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Dominant sources of $PM_{2.5}$ in Kazakhstan's urban cities: A PMF and HYSPLIT-based study for air quality management in Central Asia

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ABSTRACT

Effective air quality management in Central Asian cities is hindered by limited knowledge of $PM_{2.5}$ sources. This study employed Positive Matrix Factorization (PMF) for source apportionment of $PM_{2.5}$ in two urban cities in Kazakhstan (Almaty and Astana), representing the first comprehensive analysis for Almaty. An extensive year-long sampling campaign (August 2022–July 2023) collected $PM_{2.5}$ samples for detailed chemical characterization, including organic/elemental carbon, elements, anions, and cations. PMF results revealed five distinct sources, contributing between 14 % and 32 % to ambient $PM_{2.5}$ in both cities. Although pollution sources showed a relatively uniform distribution, several factors strongly correlated with coal and biomass combustion, which emerged as the predominant contributors to $PM_{2.5}$, highlighting their key role in urban air quality in both cities. Regional and local source influences were identified using HYSPLIT backward trajectory and Conditional Probability Function (CPF) analysis. In Almaty, dominant trajectory clusters at different altitudes involved slow-moving air masses, indicating a significant impact from urban road dust resuspension. In Astana, backward trajectory analysis demonstrated that a substantial proportion of air masses traverse nearby industrial regions (Karagandy and Pavlodar), elevating $PM_{2.5}$ levels. The findings highlighted the considerable contribution of coal combustion to $PM_{2.5}$ pollution and emphasized the need for stringent emission controls and evidence-based strategies to improve air quality and safeguard public

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health in Central Asian cities. The study proposes achievable interim $PM_{2.5}$ reduction targets for Astana and Almaty, reflecting considerable reductions from current levels.

1. Introduction

Air pollution caused by fine inhalable atmospheric particles ($PM_{2.5}$) has been widely studied, with numerous findings confirming its adverse health effects, including an increased risk of cardiovascular and respiratory diseases (Landrigan et al., 2018). Beyond its health impacts, poor air quality imposes significant economic burdens on society, including reduced labor productivity, heightened medical costs, ecosystem degradation, and biodiversity loss (Landrigan et al., 2018). According to estimations from the Centre for Research on Energy and Clean Air (CREA), the global economic impact of air pollution reached $2.9 trillion in 2018, accounting for 3.3 % of that year's world gross domestic product (CREA, 2020). Alarmingly, 92–94 % of the global population is exposed to unhealthy air, with annual $PM_{2.5}$ levels in major cities consistently surpassing World Health Organization (WHO) limits (Rentschler and Leonova, 2023; Tursumbayeva et al., 2023). Regions, such as Central Asia (CA), the Middle East, and Europe, face severe challenges related to air pollution (Neira et al., 2023; Tursumbayeva et al., 2023). Addressing this critical issue requires comprehensive studies and multi-faceted solutions.

Kazakhstan, a critical case within CA, faces diverse potential air pollution sources, including coal combustion at combined heat and power plants (CHPs) and private households, biomass burning, heavy industry, transportation, urban road dust, and construction (Adotey et al., 2022; Baimatova et al., 2022; Ibragimova et al., 2021; Mukhtarov et al., 2023; Ormanova et al., 2024; Tursumbayeva et al., 2023). Limited air quality studies have revealed concerning levels of volatile organic compounds (VOCs) (Ibragimova et al., 2021), inorganic pollutants (NO_2, SO_2, Cr^{6+}) (Adotey et al., 2022; Baimatova et al., 2022), and $PM_{2.5}$ (Mukhtarov et al., 2023; Ormanova et al., 2024) in major cities in Kazakhstan.

Electricity and heat in both cities are provided by CHPs that utilize low-grade coal with a high ash content (approximately 42–44 %) sourced from the open pit mine "Bogatyr" in Ekibastuz (CINEST, 2017). "Bogatyr Komir" stands as the largest company in Kazakhstan, accounting for approximately 60 % of the coal extracted in the Ekibastuz basin and about 40 % of the total coal mined in the country. In Almaty, coal consumption totals 3.7 million tons (CHP-2 and CHP-3), while in Astana, CHP-2 reaches 2.2 million tons annually (ALES, 2023a, 2023b; Astana Energy, 2021). These findings underline the critical shortcomings of monitoring systems and legal pollutant thresholds (Mukhtarov et al., 2023; Tursumbayeva et al., 2023), which exceeded global air quality standards (EPA, 2023a). Furthermore, prior government-affiliated inventory studies have identified transportation emissions as the primary source of air pollution, relying on outdated methodologies that summarized all air pollutants without considering their toxic properties and exposure limits (Ecoservice, 2017). Moreover, meteorological conditions, such as low planetary boundary layer height (PBLH) and reduced wind speeds, along with emissions from coal combustion at CHPs and the private sector's burning of coal and biomass, contribute to seasonal and daily $PM_{2.5}$ fluctuations, often reaching extreme levels during the heating season (Mukhtarov et al., 2023; Tursumbayeva et al., 2022, 2023). Even with reduced traffic due to the COVID-19 lockdown restrictions in 2020, Kazakhstan's major urban (Kerimray et al., 2020) and industrial cities (Baimatova et al., 2022) experienced poor air quality due to the continued operation of industrial facilities and CHPs. Studies by Tursumbayeva et al. (2023) and Mukhtarov et al. (2023) have reported instances of transboundary air pollution between Almaty (Kazakhstan) and Bishkek (Kyrgyzstan) during episode days of significantly elevated $PM_{2.5}$ concentrations. Although previous studies have proposed potential pollution sources, a critical research gap remains. There is insufficient conclusive evidence to identify all sources and quantify their relative contributions to air pollution in Kazakhstan. Thus, acquiring this knowledge is essential for facilitating the design of effective mitigation strategies and improving air quality for the CA population.

Common methods for source apportionment include source-oriented approaches, emission inventories, and receptor-based pollution models (Mircea et al., 2020). Receptor modeling, which includes methods such as positive matrix factorization (PMF), principal component analysis (PCA), unmix, and chemical mass balance (CMB) (Hopke et al., 2020), offers distinct advantages over emission inventories and source-oriented models. Unlike these methods, receptor modeling does not require prior knowledge of emission sources and meteorological data inputs. Instead, it extracts information directly from pollutant measurements at receptor sites to quantify source contributions (Mircea et al., 2020). This flexibility has made PMF the most frequently used method in recent years. Between 2016 and 2020, PMF accounted for 539 out of 741 source apportionment studies, while the CMB method was employed in only 89 cases (Hopke et al., 2020). The PMF has been widely applied in various environments, including urban (Amato et al., 2016; Jain et al., 2020; Li et al., 2019), suburban (Karadeniz et al., 2023; Lioy and Georgopoulos, 2011), industrial (Kara et al., 2015), coastal (Pandolfi et al., 2011), forested (Vestenius et al., 2021), and road tunnel (Demir et al., 2019; Karakaş et al., 2023) sites.

Despite growing concerns over air quality in CA and $PM_{2.5}$ concentrations in major cities exceeding WHO limits by 4.3 to 12.6 times (Tursumbayeva et al., 2023), the application of PMF for source identification remains limited. Existing PMF studies in CA countries, such as Kurchatov (Almeida et al., 2020) and Astana (Ormanova et al., 2024) (Kazakhstan) and Dushanbe (Tajikistan) (Papagiannis et al., 2024), provide preliminary insights into $PM_{2.5}$ sources but hinder a comprehensive understanding of regional situation dynamics. These analyses exhibit methodological gaps, including the absence of major ion characterization (Papagiannis et al., 2024), separate analysis of organic (OC) and elemental carbon (EC) (Almeida et al., 2020; Ormanova et al., 2024; Papagiannis et al., 2024), and the lack of meteorological impact assessment using back-trajectory (HYSPLIT) or conditional probability function (CPF) models (Almeida et al., 2020). For instance, Kurchatov, a city with a population of less than 12,000, may not represent larger urban areas in the CA countries, which are characterized by diverse and complex pollution sources (Almeida et al., 2020). Additionally, the findings of

Ormanova et al. (2024), which attributed to traffic emissions, contradicted those of Baimatova et al. (2022), who reported poor air quality despite a decrease in traffic during the COVID-19 pandemic in 2020. Furthermore, $PM_{2.5}$ composition exhibits significant spatial and temporal variability across CA due to differences in geographical location, proximity to emissions sources, and fuel-specific chemical profiles (e.g., coal and fuel combustion).

The recent study by Fomba et al. (2024) on PMF analysis of PM_{10} particles in Dushanbe (Tajikistan) highlighted significant seasonal variation in source contribution. Residential heating and fossil fuel burning dominated during the cold season (62.7 %), while their contribution during summer was negligible. Expanding the application of PMF analysis to other major urban centers across CA would capture the regional diversity in source contributions. Incorporating comprehensive chemical profiles, including OC, EC, and primary ion data, would provide a holistic view of sources such as biomass burning and secondary aerosol formation. Such advancements would lead to a deeper understanding of the driving factors of air pollution in the CA countries. This knowledge is vital for developing effective air quality management strategies to protect public health and the environment.

Therefore, this study presents the first application of PMF source apportionment for ambient $PM_{2.5}$ in Almaty and Astana, two major cities in Kazakhstan. As the first such approach implemented in Almaty, this research provides valuable insights into the sources of urban air pollution. The study encompasses an extensive year-long $PM_{2.5}$ sampling campaign and analysis, and correlations between $PM_{2.5}$-bound OC, EC, trace elements, and ions, ensuring a comprehensive representation of seasonal variations. The study incorporates the HYSPLIT model and CPF analyses to enhance source characterization of PMF results, further validating the effectiveness of the source identification process and strengthening the research findings.

2. Materials and methods

2.1. Description of sampling locations

$PM_{2.5}$ sampling was conducted at two urban locations: the campus of Al-Farabi Kazakh National University (43.24°N, 76.93°E) in Almaty (Fig. S1 in Supplementary material (SM)) and the Republican School of Physics and Mathematics (51.12°N, 71.43°E) in Astana (Fig. S2 in SM). Almaty and Astana are the largest cities in Kazakhstan, with populations of 2.2 and 1.4 million people, respectively (StatGov, 2024a). Although based on a single sampling site in each city and specific to their locations, the observations can be considered reflective of prevailing trends within Almaty and Astana. For simplicity, the results are presented as city averages, with the understanding that they represent trends at the monitoring locations.

