaces. Fe, Ti, Mn, Sr, Rb, and Co also showed relatively high values in some samples, supporting a possible influence from crustal and mechanically generated particles. Cu, Zn, Pb, Cr, and Ni may additionally reflect non-exhaust traffic emissions, including brake and tire wear, road-surface abrasion, and the resuspension of previously deposited material.

The industrial site exhibited relatively high median concentrations or broad distributions for several metals, including Cu, Zn, Pb, Co, Mn, Fe, and Ti, together with K and Rb. These are compatible with contributions from industrial activities, mechanical abrasion, and the resuspension of metal-containing dust [43,45].

Vanadium and Ni showed site-dependent behavior, with notable concentrations at the harbor and traffic/urban sites. Because V and Ni are commonly associated with heavy fuel oil combustion, shipping, and other oil-combustion sources, their presence may indicate an influence from port activities and fuel-combustion emissions [45,46].

Potassium concentrations were highest at the industrial and traffic sites and lower at the harbor and background locations. This pattern suggests that K may be influenced by

combustion-related sources, including biomass burning or mixed urban combustion, but it may also include contributions from mineral dust and re-suspended material.

The two school sites showed intermediate but distinct behavior. School 2 generally had higher median PM_{10} concentrations and relatively high values of several elements, including Zn, Pb, Fe, Mn, K, and Cu, than School 1. This suggests stronger influence from nearby industrial-related sources at School 2. School 1 showed lower or more moderate elemental concentrations, indicating a comparatively weaker local source impact.

Overall, Figure 2 indicates that spatial contrasts were more evident in the elemental composition than in PM_{10} mass alone. The harbor displayed the strongest marine-related signature, whereas the traffic and industrial sites showed patterns compatible with mechanically generated and metal-rich particles, respectively. The school sites generally occupied an intermediate position. These interpretations are based on descriptive concentration patterns and are further evaluated using the PMF and directional analyses.

3.4. Source Apportionment of PM_{10} by PMF

Element-based Positive Matrix Factorization (PMF) identified six contributing factors to PM_{10} concentrations. These were interpreted as representing S-rich secondary aerosol, Cl-rich marine aerosol, mixed combustion and industrial, Cu-rich traffic, Ca–Sr-rich road dust, and Pb–Zn-rich waste combustion. PMF element-based factor profiles for PM_{10} are shown in Figure 3, while the percentage of relative source contributions to PM_{10} by source category at the six monitoring stations is shown in Figure 4.

Cl-rich marine aerosol: This factor is predominantly determined by Cl (90.3%), which provides the most characteristic chemical fingerprint of marine aerosols, resulting from the emission of sea salt spray. Smaller but persistent marine contributions are observed for Sr (3.4%) and K (1.2%), which may occur in sea salt particles and/or weakly mixed marine minerals. Br (17.4%) is also significant and consistent with the influence of sea salt, as bromide is present in seawater and can be transferred to marine aerosols, often with a composition altered during atmospheric aging. Overall, the extremely strong Cl signal supports attribution to a marine (sea salt) source [47].

Mixed combustion and industrial emissions: The factor shows pronounced combustion-related signals in the form of K (50.6%), which is a widely used indicator of biomass combustion [48]. However, it also explains the very high proportions of Mn (61.8%), Fe (51.7%), and Ti (56.4%), suggesting that, in addition to K-rich ash, the source also contains a significant mineral/metal-rich particle component, which is characteristic of high-temperature processes and ash treatment. The additional contribution of Ni (37.4%), Co (38.1%), Rb (38.3%) and Zn (29.8%) further supports the mixed combustion/ash-related origin consistent with biomass and/or industrial thermal operations [49,50].

Cu-rich traffic emissions: The traffic factor is characterized by high proportions of Cu (71.2%) and Br (67.5%), together with moderate contributions of Ni (45.6%), S (16.7%), Fe (15.8%) and Ti (9.2%). This profile is consistent with a traffic-related source, mainly reflecting non-exhaust emissions, including brake wear, tyre/road wear and re-suspended road dust. The strong Cu contribution, together with Fe, is a typical indicator of brake-wear particles, while Ti may be associated with road dust, road-surface wear and mechanically re-suspended mineral material enriched by traffic activity [51–53]. The moderate Ni contribution may reflect fuel/lubricating-oil related emissions, engine wear and abrasion of vehicle components, whereas S can be linked to sulfate and sulfur-containing fuel or lubricant-derived exhaust particles [54]. Br has also been reported among trace components used in vehicle-exhaust and traffic-related source profiles, although it is not a unique traffic tracer and should therefore be interpreted cautiously [54]. Overall, the elemental

composition supports the assignment of this factor to traffic emissions, with a dominant non-exhaust component and a smaller exhaust/fuel-lubricant contribution.

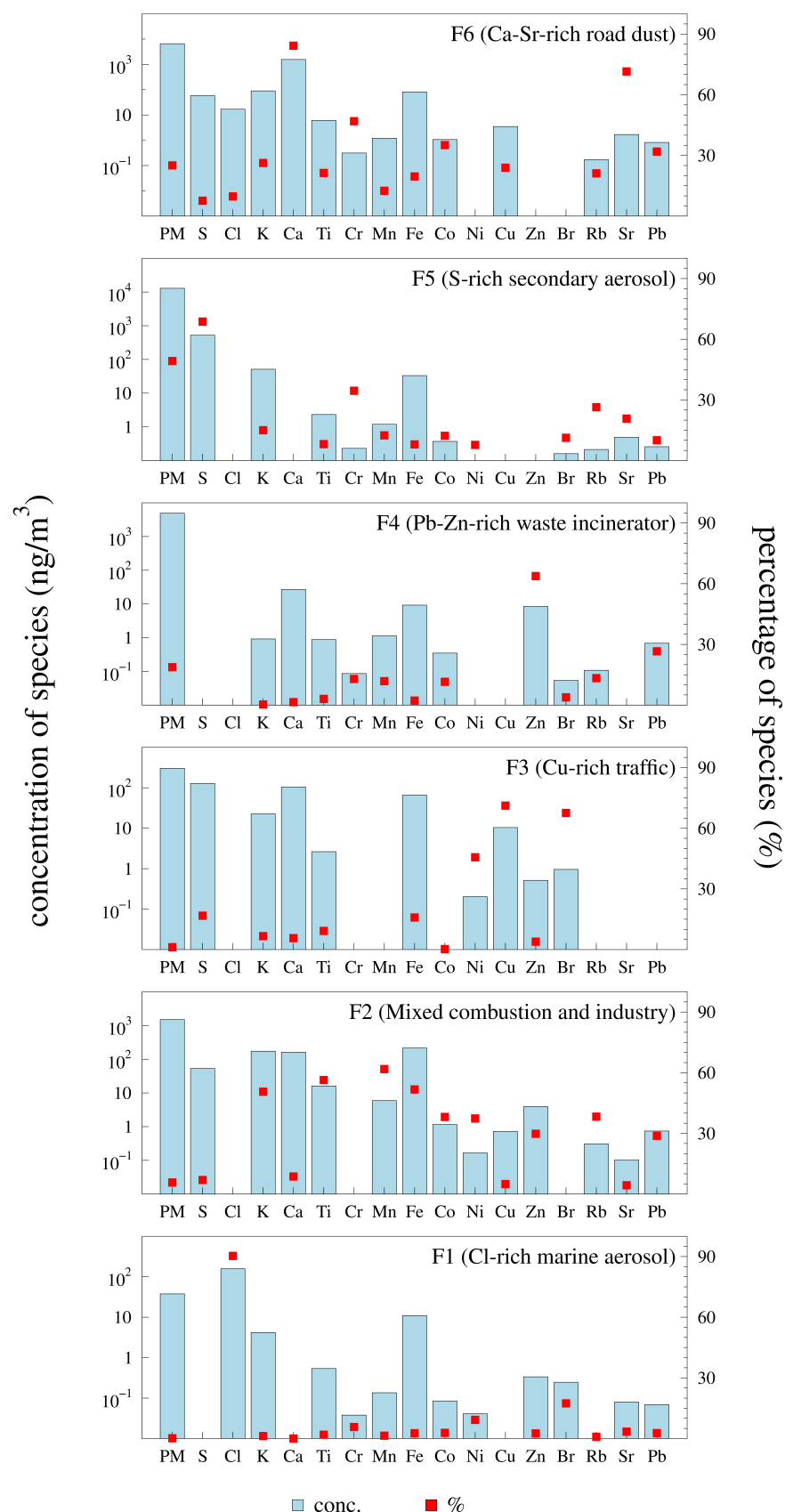


Figure 3. Elemental composition of PM₁₀ source profiles.