Both cities experience a continental climate characterized by hot summers and cold winters; however, geographical differences lead to variations in meteorological conditions. Almaty exhibits higher summer (24.4 °C in July) and winter (-−4.6 °C in January) temperatures than Astana (20.6 °C in July and − 14.5 °C in January) (Weather and Climate, 2023).

During the colder months (October–March), both cities heavily rely on CHPs for heating, resulting in increased coal combustion. Moreover, the heating season is associated with higher relative humidity, lower wind speeds, and reduced precipitation, contributing to elevated $PM_{2.5}$ concentrations and accumulation (Mukhtarov et al., 2023). Additionally, Almaty's location in a mountainous region in the southeastern part of Kazakhstan makes it prone to frequent temperature inversions and lower PBLH, restricting the vertical dispersion of pollutants near the surface (Tursumbayeva et al., 2022, 2023).

2.2. $PM_{2.5}$ sampling

$PM_{2.5}$ sampling on filters was carried out using a 5-channel MetOne SASS $PM_{2.5}$ Ambient Chemical Speciation Sampler (MetOne Instruments Inc., USA), equipped with cyclones to separate $PM_{2.5}$ from other particulate fractions. According to the guidelines (Chow and Watson, 1998), samples were collected simultaneously on four filters (two Teflon (PTFE) filters, a quartz fiber filter (QFF), and a nylon filter) every third day over 24 h at a sampling rate of 6.7 L min^{-1}. Field blanks were collected monthly during one-minute sampling to estimate the potential cross-contamination during storage and transportation. The sampling campaign spanned August 2022 to July 2023, resulting in 113 and 109 sampling days in Almaty and Astana, respectively.

The 47 mm PTFE filters (SKC Ltd., United Kingdom) were designated for elemental and ions, the 47 mm QFF (Cytiva Whatman QMA, China) for OC/EC, and the 47 mm nylon filter (Tish Scientific, US) for nitrate analysis, as a specified in the field operation manual (Met One Instruments Inc, 2001). To prevent interferences in nitrate measurements, a denuder filled with magnesium oxide (MgO) was used to trap nitric and nitrous acids during sampling (Fitz, 2002). Filter preparation and storage were conducted according to their specific types and the intended analysis (Chow and Watson, 1998). Prior to sampling, the QFF were pretreated at 550 °C in a muffle furnace (SNOL 8/21000, Lithuania) for 4 h, followed by pre-conditioning in a SICCO desiccator cabinet (Bohlender, Germany) for 24–48 h. After pre-treatment, QFF filters were stored at −10 °C in sealed Petri dishes. PTFE and nylon filters were stored in a SICCO Star desiccator (series 467–0114, Bohlender, Germany) at 20–30 °C and 30–40 % relative humidity.

2.3. Sample preparation, analysis, and data processing

2.3.1. Organic and elemental carbon analysis

The analysis of OC and EC in $PM_{2.5}$ samples was conducted using a Thermal-Optical M5L Lab OC/EC Analyzer (Sunset Laboratory Inc., US) following the National Institute for Occupational Safety and Health (NIOSH) protocol 870 (NIOSH, 1999). During thermal analysis, organic carbon undergoes pyrolysis, forming pyrolytic carbon that exhibits optical properties similar to EC under an inert helium atmosphere. This effect is corrected by monitoring filter transmittance or reflectance using a laser. The transmittance initially decreases due to pyrolyzed OC formation and increases as it combusts. The separation of OC and EC is defined by the point at which transmittance returns to its pre-heating value. Calibration involved injecting 10 μL of a sucrose standard solution (C = 3.516 μg C μL^{-1}, Sunset Laboratory Inc., US) into a 1.5 cm^2 filter punch, which was then analyzed using the same protocol applied to the samples to ensure accurate OC and EC quantification.

The Astana dataset's processing identified one OC and five EC outliers, which were excluded to ensure data reliability (Table S1 in SM). In contrast, no outliers were detected in the Almaty dataset shown.

2.3.2. Cations and anions determination

Water-soluble cations (NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, and Li^+) and anions (NO_3^-, SO_4^{2-}, Cl^-, F^-, Br^-, and PO_4^{3-}) were extracted from $PM_{2.5}$ samples collected on PTFE filters using an ultrasonic bath (Stegler, Russia) for one hour in 15 mL of deionized water. The extracts were filtered through 0.22 μm pore size PTFE syringe filters (Sigma Aldrich, US) and stored at 4 °C to minimize analyte degradation.

The eluents were analyzed by a Metrohm 930 Compact Ion Chromatography Flex instrument (Herisau, Switzerland) to determine ion concentrations. Anions were separated using A Metrosep A Supp 7–150/4.0 column and an MSM-A Rotor suppressor, with an eluent solution of 3.6 mmol L^{-1} sodium carbonate. A Metrosep C 4–150/4.0 column was used for cation determination with a mixture of 1.7 mmol L^{-1} nitric acid and 0.7 mmol L^{-1} dipicolinic acid as an eluent solution.

The PMF modeling included six ions (Na^+, NH_4^+, K^+, Cl^-, SO_4^{2-}, NO_3^-) that were consistently quantified on at least 50 % of the samples. Ions with lower quantification frequencies were excluded to ensure a robust PMF analysis (Tables S1 and S2 in SM).

2.3.3. Major and trace elements analysis

The elemental composition of $PM_{2.5}$ samples collected on PTFE filters was determined using microwave-assisted acid digestion followed by inductively coupled plasma-mass spectrometry (ICP-MS, Agilent 7500a, US). The filters were digested with a mixture of 4.5 mL nitric acid (HNO_3, 65 %, ROTIPURAN, Germany), 1.5 mL hydrochloric acid (HCl, 34–37 %, Trace-SELECT, US), and 0.3 mL hydrofluoric acid (HF, 48 %, Sigma-Aldrich, US) in a microwave digestion oven (Berghof Products®, Germany) using temperature-controlled program (130–220 °C) for 75 min. The digested solutions were subsequently diluted to 50 mL with deionized water.

Elemental analysis was conducted using high-purity argon gas (99.999 %, LLP Ihsan Technogaz, Almaty, Kazakhstan) to generate the plasma in the ICP-MS. Calibration was performed using multi-element calibration standards prepared from certified standard solutions (multi-element calibration standard solutions 1, 3, and 4, Agilent Technologies; and periodic table mix 1 for ICP (Inorganic Ventures, VA, US).

Of the 50 quantified elements, 22 were consistently detected above the limit of detection (LOD) in both cities (Tables S1 and S2 in SM). Before PMF modeling, the datasets underwent outlier identification and removal. Only elements with at least 50 % data completeness and a signal-to-noise ratio (S/N) > 0.5 (see section 2.4) were applied in the PMF analysis. These included Mg, Ca, Sc, Ti, V, Fe, Cu, As, Se, Sr, Mo, Cd, Sb, and Ba, with Zn and Pb specifically applied for Almaty, and K, Cr, Mn, and Ni for Astana.

2.4. Error estimation of the PMF model

The EPA PMF 5.0 software was applied for PMF analysis using the minimized objective function Q in PMF (Eq.1):

$$Q = \sum_{i=1}^{n}\sum_{j=1}^{m}\left[\frac{x_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj}}{u_{ij}}\right]^2 \quad (1)$$

where x_{ij} is the concentration matrix (j species of i samples), u is the uncertainties, g is the source contribution matrix (i samples and k sources), and f is the profile matrix (k sources and j chemical species).

The input data was prepared according to the EPA PMF guide (EPA, 2014). After testing four to seven factors and conducting many trials, five factors were selected as the optimal solution for both cities. Increasing the number of factors beyond five reduced the mapping rate to below 80 % for at least one factor, which is not reccomended according to the EPA guidelines (EPA, 2014), and yielded non-interpretable results: in Astana, Sb appeared as a single source, while in Almaty, chloride and ammonium were merged into a one factor, complicating interpretation. Conversely, a four-factor solution resulted in mixed sources, obscuring distinctions among major pollution sources and decreasing the robustness of the source apportionment. Expanding the dataset to incorporate additional tracers,

Table 1
Summary of error estimation diagnostics for PMF runs conducted in Almaty and Astana.

Parameters	City	
	Almaty	Astana
Q_{true}	12,031	3962
Q_{robust}	9468	3493
Q_{robust}/Q_{true}	1.02	0.88
DISP %dQ	<0.1 %	<0.1 %
DISP swaps	0	0
BS mapping	88–100 %	96–100 % (Factor 1–4) 66 % (Factor 5)

such as sulfur, silicon, other non-metals, and VOCs, would be essential for more detailed sources differentiation and identifying eight or more contributing factors.

A signal-to-noise ratio was applied for separation between strong (implemented as they are, $1 < S/N$), weak (downweighed by a factor of 3, $0.5 < S/N < 1$), and bad (removed from the modeling, $S/N < 0.5$) variables. Analytes with $S/N < 0.5$ were omitted from the original dataset. Uncertainty of the solution was assessed by implementing the Displacement (DISP) and Bootstrapping (BS) error estimation tools provided by EPA PMF 5.0 (Brown et al., 2015) (Table S3 in SM). The BS results indicated a minimum of 88 % factor mapping for both cities, except for Factor 5 in Astana, which exhibited a lower mapping rate of 66 % due to a 21 % overlap with Factor 2, potentially reflecting the interdependence of these factors. Employment of DISP analysis did not lead to any factor swaps, and the change in the Q value remained minimal (less than 0.1 %) for both cities. These findings resulted in the robustness and reliability of the obtained results. An assessment of the goodness of fit was conducted by calculating the ratio of Q_{robust} to Q_{true}, resulting in a value of 0.79 and 0.88, which falls within the acceptable range (<1.5) for Almaty and Astana (Table 1).

2.5. Analysis of air mass backward trajectories using HYSPLIT

Air mass backward trajectories for Almaty and Astana were simulated using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by the National Oceanic and Atmospheric Administration (NOAA) (Draxler, 1999; Draxler and Hess, 1998; Jeklin, 2016; Stein et al., 2015). The simulations utilized archived meteorological data from NOAA's Global Data Assimilation System (GDAS) with a spatial resolution of $1.0^{\circ} \times 1.0^{\circ}$. The coordinates of sampling sites in both cities were chosen as endpoints for the trajectory calculations.

The trajectories were simulated over a 72-h period with hourly intervals at three altitudes: 500, 1000, and 3000 m above ground level (AGL). Backward trajectories were calculated for each sampling day in both studied cities. Additionally, to identify common patterns, cluster analysis was conducted to group all backward trajectories with similar pathways. Based on the changes in total spatial variance, trajectories were divided into six groups for Almaty and seven for Astana.

2.6. Conditional probability function analysis

The CPF model was employed to assess the impact of wind on pollutant transport and identify potential source regions contributing to elevated air pollution levels at sampling sites. This approach combines source contributions estimated through PMF analysis with meteorological data, including wind speed and direction (Kim et al., 2003; Uria-Tellaetxe and Carslaw, 2014). In this analysis, a bivariate CPF was applied to consider both wind direction and speed simultaneously. The CPF for a specific wind sector *(θ)* and wind speed interval *(j)* was calculated using Eq. 2 (Carslaw, 2019):

$$CPF_{\theta,j} = \frac{m_{\theta,j}}{n_{\theta,j}} \tag{2}$$

where $m_{\theta,j}$ represents the number of episodes within the wind sector θ with wind speed interval j that exceed a pre-defined threshold value, and $n_{\theta,j}$ is the total number of episodes observed for the same wind direction and speed combination.

The threshold was selected using the 75^{th} percentile of source contributions derived from the PMF analysis. Episodes with wind speeds below 1 m s^{-1} were excluded from the dataset to avoid potential inaccuracies in wind direction at low speeds. The CPF modeling was performed using the Openair package (version 2.18–0) in R. However, the CPF analysis in both studied cities may be subject to uncertainties due to spatial discrepancies between sampling sites and meteorological stations. The lack of data from meteorological stations near the sampling locations may introduce spatial bias into the results.

3. Results and discussion

3.1. Chemical composition variations of $PM_{2.5}$

The concentrations of $PM_{2.5}$ in Almaty and Astana exhibited distinct seasonal patterns, with consistently higher annual averages in Almaty (35.6 μg m^{-3}) compared to Astana (19.4 μg m^{-3}) (AirNow, 2023). These levels exceeded the WHO guideline (5 μg m^{-3}) by 7.1 and 3.9 times, respectively, reflecting more severe pollution in Almaty (WHO, 2021).

Across both cities, OC concentrations were substantially higher than EC, indicating dominant contributions from organic sources such as biomass burning or secondary organic aerosol (SOA) formation (Sirignano et al., 2019). Almaty exhibited higher OC (11.2 μg m^{-3}) and EC (1.81 μg m^{-3}) levels than Astana (7.89 and 0.64 μg m^{-3}, respectively), consistent with its elevated $PM_{2.5}$ burden (Tables S1 and S2).

The total ionic content in $PM_{2.5}$ was also greater in Almaty (11.2 μg m^{-3}) than in Astana (4.08 μg m^{-3}). Nitrate (NO_3^-) was the dominant ion in Almaty, potentially associated with secondary nitrate formation from vehicle emissions or agricultural activities (Fan et al., 2023). In contrast, sulfate (SO_4^{2-}) predominated in Astana, reflecting secondary sulfate formation and the combustion of coal and biomass (Saraga et al., 2021). In both cities, ammonium (NH_4^+) was the most abundant cation, with higher levels in Almaty (2.04 μg m^{-3}) than in Astana (0.78 μg m^{-3}), potentially linked to combustion-related sources (Chen et al., 2022; Fomba et al., 2024).

Crustal elements such as Al, Fe, Ca, and K constituted the majority of the elemental mass in both cities (80 % in Almaty and 76 % in Astana), indicating contributions from mineral dust and natural crustal material weathering during non-heating periods, which releases these elements as oxides in coal ash, and occurs throughout all seasons (Arynov, 2007; Begum and Hopke, 2019; LLP "Bogatyr Komir", 2010) (Fig. 1). Additionally, the elevated levels of Fe and Al may be attributed to industrial activities, particularly emissions from CHPs (Cusworth et al., 2021). Calcium may originate from road dust, construction-related pollution, and crustal erosion (Siciliano et al., 2024). Conversely, lead (Pb) contributions were relatively low in both cities (0.12 % in Almaty and 0.24 % in Astana), which may be associated with the phase-out of lead gasoline (Police et al., 2018).

Both cities demonstrated significant wintertime peaks in NH_4^+, NO_3^-, SO_4^{2-} (Fig. 2), and carbonaceous species (OC, EC), indicating increased combustion emissions and limited dispersion during cold months (Fomba et al., 2024; Omarova et al., 2025). However, Almaty exhibited pronounced seasonal variation with elevated winter concentrations of NO_3^- (15.22 μg m^{-3}), NH_4^+ (6.07 μg m^{-3}), and OC (25.15 μg m^{-3}), followed by significant declines in summer (NO_3^-: 0.57 μg m^{-3}; NH_4^+: 0.62 μg m^{-3}; OC: 7.89 μg m^{-3}) (Table S4). Conversely, Astana displayed more moderate winter maxima (NO_3^-: 2.59 μg m^{-3}; NH_4^+: 1.39 μg m^{-3}; OC: 12.08 μg m^{-3}) and flatter seasonal gradients, indicating lower emission intensities coupled with more favorable meteorological dispersion conditions (Table S4 in SM).

Element's level in Almaty displayed distinct seasonal trends (Fig. 2a). Autumn was characterized by maximum concentrations of Fe (1.14 μg m^{-3}) and Cr (0.32 μg m^{-3}) (Table S4 in SM), indicating significant contributions from resuspended dust and combustion-related emissions (Begum and Hopke, 2019). Winter periods showed elevated levels of Mg (0.12 μg m^{-3}), Al (0.45 μg m^{-3}), and Ca (0.47 μg m^{-3}), suggesting substantial inputs from coal combustion in CHPs and residential heating (Shukla et al., 2023). During summer, notable concentrations were recorded for Fe (0.64 μg m^{-3}), Al (0.31 μg m^{-3}), and Ca (0.36 μg m^{-3}), attributable to enhanced road dust resuspension, soil dust, and construction activities (Siciliano et al., 2024). Spring exhibited comparatively lower overall levels but maintained detectable concentrations of Al (0.20 μg m^{-3}) and Ca (0.18 μg m^{-3}). Additional elements, including Zn, As, and Pb, displayed moderate seasonal variations, indicating mixed-sourced contribution from traffic-related non-exhaust emissions and industrial processes (Amato et al., 2011; Liu et al., 2017; Yu et al., 2019).

In Astana, peak concentrations of Al (0.59 μg m^{-3}), Ca (0.50 μg m^{-3}), and Fe (0.53 μg m^{-3}) were observed during summer months (Fig. 2b), suggesting contributions predominantly from soil dust resuspension and non-exhaust traffic emissions (Adamiec et al., 2016). Highest levels of elements during autumn were observed for Al (0.36 μg m^{-3}) and Ca (0.42 μg m^{-3}). Spring also presented considerable levels of Fe (0.26 μg m^{-3}) and Al (0.30 μg m^{-3}). Winter periods were characterized by minimum elemental concentrations, with 0.14 μg m^{-3} Al and Ca, which were significantly reduced compared to warmer seasons (Table S4 in SM), indicating reduced local dust emissions and increased influence from combustion-related regional transport (Ormanova et al., 2024). Elements, such as As (up to 0.07 μg m^{-3}) and Pb (up to 0.03 μg m^{-3}) displayed relatively higher values in summer, further supporting the role of regional and long-range transport mechanisms (Fang et al., 2021).

Overall, the pronounced seasonality and higher concentrations of $PM_{2.5}$ constituents and trace metals in Almaty highlight the dominant roles of local combustion sources (Kawashima et al., 2022; Li et al., 2022; Squizzato et al., 2018), industrial emissions, and resuspension processes, exacerbated by topographic confinement and meteorology conditions. The Almaty region experiences seasonal stagnant synoptic conditions during winter, resulting in lower PBLH and reduced wind speeds (Tursumbayeva et al., 2022). Under these conditions, both vertical and horizontal dispersion of air pollutants are restricted, thereby facilitating the accumulation of pollutants near the surface. In contrast, Astana's comparatively lower levels and smoother seasonal transitions suggest a relatively dispersed urban layout and meteorology more conducive to pollutant dilution.

3.2. Source apportionment of $PM_{2.5}$

3.2.1. Almaty

3.2.1.1. Exhaust emissions and road salt. Factor 1 (Fig. 3) was predominantly associated with vehicular exhaust emissions, as evidenced by high contributions of OC-EC (80 %), nitrate ions (94 %), and trace metals such as Zn, Ba, and Pb. Lead (Pb) exhibited a statistically significant correlation ($r = 0.537$, Fig. S3 in SM), serving as a widely recognized key marker of vehicular emissions (Zhang et al., 2022). Motor vehicle exhaust is characteristically enriched in Pb, Zn, and EC (Song et al., 2006). Additionally, the substantial nitrate ion loading in this factor reflects the contribution of traffic-related emissions to the formation of secondary nitrate aerosols (Fan et al., 2023).

This factor also included elevated concentrations of sodium and chloride ions, indicative of road salt usage during winter months

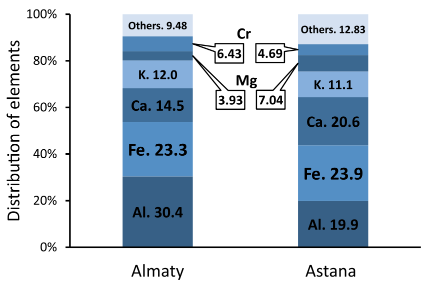

Fig. 1. Distribution of the element's composition in $PM_{2.5}$ in Almaty and Astana, Kazakhstan (August 2022 – July 2023).

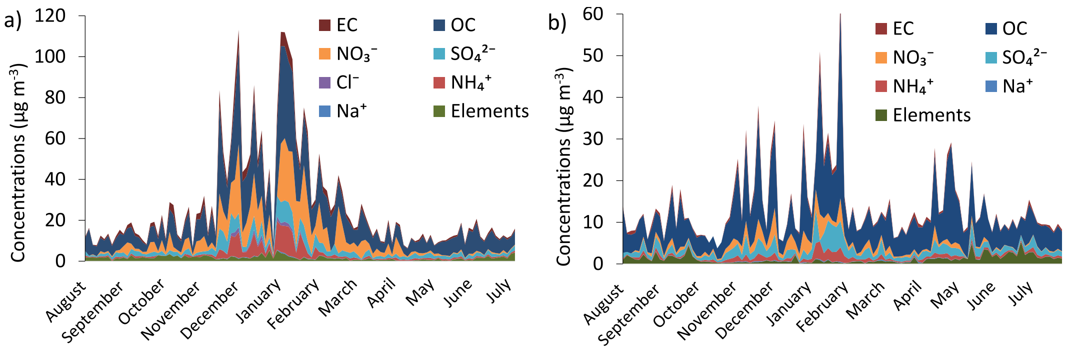

Fig. 2. Seasonal variations in $PM_{2.5}$ chemical composition in a) Almaty and b) Astana, Kazakhstan (August 2022 – July 2023).

for de-icing and preventing road slipperiness. The dominance of high G-score days in winter further corroborates the seasonal and source-specific characteristics of this factor (Fig. S4a in SM). Furthermore, the seasonal influence was further confirmed by the concentrations of sodium and chloride ions, which were observed to be approximately tenfold higher during winter compared to summer, as reflected by a correlation coefficient of 0.669 (Fig. S3 in SM).