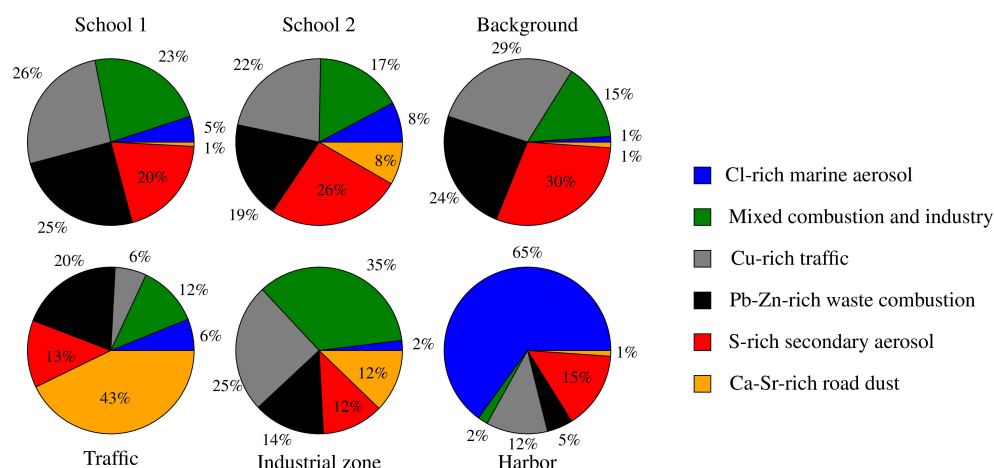


Figure 4. Percentage of relative source contribution to PM₁₀ by source category at different sampling sites.

Pb–Zn-rich waste combustion: This factor is dominated by Zn (63.8%) and also includes significant amounts of Pb (26.6%), with additional contributions from Rb (13.3%) and Cr (12.9%). Such a Zn–Pb-rich profile is characteristic of waste incineration, where volatile and semi-volatile metals evaporate at furnace temperatures and then condense into fine particles and fly ash. It is important to note that this factor also accounts for a significant proportion (18.7%) of the PM mass, which underlines its importance in terms of particle load in the data series [55,56].

S-rich secondary aerosol: This factor was mainly characterized by a dominant contribution of S (68.7%), supporting its identification as a secondary sulfate-rich aerosol component, in agreement with previous source-apportionment studies [57]. Sulfur dioxide (SO₂), the gaseous precursor of sulfate, may originate from several combustion-related sources, including diesel engines, fuel-oil combustion, natural gas or pellet burning, shipping and industrial emissions. After atmospheric oxidation, sulfate (SO₄^{2−}) may occur together with NH₄⁺, Na, OC, K, and trace metals such as Cu, Zn, and Pb [42]. Because secondary sulfate formation requires atmospheric processing time, it is often difficult to clearly distinguish locally formed secondary aerosol from regionally transported aged aerosol. This factor also accounted for a substantial fraction of the reconstructed PM mass (49.2%), indicating the important role of regionally distributed, aged secondary aerosol in the study area.

Ca–Sr-rich road dust: Dust is characterized by strong crust/cement-like signals, dominated by Ca (84.2%) and Sr (71.5%), which is consistent with re-suspended minerals and abrasion of concrete/mortar and other building materials. This factor also explains the significant proportions of Cr (46.9%), Co (35.1%) and Pb (31.9%), as well as the significant contributions of K (26.2%), Cu (23.9%), Ti (21.3%), Fe (19.6%) and Mn (12.5%), which indicates a mixture of non-exhaust-related traffic wear and local resuspension processes [52,53]. Overall, the dominance of Ca–Sr and the presence of traffic-related metals support the assumption that the re-suspended road dust is enriched by road surface/construction materials and particles from wear.

As mentioned above, Figure 4 presents the relative contributions of the PMF-resolved factors at each monitoring station. The percentage contribution represents the proportion of the total PMF-apportioned PM₁₀ mass attributed to each factor, with the sum of all factor contributions normalized to 100% at each station.

PMF analysis reveals significant spatial heterogeneity in source contributions. The Harbor site is overwhelmingly dominated by Cl-rich marine aerosol (64%), indicating a strong influence of marine aerosol, consistent with its coastal location. Secondary sources,

including S-rich aerosol (14%) and Cu-rich traffic (12%) contributions, suggest regional transport and port-related emissions.

In contrast, the traffic site exhibits a clear road dust dominance (43%), indicating significant non-exhaust resuspension processes. Contributions from the waste incinerator (20%) and mixed sources (12%), along with S-rich secondary aerosol (13%), further characterize the site's pollution profile. The nearby School 1 site exhibits a more balanced source distribution with comparable contributions from traffic (26%), waste incineration (25%), and mixed sources (23%).

Within the industrial zone, the industrial site demonstrates a complex source apportionment, driven primarily by mixed factors (35%) and traffic emissions (25%). The presence of a waste incinerator (14%), S-rich secondary aerosol (12%), and road dust (12%) indicates the co-occurrence of industrial activity and combustion-related impacts. The residential site in this zone, School 2, is characterized by a higher proportion of S-rich secondary aerosol (26%), indicative of aged aerosol, followed by contributions from traffic (22%) and the waste incinerator (19%).

The background site is primarily influenced by S-rich secondary aerosol (30%) and traffic (29%), with a substantial contribution from the waste incinerator (24%) and comparatively lower mixed sources (15%). Cl-rich marine aerosol and road dust contributions are negligible ($\approx 1\%$), confirming the site's characterization as a predominantly regional receptor with limited marine influence.

3.5. Comparison of PMF Source Interpretation Against Previous Naples Study

It should be noted that the PMF analysis in the present study was performed using only elemental concentrations, as measurements of water-soluble ions and carbonaceous species (OC/EC) were not available. Elemental tracers are suitable for identifying several major source categories, particularly mineral dust, marine aerosol, traffic-related metals, industrial emissions, and high-temperature processes. However, the absence of complementary chemical species increases the uncertainty in resolving sources with overlapping chemical signatures, especially secondary inorganic aerosol and combustion-related sources. Therefore, the PMF factors identified here should be interpreted as the most probable source profiles supported by the available elemental dataset.

To evaluate the plausibility of the resolved factors, the present results were compared with previous PM₁₀ source-apportionment results reported for Naples. Di Vaio et al. [12] investigated PM₁₀ at an urban-background site and an urban-traffic site in Naples using chemical characterization, enrichment factors, and principal component analysis. They identified six main source categories: crustal origin, sea salt, secondary inorganic aerosol, combustion sources, roadside/re-suspended dust, and industrial emissions. These categories are broadly consistent with the factors resolved in the present study. Both studies indicate the importance of marine aerosol, secondary sulfate/inorganic aerosol, combustion-related sources, traffic or roadside dust, and industrial or waste-related metal sources in the Naples area.

The main added value of the present study is its multi-site design, which provides a more spatially resolved separation of PM sources across industrial, traffic, harbor, school, and regional-background environments. In particular, the present PMF solution distinguishes between Cl-rich marine aerosol, S-rich secondary aerosol, Cu-rich traffic emissions, Ca–Sr-rich re-suspended dust, mixed combustion/industrial emission, and Zn–Pb-rich waste incineration emissions. In contrast, the previous Naples study separated source contributions mainly at two urban sites. Thus, while the present source assignments remain constrained by the elemental-only dataset, their consistency with earlier Naples PM₁₀ source categories supports the robustness of the main interpretation.

3.6. CPF Analysis of Identified Source Contributions

Although approximately 98 km apart, both the industrial zone and the background site are demonstrably influenced by regional atmospheric transport, though receptor location and local terrain modify the specific patterns observed (Figures 5 and 6).