In addition, CPF analysis identified potential source regions for various $PM_{2.5}$ contributors in Almaty (Fig. 4). The results indicate that exhaust emissions and road salt-related pollution predominantly originate from the northern and northwestern parts of the city, particularly near the sampling site.

This pattern aligns with the location of Al-Farabi Avenue, a major highway located approximately 1–3 km from the sampling site. The high traffic density in the city center to the north, along with concentrated vehicular activity from the northwestern direction, further supports the association of this factor with exhaust-related emissions. The major traffic activity in the northwestern direction shows a possible relation to the daily influx of vehicles commuting from the Almaty region into the urban center.

3.2.1.2. Urban road dust resuspension. Factor 2 in Almaty was dedicated to resuspended urban road dust emissions. This source composition was characterized by significant contributions from Ti (81 %), V (70 %), Cu (67 %), Sr (62 %), Cd (77 %), Pb (81 %), and Ba (93 %), alongside moderate contributions from Fe (34 %), Zn (24 %), As (30 %), and Mo (35 %). Moderately strong intercorrelations were observed among Sc, V, Ti, and Cu ($r = 0.523$–0.774, Fig. S3 in SM). Elements, including Ba, Fe, Cu, Zn, and Ti are primary components of PM generated from brake wear and road dust resuspension (Huang et al., 2023; OECD, 2020). V is also associated with a mix of non-exhaust traffic emissions with road dust (Silva et al., 2021; Fiala and Hwang, 2021), while Pb, Zn, Fe, and Cd are linked to resuspended road dust and tire wear (Jeong et al., 2016; Tasic et al., 2010). Additionally, Zn and Fe act as tracers of tire and road surface wear (OECD, 2020). Moreover, Pb, Zn, Ba, Cu, and Mo may indicate contributions from brake and tire wear, as well as emissions from the asphalt pavement (Srivastava et al., 2021). Analysis of brake linings and associated dust has shown the presence of multiple metals, including As, Ba, Cd, Cu, Fe, Mo, Pb, Sr, and Zn (Thorpe and Harrison, 2008). Furthermore, Thorpe and Harrison (2008) reported the possibility of using trace elements (Cd, Cu, Pb, and Zn) in the manufacturing of tires. The attribution to this source contribution is further confirmed by significant intercorrelations between Cu, Cd, Pb, Sr, and Ba ($r = 0.512$–0.674, Fig. S3 in SM).

CPF analysis indicated that the emissions from resuspension of urban road dust mainly originated from the south, southwest, and southeast, corresponding with the locations of two main highways surrounding the city, such as Al-Farabi Avenue and the Eastern Bypass Road (Fig. 4).

3.2.1.3. Urban atmosphere. Factor 3 was identified as having a mixed background, primarily consisting of emissions from industrial activity (Fe, Mo, Zn) and accumulated stagnant local pollutants from coal combustion (As, Mg, Ca, Fe) and biomass burning (K). Due to topographical conditions, emissions from various sources could accumulate in the city's atmosphere, restricting both horizontal and vertical dispersion of pollutants (Mukhtarov et al., 2023). The broader spatial distribution of urban atmospheric emissions, as observed in the CPF analysis (Fig. 4), confirms the widespread dispersion of pollutants, which contributes to the sampling sites from nearly all directions, particularly from the north and northeast, where the city center is located. Additionally, small industrial activities such as a paper recycling plant, cement and concrete facilities, small-scale pharmacies, and alcohol production facilities are located in the northwest and north of the sampling site.

Contributions from Fe (58 %), Zn (60 %), As (19 %), and Mo (20 %) may stem from local industrial activities (Altıkulaç and Turhan, 2024). At the same time, significant concentrations of various ions, including sulfates, potassium, and OC-EC, in this factor can be attributed to emissions from coal and biomass burning. Furthermore, the high contributions of Mg (59 %), Ca (74 %), and Fe (58 %) can be explained by their considerable presence in coal ash from local coal-fired CHPs and households (Fig. S5, Table S5 in SM). This factor likely reflects the accumulation of stagnant local emissions from predominant urban pollution sources.

3.2.1.4. Power plants. Factor 4 accounts for emissions from local coal-fired CHPs, as indicated by significant contributions of Sc (30 %), V (30 %), Se (73 %), Sr (37 %), and elevated concentrations of Cu, As, Ti, Cl^-, Mg, Ca, Fe, and Na^+ (Liu et al., 2017). In Almaty, electricity and heat are primarily generated by CHP-2 and CHP-3, which, as of 2021, consume approximately 3.2 million tons of coal

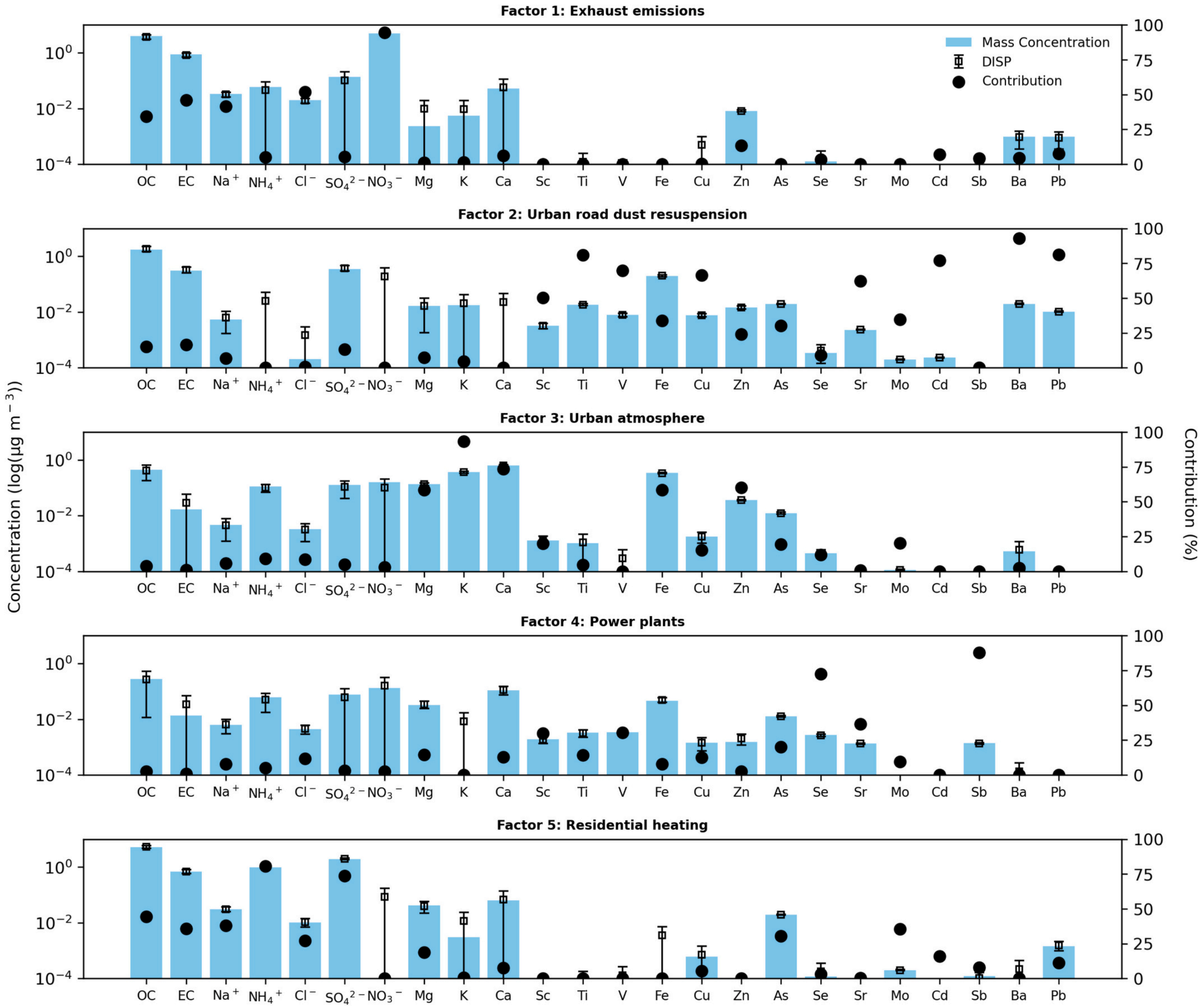

Fig. 3. Source profiles of ambient $PM_{2.5}$ in Almaty city identified by the PMF analysis.

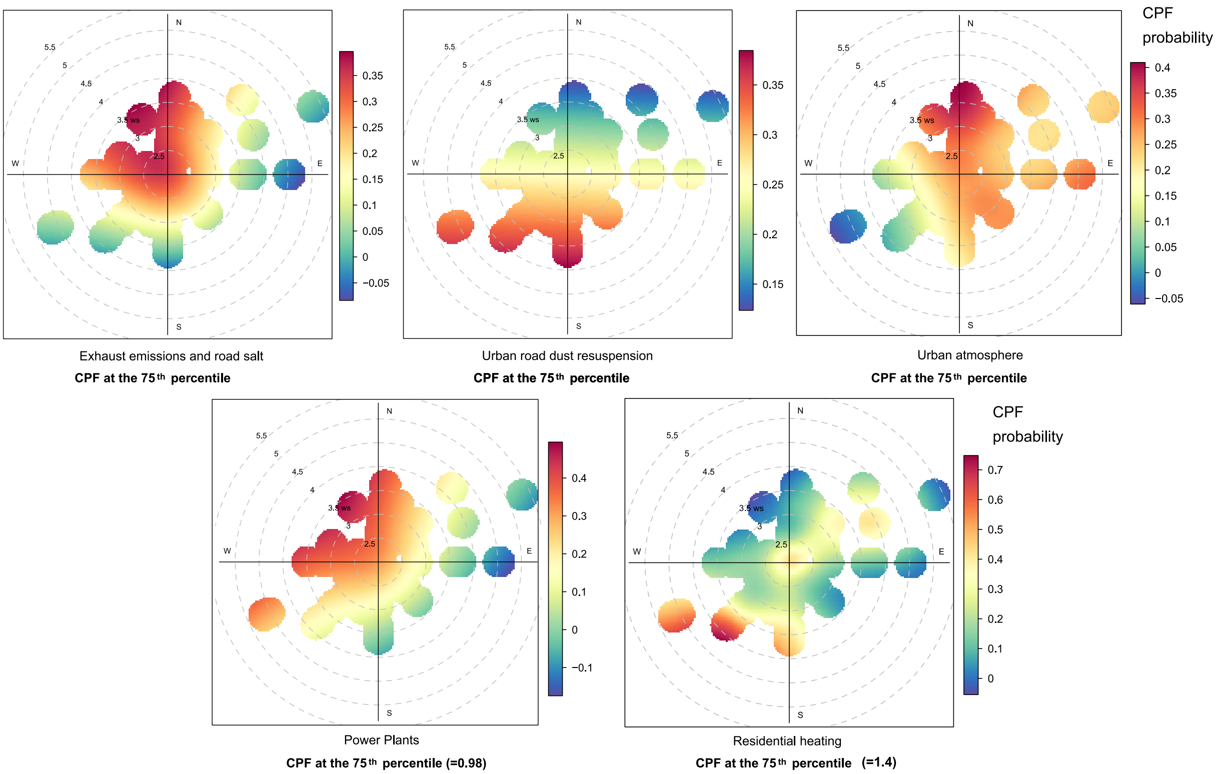

Fig. 4. CPF plots identifying directional source contributors to $PM_{2.5}$ in Almaty.

(Mukhtarov et al., 2023). Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS) analysis of local coal fly ash revealed substantial levels of Fe (89.5 %), Mg (2.8 %), Ca (4.7 %), and Ti (1.48 %), highlighting coal's impact on this factor (Fig. S5, Table S5 in SM). These elements are recognized markers of coal combustion (Shukla et al., 2023), while V is linked to oil combustion in industrial applications (Srivastava et al., 2021).

The results of the CPF analysis demonstrates that power plants emissions in Almaty originate predominantly from the northern, northwestern, and western areas of the city (Fig. 4). This overlap of these source regions indicates the potential co-location of emission sources with CHP-2 and CHP-3, which suggests a significant impact on local air quality.

3.2.1.5. Residential heating. The significant contributions of OC (45 %), EC (36 %), Na^+ (38 %), NH_4^+ (81 %), Cl^- (27 %), SO_4^{2-} (74 %), As (30 %), and Mo (36 %) in Factor 5 indicate that residential coal and biomass combustion as major sources of $PM_{2.5}$ pollution in Almaty. Specifically, OC, EC, SO_4^{2-}, Cl^-, and As are well-established tracers of coal combustion emissions (Feng et al., 2022; Liu et al., 2017; Zong et al., 2018). This interpretation aligns with findings from Beijing, where NH_4^+ and SO_4^{2-} were found to be associated with coal-derived emissions. Sulfate ions form primarily through the atmospheric oxidation of sulfur dioxide released during coal combustion (Zhang et al., 2022). These ion species exhibit strong intercorrelation coefficients ranging from 0.572 to 0.945 (Fig. S3 in SM).

In addition to coal, private households, particularly in low-income or peripheral areas, often rely on biomass and household waste for heating. This reliance is reflected in the elevated levels of Na^+, NH_4^+, and Cl^- (markers of biomass combustion), as well as Pb, As, and Cu (indicative of waste incineration) (Abanades et al., 2002; Song et al., 2006; Srivastava et al., 2021; Chuai et al., 2022). In 2013, while 93 % of Almaty households used the gas network for heating, the remaining 7 % relied on alternative fuels, including coal (Kerimray et al., 2018a), with an average daily consumption of 16 kg/day per household in 2018 (IEA, 2020).

However, factor 5 is also influenced by aged air masses associated with transboundary pollution, as evidenced by the presence of sodium and chloride ions (markers of sea salt) (Yen et al., 2024), and by the occurrence of nitrates and sulfates (precursors of secondary aerosols) (Ning et al., 2021). CPF analysis for Almaty indicated a probability of pollutant contributions from residential heating, primarily from the south and southwest directions, suggesting influence by transboundary pollution transported by the Trans-Ili Alatau ridge (Fig. 4).

Biomass combustion for heating in neighboring Kyrgyzstan rural regions (Mehta et al., 2021) may explain the presence of biomass burning markers in this factor. Backward air mass trajectories analysis on days with the highest G-scores for Factor 5 (Fig. S4e, S6 in SM) confirms contributions from both local and transboundary sources of air pollution in Almaty. This is further supported by cluster analysis of air mass trajectories, illustrating air masses passing over the Balkhash Sea (clusters 2, 3, 6, accounting for 33 %, 10 %, and 2 % of trajectory at 1000 AGL, Fig. 5), Caspian Sea, and deserted Aral Sea territory, with salt-rich soils (Issanova et al., 2022) (cluster 4, accounting for 24 % of trajectory at 1000 AGL).

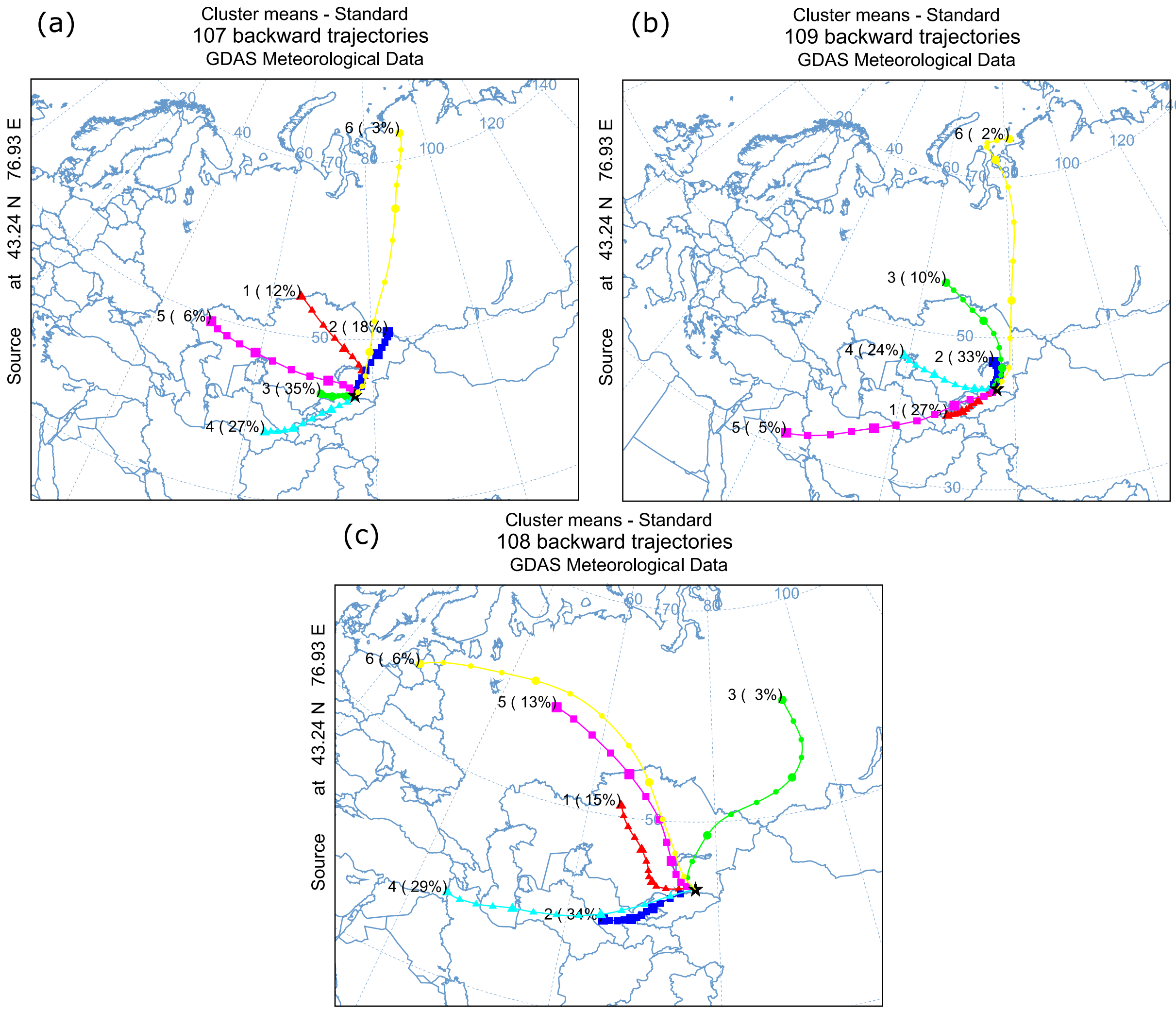

Fig. 5. The cluster analysis of backward trajectories for Almaty at (a) 500 m, (b) 1000 m, and (c) 3000 m AGL.

However, rapid urbanization and population growth from 1.95 million to 2.23 million residents could drive increased private housing development (StatGov, 2024a). Additionally, the unregulated use of coal and biomass in urban saunas and restaurants can exacerbate air pollution. As residential areas are dispersed throughout the city, emissions from the private sector can have a direct impact on local air quality, particularly during the heating season.

3.2.2. Astana

3.2.2.1. Industrial emissions. The elevated concentrations of Ni (32 %), Cr (21 %), and V (28 %), and sulfate ions in Factor 1 strongly indicate an industrial origin, as these pollutants are commonly emitted from factories and refineries (Fang et al., 2021; Tao et al., 2021). A previous study by Zong et al. (2018) identified Cu and As, coupled with high sulfate ion levels, as markers of industrial emissions, a finding consistent with the results of this study (Fig. 6).

While Astana is not widely recognized as a heavily industrialized city, adjacent regions within air transportable distances maintain significant industrial activities. The neighboring Karagandy region, known for mining, metallurgy, and industrial facilities (Qazindustry, 2023), emits pollutants such as Ni and Cr, which exhibit a strong correlation ($r = 0.906$, Fig. S7 in SM). Similarly, large oil refineries and chemical plants in the Pavlodar Region (Samruk-Energy, 2025) contribute sulfates and heavy metals to regional air quality. The results of the CPF analysis indicate that the southern, southwestern, and southeastern directions were associated with industrial emissions pollutants (Fig. 7).