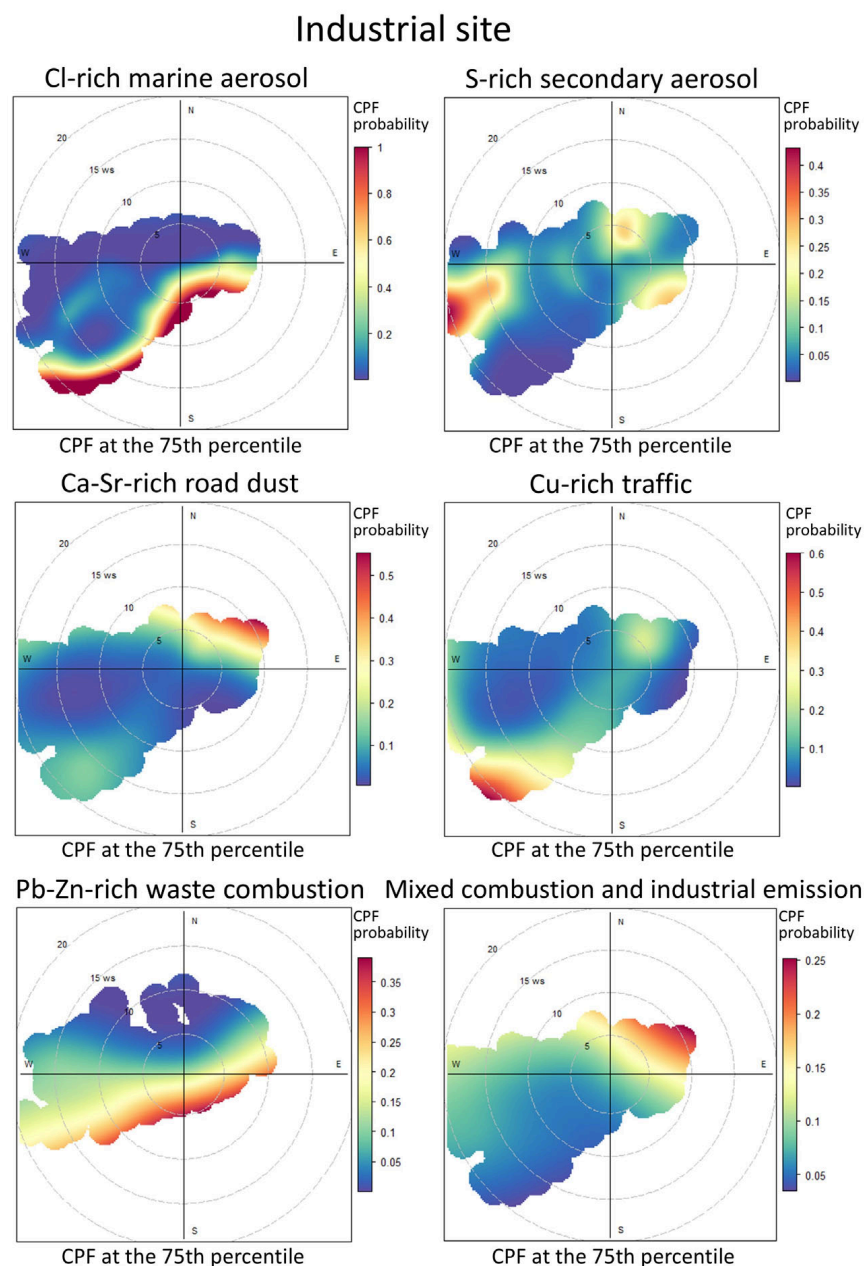


Figure 5. Polar plots of PM₁₀ source contributions derived from CPF calculations at the industrial site. Wind speed (m s^{-1}) is shown on the radial axis, while colour indicates the calculated probability.

Sea-salt concentrations at the industrial zone peak with moderate-to-strong winds from the S-SE-E, consistent with direct marine aerosol penetration. In contrast, the background site exhibits sea-salt enrichment from the W-WSW sector, occurring primarily during higher wind speed events, suggesting topographically funnelled intrusions from the Tyrrhenian Sea. Secondary sulfate at the industrial zone displays two distinct probability maxima: one associated with WSW flow at higher speeds, and another with E-ESE flow at moderate speeds, indicative of multiple regional source pathways. The background site, however, presents a broader, multi-sector pattern, likely reflecting the influence of aged, well-mixed

regional air masses. Regarding anthropogenic contributions, the industrial zone reveals a narrow E-ENE sector linked to near-field road dust resuspension at low wind speeds, and stronger E-ENE/NE signals for mixed/industrial factors at higher speeds, highlighting a localized industrial corridor. Finally, the incinerator exerts its strongest influence from the S-SE direction, predominantly during stronger wind events—a pattern consistent with plume impact under favorable atmospheric conditions.

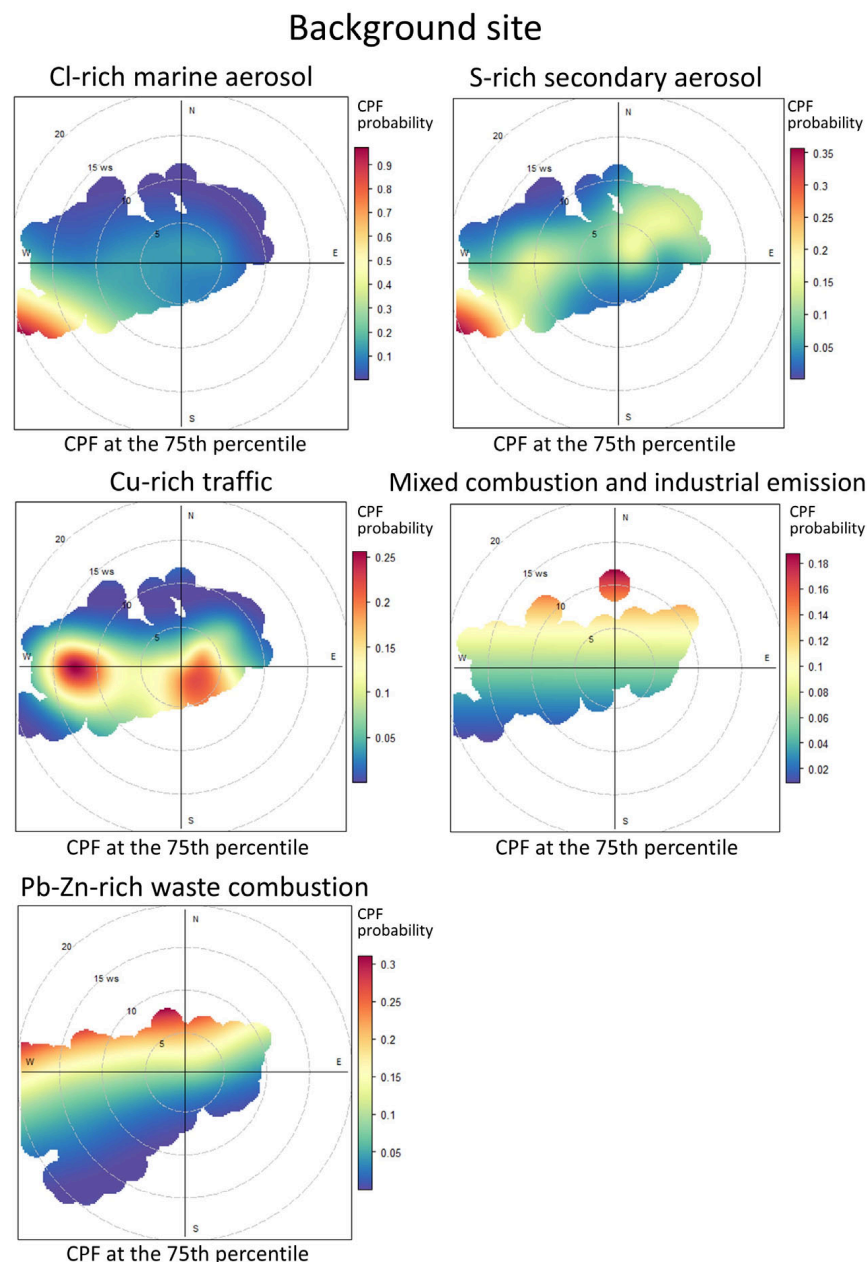


Figure 6. Polar plots of PM_{10} source contributions derived from CPF calculations at the background site. Wind speed ($m s^{-1}$) is shown on the radial axis, while colour indicates the calculated probability.

3.7. Comparison of Air-Mass Trajectory Clusters at Polluted and Background Locations

The number of clusters varied among the sampling sites. Therefore, representative examples were selected from a polluted industrial zone and a background site, as shown in Figure 7.