These direction patterns are influenced by air masses originating from the Karagandy and parts of the Pavlodar regions, as well as from residential areas located to the south and southwest of the city, suggesting the potential transport of urban pollution to the sampling site. Additionally, the highest G-scores observed during winter (Fig. S8a in SM) support the impact of urban atmosphere,

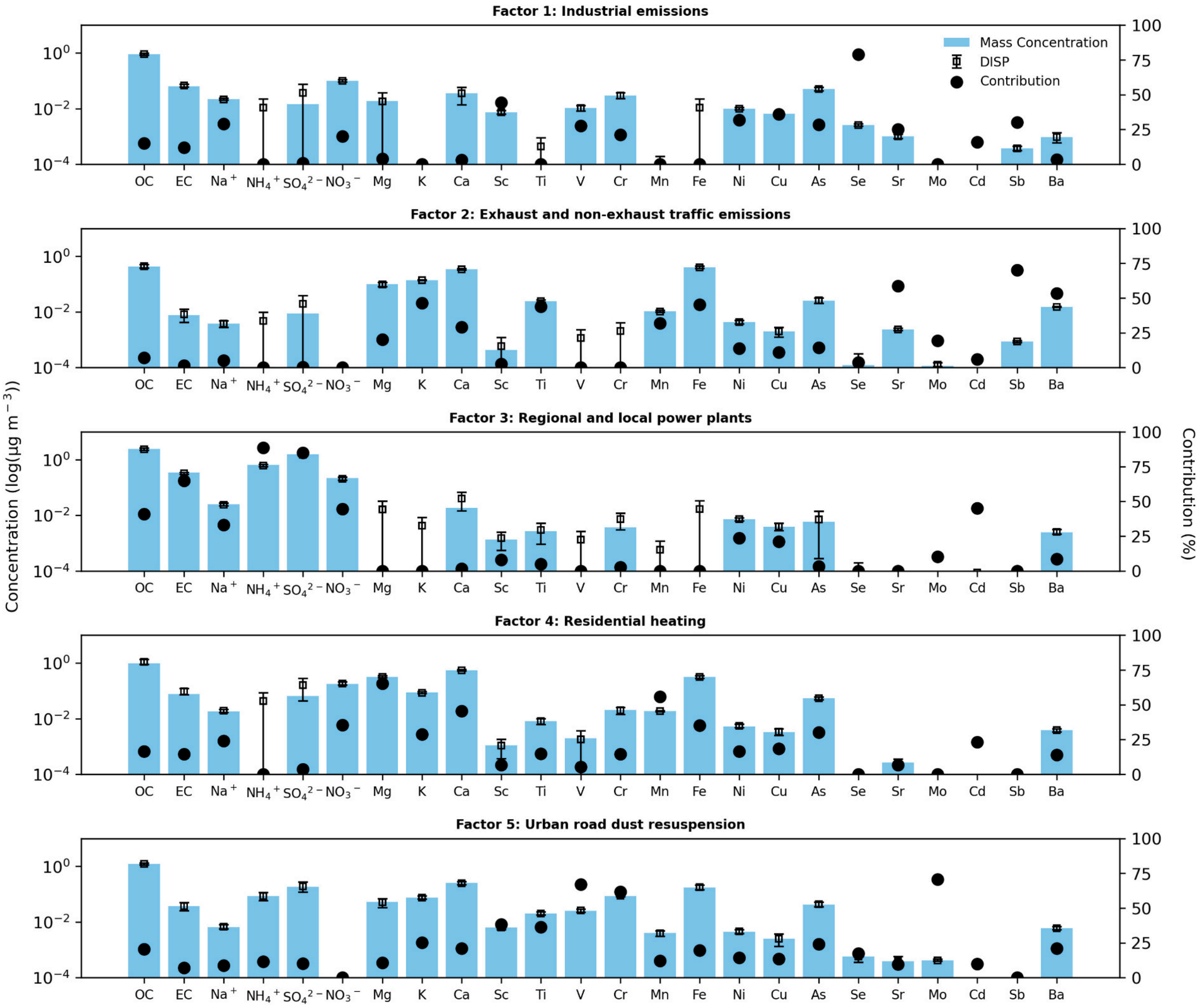

Fig. 6. Source profiles of ambient $PM_{2.5}$ in Astana city identified by the PMF.

likely driven by increased emissions and seasonal meteorological conditions. Analysis of short- and regional-distance backward trajectories demonstrates that a substantial proportion of air masses traverse these industrialized neighboring regions (Fig. S9 in SM). Specifically, 17 %, 24 %, and 10 % of trajectories originate from Karagandy region, while 7 %, 8 %, and 16 % are from Pavlodar region at AGL heights of 500, 1000, and 3000 m, respectively (Fig. 8). This trajectory pattern highlights the significant enrichment of air masses by industrial emissions along their regional pathways.

3.2.2.2. Exhaust and non-exhaust traffic emissions. Factor 2, associated to traffic-related emissions in Astana (Fig. 6), is characterized by elevated contributions of Sr (59 %), Sb (70 %), Ba (53 %), Ti (44 %), Fe (45 %), Mn (32 %), and K (46 %), elements consistently identified as markers of vehicular sources (Amato et al., 2011; Boogaard et al., 2011). The relatively low contributions of OC and EC in this factor may result from a 20 % profile overlap with Factor 5, which is associated with road dust. Moreover, Factors 2 and 5 share contributions from Mg, K, Ca, Ti, Fe, and As, as these elements occur in both combustion ash, resuspended dust, and tire and brake wear.

Further analysis revealed that traffic emissions comprised both exhaust and non-exhaust sources. Non-exhaust emissions originate from tire and brake wear, road dust resuspension, and engine components, whereas exhaust emissions emerge from the combustion of gasoline and diesel fuels (Grigoratos et al., 2023). The presence of Ti alloys in vehicle engine components is explained by their high strength-to-weight ratio and thermal stability (Liu and Liu, 2021), while Ti is commonly associated with tire and brake wear (Fussell et al., 2022; Liu et al., 2023). Similarly, Fe, Cr, Mn, Cu, Sr, Sb, V, and Ba are indicators of non-exhaust emissions from local traffic, with their substantial contributions to this factor supporting its attribution to traffic emissions (Amato et al., 2011; Boogaard et al., 2011; Goddard et al., 2019; Gonet et al., 2021; Mielke and Egendorf, 2023). Additionally, Ti, Mn, and K can reflect a combination of road dust and non-exhaust emissions, explaining their presence in this factor (Adamiec et al., 2016; AQEG, 2019). The higher prevalence of these trace elements suggests that non-exhaust pollution exceeds exhaust emissions in this factor. According to the CPF analysis (Fig. 7),

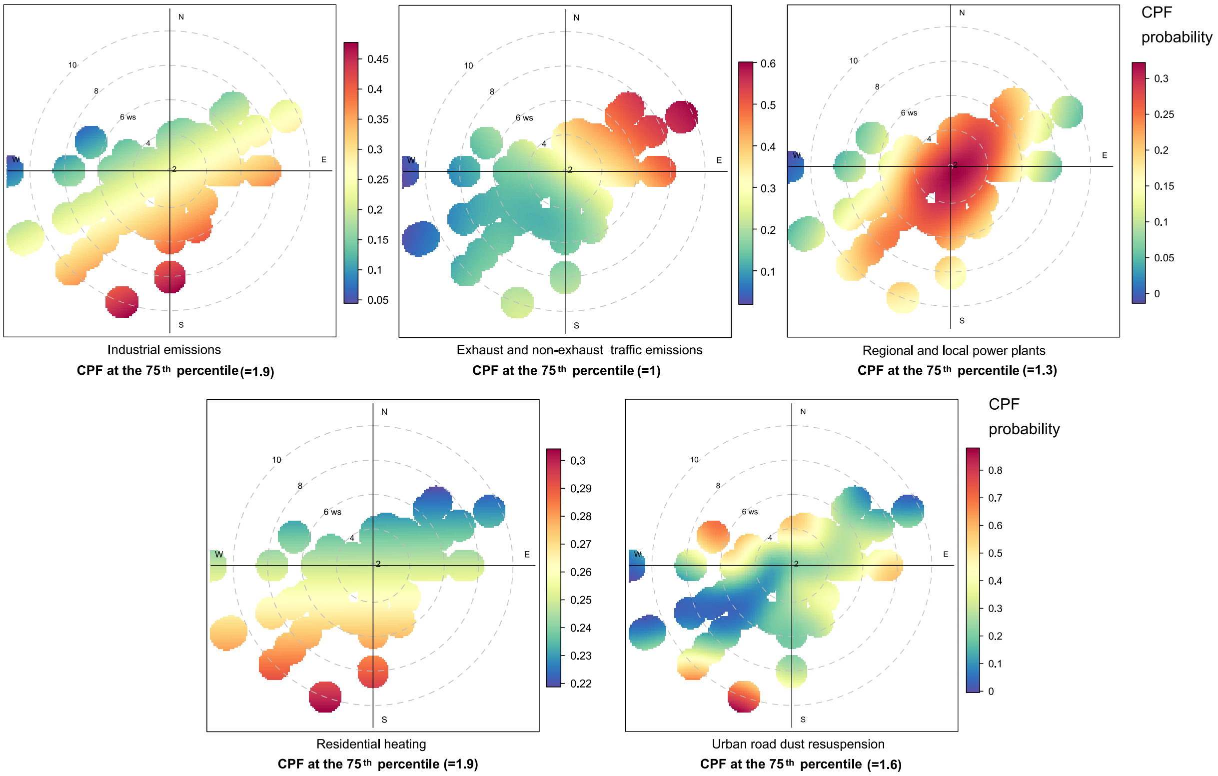

Fig. 7. CPF identifying directional source contributors to $PM_{2.5}$ in Astana.

traffic-related pollutants predominantly originated from the northern and northeastern directions, characterized by intense traffic density and the presence of two major highway bridges spanning the Esil River. These areas also host railway infrastructure, including two railway stations, which may contribute to non-exhaust emissions such as resuspended particles and metal-rich dust.

3.2.2.3. Regional and local power plants. Factor 3 represented high-temperature coal combustion processes occurring in both regional and local power plants, including privately operated facilities owned by regional industries (Qazindustry, 2023). It is characterized by substantial contributions from sulfate (85 %) and nitrate (44 %) ions (Fig. 6), which may form as secondary aerosols from remote coal combustion sources and interact with ammonium (89 %) as a counterion (Ning et al., 2021). Sulfur dioxide, a known marker of high-temperature coal combustion, tends to oxidize during regional transport into sulfates, thereby affecting the receptor site. High contributions of OC (41 %), EC (65 %), and Na^{+} (33 %) can also be attributed to coal combustion, further supporting this interpretation (Huang et al., 2023; Lou et al., 2021). These indicators demonstrate moderately strong intercorrelation, varying from 0.576 to 0.895. Furthermore, elevated Ni (25 %) levels can be linked to the use of oil during the ignition processes of CHPs (Ormanova et al., 2024). In a recent PMF study in Astana, Ormanova et al. (2024) identified CHP-related coal combustion as a significant contributor to $PM_{2.5}$ pollution, with a factor profile consistent with findings of this study.