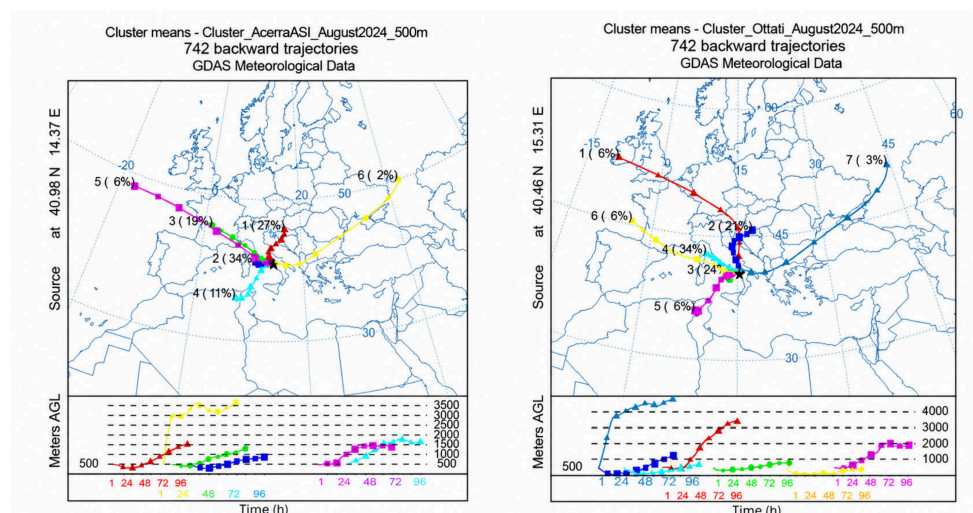


Figure 7. Cluster means of backward trajectories calculated using HYSPLIT trajectory clustering for the entire study period at the industrial site (left) and the background site (right).

Six air-mass trajectory clusters were identified at the industrial site, whereas seven clusters were identified at the regional background site. Despite this difference, a high similarity between the air mass patterns can be identified at both sites based on their distance travelled and pathway. The most significant difference is observed in the frequency associated with each of these patterns. In both cases, two long-range patterns are observed: one from the west (C5 in industrial zone and C1 in background, both at 6% and one from the east (C6 at 2% in industrial and C7 at 3% in background, respectively). A pattern closer to the west is also recorded at both sites, with greater dominance in the background (C4 at 34%) than in the industrial site (C5 and C3, with a total of 24%). In both locations, in the short-range air masses, a southern circulation pattern was present, more frequent in the industrial zone (C4 at 11%) than in the background (C5 at 6%), as well as another from the north, also more frequent in industrial zone (C1 at 27%) than in background (C2 at 21%). Finally, those with the shortest trajectory also predominate more in industrial site (C2 at 34%) than in background (C3 at 24%). The vertical patterns were also similar, as few patterns exceed 2000 m AGL in their displacement. While only one such pattern is observed in industrial site (C6 from the east), two are observed in background (C7 from the east and C1 from the west). Considering these results, it is clear that both locations are dominated by short-range air mass patterns with a displacement close to the ground, with a higher predominance of westerly air masses in the background compared to the industrial site.

3.8. S-Rich Secondary Aerosol

Sulphur was a significant component at all stations and showed much weaker spatial gradients than fractions of more local origin (e.g., sea salt, mineral dust, smoke-related and trace elements). This may indicate that the S-rich secondary aerosol profile was predominantly influenced by secondary formation and regional transport rather than by highly site-specific emissions. Based on this, the temporal evolution of secondary sulfates in August 2024 (Figure 8) shows largely synchronized behavior across the network.

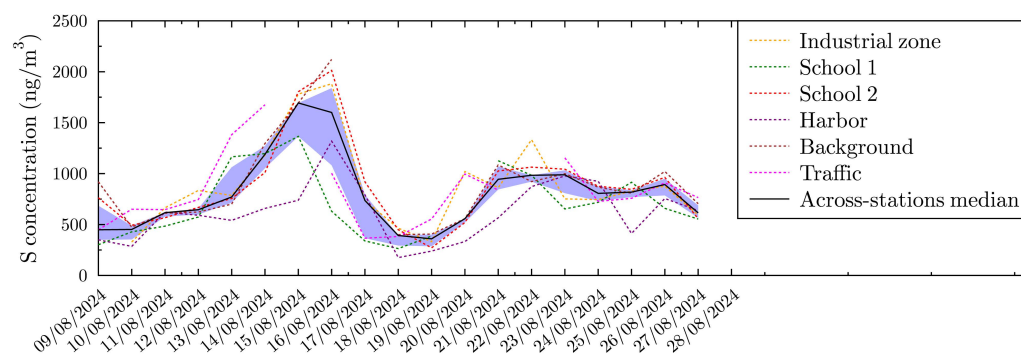


Figure 8. Temporal variation of sulphur during August 2024 across the monitoring network. Coloured lines represent site-specific concentrations (Traffic site, Harbor, Industrial zone, School 1, School 2, Background). The black line shows the across-stations median, while the shaded envelope indicates the inter-station variability.

The strong correlation between stations—and the relatively narrow spread between stations on most days—supports the interpretation that sulphur was primarily driven by common regional air mass processes, with only short-lived, site-specific variations. Concentrations increased during the first half of the month, reaching a maximum in mid-August, with values of $1.7\text{--}2.1\ \mu\text{g}/\text{m}^3$ at several sites, followed by a rapid decline on 16–17 August.

Satellite observations are consistent with this temporal pattern. The Sentinel-5P/TROPOM [58–60] overpass on 15 August 2024 shows a significant increase in tropospheric SO_2 over the central Mediterranean, with the highest columns concentrated over eastern Sicily, i.e., the Etna region (Figure S1). A well-defined smoke plume spreads in an ENE direction across the Ionian Sea towards western Greece. The narrow, coherent axis of the smoke cloud indicates rapid synoptic-scale advection of an episodic emission, suggesting volcanic gas emissions/eruption activity rather than diffuse regional anthropogenic sources. The local statistics shown on the map (total SO_2 mass and maximum column) support significant short-term emissions. This increase is supported by our PSCF calculations (Figure 9).

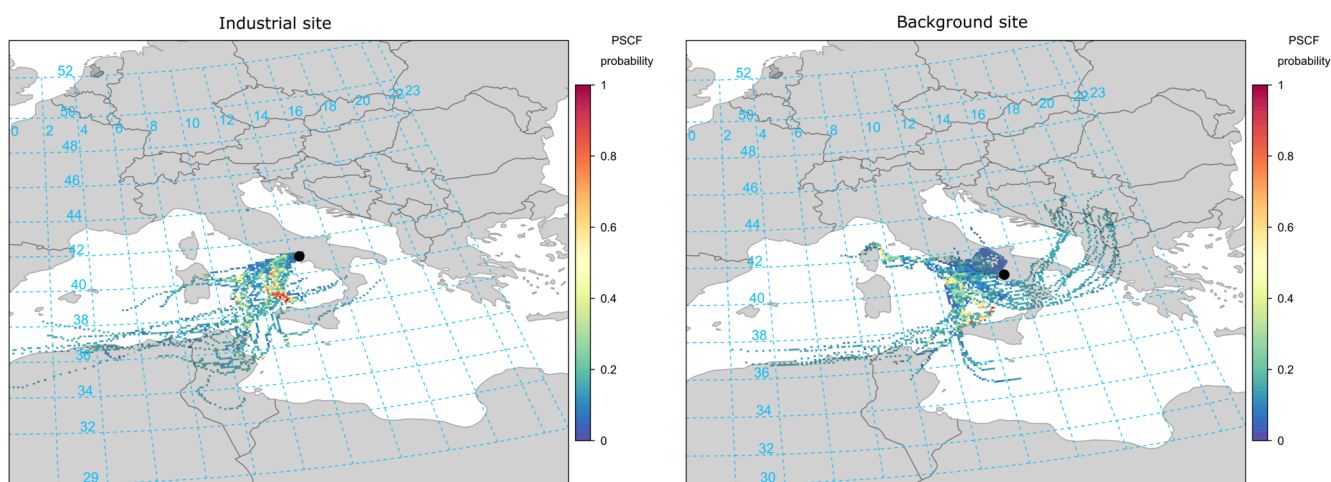


Figure 9. PSCF maps (threshold: 75%) for secondary sulfate at the industrial (left) and background (right) sites.

3.9. Overall Interpretation of Directional and Transport Analyses

The CPF and trajectory-cluster analyses indicated contributions from both local-scale processes and regional transport at the industrial and background sites. At the industrial

site, elevated contributions of the Cl-rich profile were associated with southern to southeastern winds, whereas the road-dust and mixed combustion/industrial profiles were associated mainly with eastern to northeastern sectors. Broader directional distributions were observed for some profiles at the background site. However, in the absence of georeferenced emission-source data, these patterns represent probable transport sectors rather than confirmed source locations.