Elevated G-scores were predominantly observed during the cold season (Fig. S8c in SM), corresponding to the heating period and consequently increased coal consumption at power plants. HYSPLIT backward trajectory analysis performed on days with the highest G-scores revealed the air mass transport from multiple directions, confirming the influence of regional sources (Fig. S10 in SM). Several coal-fired CHPs are located southeast of Astana in the Karagandy region, including power plants dedicated exclusively to industrial operations. Notably, one of the oldest power plants, "Karagandy GRES-1", in Temirtau city (Electrical networks, 2025), may influence air masses arriving from this direction. To the east and northeast of Astana, large power plants operate in the Pavlodar region, particularly those in Ekibastuz city (Samruk-Energy, 2025). Furthermore, CPF analysis (Fig. 7) indicated that pollutants are transported from all directions, reflecting the combined influence of both regional and local sources, including emissions from CHP-1 and CHP-2 in Astana.

3.2.2.4. Residential heating. Factor 4 in Astana was marked by considerable contributions from Mg (65 %), Ca (45 %), Mn (56 %), NO_3^- (35 %), K (45 %), Fe (35 %), and As (30 %) along with moderate levels of EC (14 %), OC (16 %), Ti (15 %), Cr (15 %), Na^{+} (24 %), Ni (16 %), Cu (18 %), and Ba (14 %). Markers, such as Mg, Ca, Mn, K, and Fe, exhibited moderate and frequent intercorrelations (r = 0.530–0.786, Fig. S7 in SM). This chemical profile is indicative of residential heating emissions, encompassing both coal and biomass combustion. Arsenic (As) is a well-established marker for coal combustion (Feng et al., 2016), and its association with Mg and Fe further supports this attribution. As previously discussed, (Section 3.2.1.4), Mg, Ca, Ti, and Fe were detected in local coal fly ash

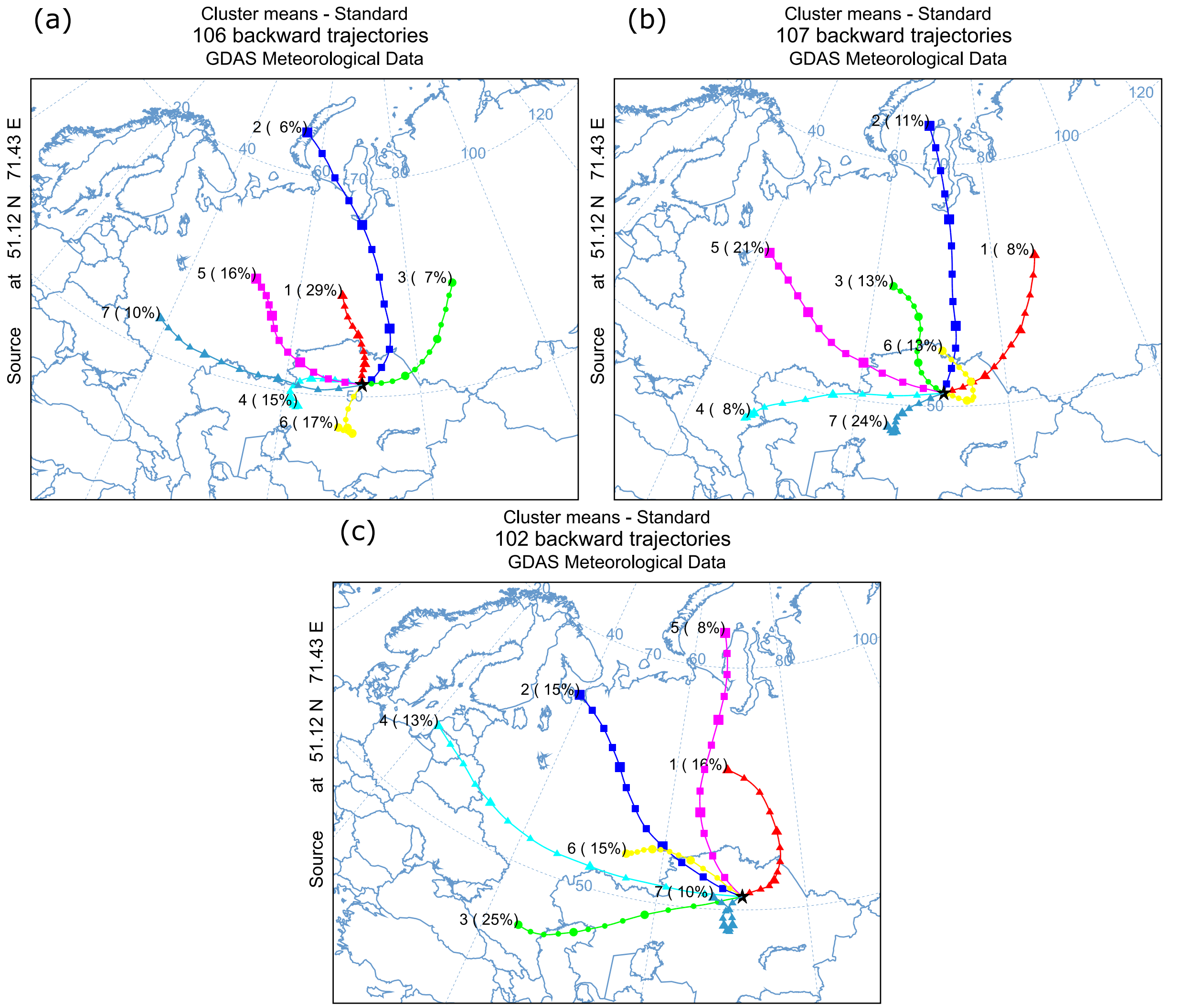

Fig. 8. The cluster analysis of backward trajectories for Astana at (a) 500 m, (b) 1000 m, and (c) 3000 m AGL.

samples (Fig. S5, Table S5 in SM), reinforcing the link between these elemental signatures and coal consumption emissions. Additionally, the elevated NO_3^- concentrations can be explained by their secondary formation from NO_x emissions, a major byproduct of fossil fuel combustion.

The co-occurrence of potassium with OC and EC is a well-recognized indicator of biomass burning (Huang et al., 2023; Li et al., 2007; Taghvaee et al., 2018; Xu et al., 2021), which releases significant quantities of particulate matter into the atmosphere, including carbonaceous aerosols (Park et al., 2022) and inorganic species (Li et al., 2023; Liu et al., 2017; Song et al., 2006; Taghvaee et al., 2018). Studies in Beijing have also identified sodium ions as significant contributors to biomass burning emissions (Song et al., 2006), which aligns with the findings of this study.

In Astana, the private household sector heavily relies on the use of coal and biomass for heating, with consumption increasing significantly during the heating season (October–April). In 2013, 10 % of households in Astana used coal (Kerimray et al., 2018a), with an average daily consumption of 6 kg per household in 2018 (IEA, 2020). A comprehensive survey examining 11,944 households across three regions revealed that Astana households annually consumed 39,000 tons of coal and 13,000 m^3 of biomass (wood) (IEA, 2022).

The CPF analysis indicates that residential heating emissions in Astana predominantly originate from the southern, southwestern, and, to a lesser extent western parts of the city (Fig. 7). This pattern corresponds to the location of private households in suburbs such as Karaotkel (west) and Kosshy (south), where dependence on solid fuels (coal and wood) is particularly high, despite the availability of natural gas (Srivastava et al., 2021).

3.2.2.5. Urban road dust resuspension. Despite Astana's location in CA, where desert dust could affect air quality, HYSPLIT cluster analysis for Factor 5 indicates that majority of air mass trajectories originate from various regions in Russia (Fig. 8). This suggests that the regional sources, rather than desert or soil dust, primarily impact the composition of road dust in the area. Factor 5 is characterized by substantial contributions from Ti (36 %), V (67 %), Cr (62 %), and Mo (71 %), and significant concentrations of K, Ca, Mn, Fe, Ni, Cu, As, Ba, and OC. Most of these elements serve as tracers for tire and brake wear, road dust, and/or materials used in tire manufacturing (Fiala and Hwang, 2021; OECD, 2020; Oroumiyeh et al., 2022; Silva et al., 2021; Thorpe and Harrison, 2008), and titanium is a reliable marker of road dust (Taghvaee et al., 2018). Barrera et al. (2023) reported that resuspended particles containing Mn, Cr, and Fe can result from the wear and abrasion of train tracks and brakes, while Fe, Ni, Ba, and Mn are commonly associated with brake and tire wear. Additionally, Ca and Mg are indicative of road dust (Cheng et al., 2024). In the comprehensive review, Thorpe and Harrison (2008) concluded that car brake linings contain Ca, Cr, Mn, Ni, and Se.

CPF analysis shows that emissions associated with urban road dust were distributed from all directions to the sampling site (Fig. 7). The potential locations of these emissions are not in immediate proximity to the sampling location. This widespread distribution suggests contributions from multiple high-traffic roadways throughout Astana, with wind patterns potentially facilitating the dispersion of resuspended particles.

3.3. Sources of contributions to $PM_{2.5}$ in Almaty and Astana

The annual relative contribution of each source to air pollution in Almaty and Astana was determined through chemical profiles of $PM_{2.5}$ by the PMF analysis (Fig. 9). In Almaty, the sources of $PM_{2.5}$ included resuspended urban road dust (32 %), urban atmosphere (20 %), power plants (18 %), residential heating (16 %), and exhaust emissions (14 %). Notably, both the urban atmosphere and residential heating factors displayed fingerprints of coal and biomass burning markers, and emissions from power plants strongly correlated with high-temperature coal combustion signatures. These findings are consistent with Papagiannis et al. (2024) who reported contributions from power plants (17 %) and coal burning (21 %) in Dushanbe, totaling 38 % from coal-related combustion sources. $PM_{2.5}$ particles attributed to the urban atmosphere in Almaty can be explained by the city's geographical location, which restricts vertical and horizontal pollutant dispersion, thereby facilitating the accumulation and persistence of particles (Mukhtarov et al., 2023). Contributions of secondary aerosols in the region were consistent, ranging from 12 % to 24 % across studies (Fomba et al., 2024; Papagiannis et al., 2024; Ormanova et al., 2024), aligning well with the urban atmosphere factor identified in Almaty. Furthermore, Papagiannis et al. (2024) reported a 17 % contribution from power plants in Dushanbe, closely matching the 18 % contribution observed in Almaty.