Both sites were predominantly influenced by short-range, low-altitude air masses, although westerly trajectories occurred more frequently at the background site. Less frequent long-range trajectories from eastern and western sectors also indicated the possibility of episodic transport from more distant regions. The synchronized temporal variation and limited spatial variability of sulfur across the monitoring network further support a regional contribution to the S-rich PMF profile. The mid-August sulfur maximum coincided with enhanced tropospheric SO₂ over the central Mediterranean and PSCF probability regions extending towards southern and southeastern sectors. Taken together, these observations suggest that episodic volcanic emissions from the Etna region may have contributed to the observed increase in sulfur concentrations.

3.10. Single-Particle Analysis by Scanning Electron Microscopy (SEM)

Particle morphology provides important complementary information for identifying potential aerosol sources. Therefore, following the bulk chemical analysis, selected samples were examined by scanning electron microscopy (SEM), as shown in Figure 9. The following particle types were identified: irregularly shaped (K-rich, S-rich, Ca-rich), spherical (Fe-O-rich, Fe-Cu-rich) and cubic (NaCl).

Figure 10a,b presents a PM₁₀ sample collected at the Port of Naples. The corresponding SEM-EDS elemental maps and spectra are provided in Figures S2 and S3, respectively. Elemental mapping (Figure S1) reveals abundant particles rich in sodium chloride (NaCl), often occurring as crystalline structures. This observation supports the strong influence of primary marine aerosol (sea spray) at this location. Additionally, particles with irregularly shaped K-Ca-S compositions are observed, alongside aggregates and approximately 1 µm spherical particles enriched in iron oxide (Fe-O-rich), derived from high-temperature processes. Elemental mapping indicated that the K-Ca-rich particles were associated with Ca, K, and S, suggesting the presence of sulfate phases or sulfate coatings.

Figure 10c,d presents particles at the traffic site. The corresponding SEM-EDS elemental maps and spectra are provided in Supplementary Figures S4 and S5, respectively. SEM images revealed predominantly amorphous and irregular-shaped particles. Elemental mapping indicated that these particles were strongly enriched in calcium, consistent with mineral or construction-related material and re-suspended road dust. The presence of sulfur suggests the contribution of sulfate (e.g., from coatings). Furthermore, a spherical metal-rich particle containing iron, copper, cobalt and nickel is identified. Furthermore, spherical metal-rich particles containing Fe, Cu, Co, and Ni, as well as spherical Pb-rich particles, were identified. These particles may reflect contributions from traffic-related non-exhaust emissions, including brake and tire wear, and resuspended road dust, alongside the dominant Ca-rich particles.

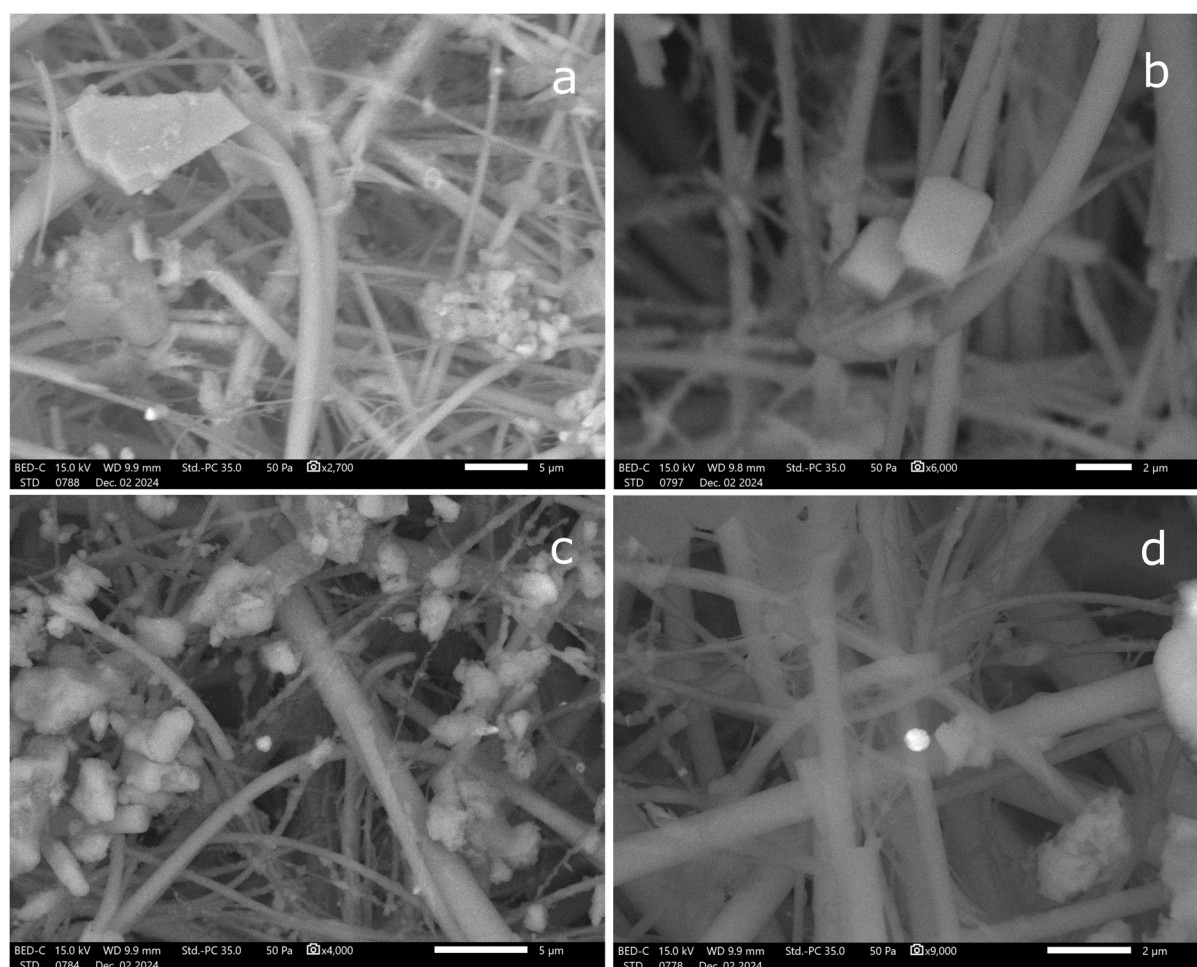


Figure 10. SEM–EDS characterization of selected particle types: (a) irregular S–K-rich and spherical Fe–O-rich particles; (b) cubic NaCl-rich particles; (c) irregular Ca-rich and spherical Fe–Cu–Co–Ni–Cr–Mn-rich particles; and (d) spherical Pb-rich particles.

4. Conclusions

This multi-site study provides a spatially resolved assessment of summertime PM₁₀ sources across traffic, harbor, industrial, school, and rural-background environments in Campania. PM₁₀ variability reflected the combined influence of local emissions, regional transport, natural contributions, and meteorological conditions. Element-based positive matrix factorization resolved six profiles interpreted as S-rich secondary aerosol, Cl-rich marine aerosol, Ca–Sr-rich road dust, Cu-rich traffic emissions, mixed combustion and industrial emissions, and Pb–Zn-rich waste-combustion emissions. SEM–EDS observations supported the presence of irregular mineral and road-dust particles, cubic NaCl-rich particles, and fine metal-rich spherical particles consistent with high-temperature processes. Elevated V and Ni concentrations at the harbor site were also consistent with a possible contribution from shipping activities.

The results have practical implications for regional air-quality management. Measures targeting non-exhaust traffic emissions, industrial and waste-combustion activities, and harbor-related emissions could reduce locally generated particulate pollution. Nevertheless, the substantial S-rich component and evidence of regional transport indicate that local measures alone may be insufficient. Effective mitigation will also require coordinated regional action addressing gaseous precursors involved in secondary aerosol formation. Future monitoring should combine urban, source-oriented, and regional-background stations with measurements of ionic, carbonaceous, and organic aerosol components.

Several limitations should be considered. The exclusive use of elemental concentrations in the PMF analysis restricted the separation of sources with overlapping chemical signatures; consequently, the assigned source types remain indicative rather than definitive. In particular, the attribution of the S-rich profile to secondary aerosol was inferred because particulate sulfate was not measured directly. CPF and trajectory analyses indicated contributions from both local-scale processes and regional transport, with short-range, low-altitude air masses predominating at the industrial and background sites. However, the identified directional patterns represent probable transport sectors rather than confirmed source locations because detailed georeferenced emission-source data were unavailable. The synchronized variation in elemental sulfur across the monitoring network supported a regional contribution to the S-rich profile and suggested a possible episodic influence from the central Mediterranean and the Etna region. This interpretation remains tentative because neither particulate sulfate nor SO_2 was measured directly.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos17080782/s1>, Figure S1: Temporal evolution of tropospheric SO_2 over the central Mediterranean observed by Sentinel-5P/TROPOMI (14–17 August 2024); Table S1: Summary of the PMF input, modelling parameters, output and diagnostic; Figure S2: SEM–EDS analysis of the investigated area and selected individual aerosol particle shown in Figure 10a, collected at the harbor site. The upper-left panel presents the SEM image, with the selected particle indicated by a red arrow. The S–K, Ca–K, K–K, and Fe–K maps show the spatial distributions of the corresponding characteristic X-ray signals; coloured pixels indicate the detected elemental signals, whereas black regions indicate no detectable or only weak signals. The upper-right spectrum and the table below it represent the EDS analysis of the entire mapped area. The lower-left spectrum and its corresponding table represent the selected Fe–Si-rich particle indicated by the arrow. Elemental abundances are reported as semi-quantitative mass and atomic percentages. Figure S3: SEM–EDS analysis of the investigated area and selected individual aerosol particle shown in Figure 10b, collected at the harbor site. The upper-left panel presents the SEM image, with the selected particle indicated by a red arrow. The Na–K, S–K, Cl–K, and Ca–K maps show the spatial distributions of the corresponding characteristic X-ray signals; coloured pixels indicate detected elemental signals, whereas black regions indicate no detectable or only weak signals. The upper-right spectrum and the table below it represent the EDS analysis of the entire mapped area. The lower-left spectrum and its corresponding table represent the selected Na–Cl-rich particle indicated by the arrow. Elemental abundances are reported as semi-quantitative mass and atomic percentages. Figure S4: SEM–EDS analysis of the investigated area and selected individual aerosol particle shown in Figure 10c, collected at the traffic site. The upper-left panel presents the SEM image, with the selected particle indicated by a red arrow. The Al–K, Ca–K, and K–K maps show the spatial distributions of the corresponding characteristic X-ray signals; coloured pixels indicate detected elemental signals, whereas black regions indicate no detectable or only weak signals. The upper-right spectrum and the table below it represent the EDS analysis of the entire mapped area. The lower-left spectrum and its corresponding table represent the selected Fe-rich, metal-containing particle indicated by the arrow. Elemental abundances are reported as semi-quantitative mass and atomic percentages. Figure S5: SEM–EDS analysis of the area and selected aerosol particle shown in Figure 10d, collected at the traffic site. The upper-left panel presents the SEM image, with the selected particle indicated by a red arrow. The Ca–K and Pb–M maps show the spatial distributions of the characteristic Ca K-line and Pb M-line X-ray signals, respectively; coloured pixels indicate the detected elemental signal, whereas black regions indicate no detectable or only weak signal. The upper-right spectrum and the table below it represent the EDS analysis of the entire mapped area. The lower-left spectrum and its corresponding table represent the selected Pb-rich particle indicated by the arrow. Elemental abundances are reported as semi-quantitative mass and atomic percentages.

Author Contributions: Conceptualization, A.A.; methodology, A.A.; validation, A.A. and F.B.; formal analysis, G.C., F.M., M.R., and A.A.; investigation, G.C., F.M., M.R., F.B., A.A., M.A.H.-C. and E.P.; data curation, G.C. and A.A.; writing—original draft preparation, G.C. and A.A.; writing—review and editing, F.M., M.R., M.A.H.-C., F.B., E.P. and Z.K.; visualization, A.A.; supervision, A.A.; project administration, A.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

Funding: The accelerator of HUN-REN ATOMKI is a Research Infrastructure of the Cluster of Low Energy Accelerators for Research (CLEAR) of the EURO-LABS project. Giuseppe Caso, Fabio Marzaioli, and Mauro Rubino were supported by the Transnational Access of the CLEAR EUROLABS project. The EURO-LABS project has received funding from the European Union’s Horizon Europe Research and Innovation Programme under Grant Agreement No. 101057511.

Data Availability Statement: The data supporting the results of this study are not publicly available because they have not been deposited in a public repository. They are available from the corresponding author upon reasonable request.

Acknowledgments: Anikó Angyal is supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences (BO/00499/24).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Pérez Velasco, R.; Jarosińska, D. Update of the WHO Global Air Quality Guidelines: Systematic Reviews—An Introduction. *Environ. Int.* **2022**, *170*, 107556. [[CrossRef](#)]
2. Manisalidis, I.; Stavropoulou, E.; Stavropoulos, A.; Bezirtzoglou, E. Environmental and Health Impacts of Air Pollution: A Review. *Front. Public Health* **2020**, *8*, 14. [[CrossRef](#)] [[PubMed](#)]
3. Rosales, C.M.F.; Weber, F.; Dombek, T.L.; Levine, K.; McWilliams, A.; Spada, N.J.; Hyslop, N.P. Evaluating PM_{2.5} Element Concentration Measurements for a Nationwide Monitoring Network. *J. Air Waste Manag. Assoc.* **2023**, *73*, 730–736. [[CrossRef](#)] [[PubMed](#)]
4. Tørseth, K.; Aas, W.; Breivik, K.; Fjæraa, A.M.; Fiebig, M.; Hjellbrekke, A.G.; Lund Myhre, C.; Solberg, S.; Yttri, K.E. Introduction to the European Monitoring and Evaluation Programme (EMEP) and Observed Atmospheric Composition Change during 1972–2009. *Atmos. Chem. Phys.* **2012**, *12*, 5447–5481. [[CrossRef](#)]
5. Yu, L.; Wang, G.; Zhang, R.; Zhang, L.; Song, Y.; Wu, B.; Li, X.; An, K.; Chu, J. Characterization and Source Apportionment of PM_{2.5} in an Urban Environment in Beijing. *Aerosol Air Qual. Res.* **2013**, *13*, 574–583. [[CrossRef](#)]
6. Johnson, K.S.; de Foy, B.; Zuberi, B.; Molina, L.T.; Molina, M.J.; Xie, Y.; Laskin, A.; Shutthanandan, V. Aerosol Composition and Source Apportionment in the Mexico City Metropolitan Area with PIXE/PESA/STIM and Multivariate Analysis. *Atmos. Chem. Phys.* **2006**, *6*, 4591–4600. [[CrossRef](#)]
7. Khodeir, M.; Shamy, M.; Alghamdi, M.; Zhong, M.; Sun, H.; Costa, M.; Chen, L.-C.; Maciejczyk, P. Source Apportionment and Elemental Composition of PM_{2.5} and PM₁₀ in Jeddah City, Saudi Arabia. *Atmos. Pollut. Res.* **2012**, *3*, 331–340. [[CrossRef](#)] [[PubMed](#)]
8. Doumbia, T.; Liousse, C.; Ouafou-Loumbe, M.-R.; Ndiaye, S.A.; Gardrat, E.; Galy-Lacaux, C.; Zouiten, C.; Yoboué, V.; Granier, C. Source Apportionment of Ambient Particulate Matter (PM) in Two Western African Urban Sites (Dakar in Senegal and Bamako in Mali). *Atmosphere* **2023**, *14*, 684. [[CrossRef](#)]
9. Krupnova, T.G.; Rakova, O.V.; Bondarenko, K.A.; Saifullin, A.F.; Popova, D.A.; Potgieter-Vermaak, S.; Godoi, R.H.M. Elemental Composition of PM_{2.5} and PM₁₀ and Health Risks Assessment in the Industrial Districts of Chelyabinsk, South Ural Region, Russia. *Int. J. Environ. Res. Public Health* **2021**, *18*, 12354. [[CrossRef](#)] [[PubMed](#)]
10. Cattani, G.; Vaccaro, L. I Dati Di Qualità Dell’aria in Italia. *Urban. Inf.* **2024**, *314*, 168–169. [[CrossRef](#)]
11. De Vivo, B.; Lima, A.; Cicchella, D.; Qu, C.; Hope, D.; Cerino, P.; Esposito, M.; Pizzolante, A.; Albanese, S. Potentially Toxic Metals and High Resolution Monitoring at Regional and Local Scale of Persistent Organic Pollutants in the Soil, Air, and Bulk Deposition of the Campania Region, Southern Italy: Sources and Environmental Processes. In *EGU General Assembly Conference Abstracts*; The European Geosciences Union (EGU): Munich, Germany, 2022.
12. Di Vaio, P.; Magli, E.; Barbato, F.; Caliendo, G.; Coccoziello, B.; Corvino, A.; De Marco, A.; Fiorino, F.; Frecentese, F.; Onorati, G.; et al. Chemical Composition of PM₁₀ at Urban Sites in Naples (Italy). *Atmosphere* **2016**, *7*, 163. [[CrossRef](#)]

13. Di Vaio, P.; Coccoziello, B.; Corvino, A.; Fiorino, F.; Frecentese, F.; Magli, E.; Onorati, G.; Saccone, I.; Santagada, V.; Settimo, G.; et al. Level, Potential Sources of Polycyclic Aromatic Hydrocarbons (PAHs) in Particulate Matter (PM₁₀) in Naples. *Atmos. Environ.* **2016**, *129*, 186–196. [\[CrossRef\]](#)
14. Chianese, E.; Tirimberio, G.; Riccio, A. PM_{2.5} and PM₁₀ in the Urban Area of Naples: Chemical Composition, Chemical Properties and Influence of Air Masses Origin. *J. Atmos. Chem.* **2019**, *76*, 151–169. [\[CrossRef\]](#)
15. Dinoi, A.; Cesari, D.; Marinoni, A.; Bonasoni, P.; Riccio, A.; Chianese, E.; Tirimberio, G.; Naccarato, A.; Sprovieri, F.; Andreoli, V.; et al. Inter-Comparison of Carbon Content in PM_{2.5} and PM₁₀ Collected at Five Measurement Sites in Southern Italy. *Atmosphere* **2017**, *8*, 243. [\[CrossRef\]](#)
16. Sirignano, C.; Riccio, A.; Chianese, E.; Ni, H.; Zenker, K.; D’Onofrio, A.; Meijer, H.A.J.; Dusek, U. High Contribution of Biomass Combustion to PM_{2.5} in the City Centre of Naples (Italy). *Atmosphere* **2019**, *10*, 451. [\[CrossRef\]](#)
17. Rubino, M.; Sirignano, C.; Chianese, E.; Hernández-Ceballos, M.-A.; Angyal, A.; Marzaioli, F.; Di Rosa, D.; Caso, G.; Riccio, A. A Case Study of the Usefulness of $\delta^{13}C$ and $\delta^{15}N$ for PM Source Apportionment under Different Meteorological Conditions. *Atmos. Environ.* **2026**, *376*, 122015. [\[CrossRef\]](#)
18. Riccio, A.; Chianese, E.; Monaco, D.; Costagliola, M.A.; Perretta, G.; Prati, M.V.; Agrillo, G.; Esposito, A.; Gasbarra, D.; Shindler, L.; et al. Real-World Automotive Particulate Matter and PAH Emission Factors and Profile Concentrations: Results from an Urban Tunnel Experiment in Naples, Italy. *Atmos. Environ.* **2016**, *141*, 379–387. [\[CrossRef\]](#)
19. Riccio, A.; Chianese, E.; Tirimberio, G.; Prati, M.V. Emission Factors of Inorganic Ions from Road Traffic: A Case Study from the City of Naples (Italy). *Transp. Res. D. Transp. Environ.* **2017**, *54*, 239–249. [\[CrossRef\]](#)
20. Murena, F.; Mocerino, L.; Quaranta, F.; Toscano, D. Impact on Air Quality of Cruise Ship Emissions in Naples, Italy. *Atmos. Environ.* **2018**, *187*, 70–83. [\[CrossRef\]](#)
21. Chianese, E.; Tirimberio, G.; Appolloni, L.; Dinoi, A.; Contini, D.; Di Gilio, A.; Palmisani, J.; Cotugno, P.; Miniero, D.V.; Dusek, U.; et al. Chemical Characterisation of PM₁₀ from Ship Emissions: A Study on Samples from Hydrofoil Exhaust Stacks. *Environ. Sci. Pollut. Res.* **2022**, *29*, 17723–17736. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Fortelli, A.; Scafetta, N.; Mazzarella, A. Influence of Synoptic and Local Atmospheric Patterns on PM₁₀ Air Pollution Levels: A Model Application to Naples (Italy). *Atmos. Environ.* **2016**, *143*, 218–228. [\[CrossRef\]](#)
23. Toscano, D.; Murena, F.; Quaranta, F.; Mocerino, L. Impact of Ship Emissions at a High Receptor Point in the Port of Naples. *Atmos. Environ.* **2022**, *286*, 119253. [\[CrossRef\]](#)
24. Triassi, M.; Alfano, R.; Illario, M.; Nardone, A.; Caporale, O.; Montuori, P. Environmental Pollution from Illegal Waste Disposal and Health Effects: A Review on the “Triangle of Death.”. *Int. J. Environ. Res. Public Health* **2015**, *12*, 1216–1236. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Mazza, A.; Piscitelli, P.; Neglia, C.; Rosa, G.; Iannuzzi, L. Illegal Dumping of Toxic Waste and Its Effect on Human Health in Campania, Italy. *Int. J. Environ. Res. Public Health* **2015**, *12*, 6818–6831. [\[CrossRef\]](#) [\[PubMed\]](#)
26. ARPAC Qualità Dell’aria in Campania Nel 2025. Focus Su PM₁₀, PM_{2.5}, Biossido Di Azoto, Ozono. Available online: <https://www.arpacampania.it/-/qualit%C3%A0-dell-aria-in-campania-nel-2025.-focus-su-pm10-pm2.5-biossido-di-azoto-ozono> (accessed on 2 July 2026).
27. UNI EN 12341:2023; Ambient Air—Standard Gravimetric Measurement Method for the Determination of the PM₁₀ or PM_{2.5} Mass Concentration of Suspended Particulate Matter. UNI—Ente Italiano di Normazione: Milan, Italy, 2023.
28. Bucur, E.; Motisan, R.; Vasile, A.; Tanase, G.; Florentina Pascu, L.; Blaziu Lehr, C.; Cuciureanu, A. Assessment of the Accuracy of Analyzers for Automatic Determination of PM₁₀ and PM_{2.5} Particulate Matter in Ambient Air. *Rev. Chim.* **2020**, *71*, 83–87. [\[CrossRef\]](#)
29. Maenhaut, W. Present Role of PIXE in Atmospheric Aerosol Research. *Nucl. Instrum. Methods Phys. Res. B* **2015**, *363*, 86–91. [\[CrossRef\]](#)
30. Rajta, I.; Vajda, I.; Gyürky, G.; Csedreki, L.; Kiss, Á.Z.; Biri, S.; van Oosterhout, H.A.P.; Podaru, N.C.; Mous, D.J.W. Accelerator Characterization of the New Ion Beam Facility at MTA Atomki in Debrecen, Hungary. *Nucl. Instrum. Methods Phys. Res. A* **2018**, *880*, 125–130. [\[CrossRef\]](#)
31. Aljboor, S.; Angyal, A.; Baranyai, D.; Papp, E.; Szarka, M.; Szikszai, Z.; Rajta, I.; Vajda, I.; Kertész, Z. Light-Element Sensitive in-Air Millibeam PIXE Setup for Fast Measurement of Atmospheric Aerosol Samples. *J. Anal. At. Spectrom.* **2023**, *38*, 57–65. [\[CrossRef\]](#)
32. Campbell, J.L.; Boyd, N.I.; Grassi, N.; Bonnicksen, P.; Maxwell, J.A. The Guelph PIXE Software Package IV. *Nucl. Instrum. Methods Phys. Res. B* **2010**, *268*, 3356–3363. [\[CrossRef\]](#)
33. Chiari, M.; Yubero, E.; Calzolari, G.; Lucarelli, F.; Crespo, J.; Galindo, N.; Nicolás, J.F.; Giannoni, M.; Nava, S. Comparison of PIXE and XRF Analysis of Airborne Particulate Matter Samples Collected on Teflon and Quartz Fibre Filters. *Nucl. Instrum. Methods Phys. Res. B* **2018**, *417*, 128–132. [\[CrossRef\]](#)
34. Paatero, P.; Tapper, U. Positive Matrix Factorization: A Non-negative Factor Model with Optimal Utilization of Error Estimates of Data Values. *Environmetrics* **1994**, *5*, 111–126. [\[CrossRef\]](#)

35. Brown, S.G.; Eberly, S.; Paatero, P.; Norris, G.A. Methods for Estimating Uncertainty in PMF Solutions: Examples with Ambient Air and Water Quality Data and Guidance on Reporting PMF Results. *Sci. Total Environ.* **2015**, *518*–519, 626–635. [[CrossRef](#)] [[PubMed](#)]
36. Kim, E.; Hopke, P.K. Improving Source Identification of Fine Particles in a Rural Northeastern U.S. Area Utilizing Temperature-resolved Carbon Fractions. *J. Geophys. Res. Atmos.* **2004**, *109*, D09204. [[CrossRef](#)]
37. Hersbach, H.; Bell, B.; Berrisford, P.; Hirahara, S.; Horányi, A.; Muñoz-Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Schepers, D.; et al. The ERA5 Global Reanalysis. *Q. J. R. Meteorol. Soc.* **2020**, *146*, 1999–2049. [[CrossRef](#)]
38. Carslaw, D.C.; Ropkins, K. Openair—An R Package for Air Quality Data Analysis. *Environ. Model. Softw.* **2012**, *27*–28, 52–61. [[CrossRef](#)]
39. Stein, A.F.; Draxler, R.R.; Rolph, G.D.; Stunder, B.J.B.; Cohen, M.D.; Ngan, F. NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System. *Bull. Am. Meteorol. Soc.* **2015**, *96*, 2059–2077. [[CrossRef](#)]
40. dos Santos, O.N.; Hoinaski, L. Incorporating Gridded Concentration Data in Air Pollution Back Trajectories Analysis for Source Identification. *Atmos. Res.* **2021**, *263*, 105820. [[CrossRef](#)]
41. Malm, W.C.; Trijonis, J.; Sisler, J.; Pitchford, M.; Dennis, R.L. Assessing the Effect of SO₂ Emission Changes on Visibility. *Atmos. Environ.* **1994**, *28*, 1023–1034. [[CrossRef](#)]
42. Viana, M.; Kuhlbusch, T.A.J.; Querol, X.; Alastuey, A.; Harrison, R.M.; Hopke, P.K.; Winiwarter, W.; Vallius, M.; Szidat, S.; Prévôt, A.S.H.; et al. Source Apportionment of Particulate Matter in Europe: A Review of Methods and Results. *J. Aerosol Sci.* **2008**, *39*, 827–849. [[CrossRef](#)]
43. Belis, C.A.; Karagulian, F.; Larsen, B.R.; Hopke, P.K. Critical Review and Meta-Analysis of Ambient Particulate Matter Source Apportionment Using Receptor Models in Europe. *Atmos. Environ.* **2013**, *69*, 94–108. [[CrossRef](#)]
44. Clemente, Á.; Galindo, N.; Nicolás, J.F.; Crespo, J.; Pastor, C.; Yubero, E. Local versus Regional Contributions to PM₁₀ Levels in the Western Mediterranean. *Aerosol Air Qual. Res.* **2023**, *23*, 230218. [[CrossRef](#)]
45. Liu, X.; Zhang, X.; Jin, B.; Wang, T.; Qian, S.; Zou, J.; Dinh, V.N.T.; Jaffrezo, J.-L.; Uzu, G.; Dominutti, P.; et al. Source Apportionment of PM₁₀ Based on Offline Chemical Speciation Data at 24 European Sites. *npj Clim. Atmos. Sci.* **2025**, *8*, 255. [[CrossRef](#)]
46. Corbin, J.C.; Mensah, A.A.; Pieber, S.M.; Orasche, J.; Michalke, B.; Zannata, M.; Czech, H.; Massabò, D.; Buatier de Mongeot, F.; Mennucci, C.; et al. Trace Metals in Soot and PM_{2.5} from Heavy-Fuel-Oil Combustion in a Marine Engine. *Environ. Sci. Technol.* **2018**, *52*, 6714–6722. [[CrossRef](#)] [[PubMed](#)]
47. Adachi, K.; Buseck, P.R. Changes in Shape and Composition of Sea-Salt Particles upon Aging in an Urban Atmosphere. *Atmos. Environ.* **2015**, *100*, 1–9. [[CrossRef](#)]
48. Stracquadanio, M.; Petralia, E.; Berico, M.; La Torretta, T.M.G.; Malaguti, A.; Mircea, M.; Gualtieri, M.; Ciancarella, L. Source Apportionment and Macro Tracer: Integration of Independent Methods for Quantification of Woody Biomass Burning Contribution to PM₁₀. *Aerosol Air Qual. Res.* **2019**, *19*, 711–723. [[CrossRef](#)]
49. Westberg, H.M.; Byström, M.; Leckner, B. Distribution of Potassium, Chlorine, and Sulfur between Solid and Vapor Phases during Combustion of Wood Chips and Coal. *Energy Fuels* **2003**, *17*, 18–28. [[CrossRef](#)]
50. Zhang, J.; Shen, H.; Chen, Y.; Meng, J.; Li, J.; He, J.; Guo, P.; Dai, R.; Zhang, Y.; Xu, R.; et al. Iron and Steel Industry Emissions: A Global Analysis of Trends and Drivers. *Environ. Sci. Technol.* **2023**, *57*, 16477–16488. [[CrossRef](#)] [[PubMed](#)]
51. Fussell, J.C.; Franklin, M.; Green, D.C.; Gustafsson, M.; Harrison, R.M.; Hicks, W.; Kelly, F.J.; Kishta, F.; Miller, M.R.; Mudway, I.S.; et al. A Review of Road Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures. *Environ. Sci. Technol.* **2022**, *56*, 6813–6835. [[CrossRef](#)] [[PubMed](#)]
52. Grigoratos, T.; Martini, G. Brake Wear Particle Emissions: A Review. *Environ. Sci. Pollut. Res.* **2015**, *22*, 2491–2504. [[CrossRef](#)] [[PubMed](#)]
53. Pant, P.; Harrison, R.M. Estimation of the Contribution of Road Traffic Emissions to Particulate Matter Concentrations from Field Measurements: A Review. *Atmos. Environ.* **2013**, *77*, 78–97. [[CrossRef](#)]
54. Liu, Y.; Zhang, W.; Yang, W.; Bai, Z.; Zhao, X. Chemical Compositions of PM_{2.5} Emitted from Diesel Trucks and Construction Equipment. *Aerosol Sci. Eng.* **2018**, *2*, 51–60. [[CrossRef](#)]
55. Wiedinmyer, C.; Yokelson, R.J.; Gullett, B.K. Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste. *Environ. Sci. Technol.* **2014**, *48*, 9523–9530. [[CrossRef](#)] [[PubMed](#)]
56. Ziegler, D.; Malandrino, M.; Barolo, C.; Adami, G.; Sacco, M.; Pitasi, F.; Abollino, O.; Giacomino, A. Influence of Start-up Phase of an Incinerator on Inorganic Composition and Lead Isotope Ratios of the Atmospheric PM₁₀. *Chemosphere* **2021**, *266*, 129091. [[CrossRef](#)] [[PubMed](#)]
57. Amato, F.; Lucarelli, F.; Nava, S.; Calzolari, G.; Karanasiou, A.; Colombi, C.; Gianelle, V.L.; Alves, C.; Custódio, D.; Eleftheriadis, K.; et al. Case Studies of Source Apportionment and Suggested Measures at Southern European Cities. In *Airborne Particulate Matter*; The Royal Society of Chemistry: London, UK, 2016; pp. 168–263.

58. Veefkind, J.P.; Aben, I.; McMullan, K.; Förster, H.; de Vries, J.; Otter, G.; Claas, J.; Eskes, H.J.; de Haan, J.F.; Kleipool, Q.; et al. TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of atmospheric composition for climate, air quality and ozone-layer applications. *Remote Sens. Environ.* **2012**, *120*, 70–83.
59. Theys, N.; Hedelt, P.; De Smedt, I.; Lerot, C.; Yu, H.; Vlietinck, J.; Pedernana, M.; Arellano, S.; Galle, B.; Fernandez, D.; et al. Global monitoring of volcanic SO₂ degassing with unprecedented resolution from TROPOMI onboard Sentinel-5 Precursor. *Sci. Rep.* **2019**, *9*, 2643.
60. National Aeronautics and Space Administration. Global Sulfur Dioxide Monitoring. Available online: <https://so2.gsfc.nasa.gov/> (accessed on 5 August 2026).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.