In contrast, Astana exhibited distinct $PM_{2.5}$ source profiles characterized by fresher (recently emitted) emissions with pronounced exhaust and non-exhaust traffic contributions. Unlike Almaty, where traffic markers may be confounded by road salt usage, Astana's $PM_{2.5}$ composition was less influenced by such factors. In Astana, residential heating, regional and local power plants, and exhaust and non-exhaust traffic emissions each contributed 20 % to the $PM_{2.5}$ composition, while resuspended urban road dust and industrial emissions accounted for 22 % and 18 %, respectively. The combined coal-related combustion sources reached 40 %, which aligns with Ormanova et al., 2024, who identified coal-related sources at 39.6 % in Astana. Traffic contributions in Astana were consistent with exhaust emissions in Almaty (14 %) and with the secondary aerosol and traffic factor reported by Fomba et al. (2024) (15 %).

Although the pollution sources were distributed relatively evenly in both cities, multiple source factors indicated significant influence from coal and biomass burning, establishing these combustion processes as predominant contributors to $PM_{2.5}$ pollution in both cities.

3.4. Policy implications and recommendations for effective air quality management

This study highlights air quality challenges in Almaty and Astana, Kazakhstan's major cities, focusing on their distinct pollution profiles and the lack of sufficient legislation. Tackling air pollution while considering Kazakhstan's socioeconomic context requires a collaboration between academia, government, and industry (Pui et al., 2014).

Kazakhstan's continental climate and geographical location cause extreme temperature variations, leading to frequent inversion

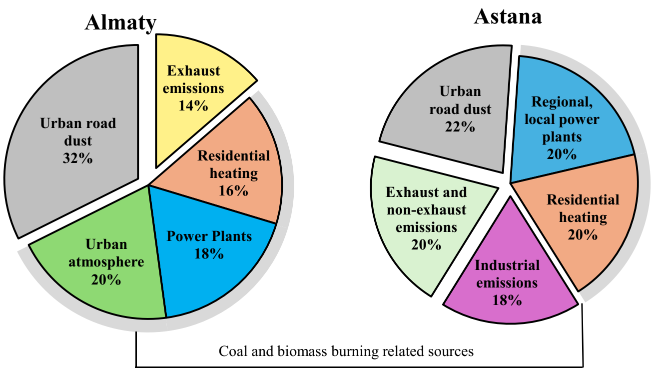

Fig. 9. Relative contribution of PMF-identified sources to $PM_{2.5}$ air pollution in Almaty and Astana.

layers (Tursumbayeva et al., 2022; Mukhtarov et al., 2023), which exacerbates smog formation from coal combustion, a primary source of air pollution, elevating $PM_{2.5}$ levels in Almaty year-round and in Astana during the colder months. Therefore, effective air quality strategies should prioritize reducing emissions from CHPs and household coal consumption, despite Kazakhstan's large coal reserves (over 29.3 B tons, 10th globally) (Kazenergy, 2023). Transitioning to natural gas (138 T m^3, 16th worldwide (Kazenergy, 2023)), which decreases emissions and improves heat generation efficiency, but requires shifts through infrastructure incentives and promoting public-private partnerships. Furthermore, a lack of modern emission control systems suggests considering air pollution control technologies, such as baghouse filters, electrostatic precipitators, and a wet flue gas desulfurization scrubber (Chicherin et al., 2024). However, these methods involve drawbacks, including high installation and maintenance costs, space requirements, and temperature limitations for optimal operation, especially for aging CHPs equipment (wear rates: 67–77 % in Almaty, 31–49 % in Astana) (Official information resource, 2023). Thus, the modernization of CHPs is urgent, with a priority on new gas-operated plants. The European Union (EU) could serve as a case scenario for Kazakhstan, demonstrating significant emissions declines (SO_2 by 92 %, dust by 90 %, and NO_x by 70 %) from 2004 to 2021 at large combustion plants (LCPs) (EPA, 2023b). These reductions resulted from a gradual phase-out of coal (−48 %) and liquid fuels (−44 %) since 2010, and implementation of the Industrial Emission Directive, which set stricter emission limits, prompting LCPs to optimize operations and integrate advanced pollution abatement technologies. The only major planned measure known is the modernization of the CHPs in Almaty, which involves shifting from coal to gas, intending to reduce emissions by 80 % (Prime Minister, 2022).

Residential coal and biomass burning significantly contribute to air pollution, but restrictive policies have demonstrated a notable improvement in atmospheric pollution, benefiting both human health and the environment (Kerimray et al., 2018a). However, Kazakhstan faces economic affordability, public acceptability, and limited environmental awareness challenges requiring comprehensive measures such as (i) prohibiting solid fuel sales; (ii) promoting cleaner fuels; (iii) offering subsidies; and (iv) public education. Several case studies show the effectiveness of policies and financial intervention programs worldwide in combating air pollution from residential fuels. For example, Poland's "Anti-smog Resolution" banned residential coal use and provided financial support for cleaner technologies (Gov.pl, 2019; Jonek-Kowalska, 2023), while China's "Coal to Gas/Electricity" programs achieved 25 % $PM_{2.5}$ reduction by 2020 (Barrington-Leigh et al., 2019; Yan et al., 2020) through subsidies for electric alternatives over coal stoves. Cost-effective measures such as weather stripping can reduce household heat loss (The World Bank, 2021) and enhance energy efficiency in Kazakhstan. The use of coal for residential heating in Kazakhstan depends on its affordability, limited access to alternatives, and household characteristics (Azhgaliyeva et al., 2021). The research by Kerimray et al. (2018b) investigated the energy transition to a coal-free residential sector in Kazakhstan, showing that a scenario for a coal ban in the residential sector was estimated to achieve emissions reductions of 92 % for $PM_{2.5}$. However, the energy transition from solid fuels to cleaner alternatives is rarely feasible without government intervention, as also supported by the World Bank report (The World Bank, 2022).

The transport sector significantly pollutes Almaty (651,068 vehicles) and Astana (412,396 vehicles) (StatGov, 2024b), with over 20-year-old vehicles, comprising 35 % and 25 %, respectively (StatGov, 2023). Effective mitigation requires developing public transportation infrastructure, enforcing strict vehicle inspection and maintenance protocols, and designing pedestrian-friendly urban environments. Reallocating public transportation space and promoting non-motorized, alternative options (walking, cycling, scooters, etc.) show a reduction in air pollution (Slovic and Ribeiro, 2018), as well as demonstrated by Beijing's metro expansion ($PM_{2.5}$ by 155 %, PM_{10} by 125 %) (Guo and Chen, 2019). Transparent vehicle inspections and differentiated taxes incentivize the use of cleaner vehicles and proper maintenance, resulting in a 12 % reduction in NO_x and a 13 % reduction in $PM_{2.5}$ in the EU (Zimmer and Koch, 2017). However, in developing countries like Brazil, such regulations have contributed to deteriorating air quality due to the population's perceptions and constraints on transportation affordability (Aydin and Bozatli, 2022). During the 27-day COVID-19 lockdown in Almaty, a unique scenario occurred with traffic-free urban conditions (Kerimray et al., 2020). While $PM_{2.5}$ levels decreased by 30–34 % at sensors at lower elevations, the air quality remained far from clean at those sites due to various complex impacting factors.

Effective air quality management relies on well-defined standards and robust enforcement, such as the WHO's science-based Air Quality Guidelines (AQGs) (WHO, 2024), setting safe pollutant levels for long-term human exposure to minimize health risks. Annual $PM_{2.5}$ concentrations in Almaty (38.8 μg m^{-3}) and Astana (19.8 μg m^{-3}) exceed the WHO-recommended 5 μg m^{-3} (WHO, 2024). For countries with high pollution levels, science-based interim targets can guide policy development and track progress toward cleaner air. The U.S. National Ambient Air Quality Standards (NAAQS) exemplify the benefits of regulations through progressively lower target limits, with $PM_{2.5}$ thresholds decreasing from 65 μg m^{-3} (1997) to 9 μg m^{-3} (2024), reflecting advances in emission control technologies and increased awareness of health impacts (EPA, 2024; Pui et al., 2014). Although Kazakhstan lacks annual air pollutant limits, this study suggests achievable interim annual $PM_{2.5}$ targets of 15 μg m^{-3} (57th percentile) for Astana and 25 μg m^{-3} (70th percentile) for Almaty, signifying a decrease from levels identified in this research. These could be formalized as Environmental Quality Standards (EQS) by updating the Environmental Code, which serves as the legal framework for environmental protection in Kazakhstan (Adilet, 2021). Strict enforcement for "Category I" emitters (e.g., CHPs) is critical, requiring Best Available Techniques (BAT) compliance through Comprehensive Environmental Permits (CEPs) and incentive-aligned fee structures (IEA, 2022). Regular EQS reviews must be based on continuous air quality monitoring and improvements in emission control technologies.

However, Kazakhstan's air quality management is hindered by the lack of a comprehensive monitoring system, which provides valuable insights into the pollution formation mechanisms, forecasting, early warning systems, emissions inventories, pollution source identification (Belis et al., 2019), and evaluating the efficiency of measures taken to reduce emissions (Kuula et al., 2022). Persistent air pollution from coal-driven CHPs is attributable to insufficient legislative measures, which pose a continuing threat to environmental quality. Implementing the complete set of technical measures could decrease $PM_{2.5}$ exposure to 18 μg m^{-3} in Almaty and 8 μg m^{-3} in Astana by 2030 (The World Bank, 2022). However, fiscal policy reforms are necessary to close the incentive gap, encouraging private enterprises and households to adopt socially optimal air quality and climate actions. A comprehensive strategy should also involve public education on the health risks associated with air pollution, standard notification protocols aligned with global practices, and transparent communication of pollution alerts. Establishing partnerships among communities, NGOs, industries, and government agencies is crucial for developing effective air quality management.

4. Conclusions

This study provides a comprehensive characterization of ambient $PM_{2.5}$ sources in Almaty and Astana, two of Kazakhstan's largest cities, thereby addressing a critical knowledge gap in Central Asian urban air quality research. By integrating chemical composition correlation analysis with PMF source apportionment, CPF, and HYSPLIT trajectory clustering, distinct urban $PM_{2.5}$ pollution patterns were identified, influenced by local emission sources, regional transport, and geographical factors.

Throughout the study period (August 2022 to July 2023), annual $PM_{2.5}$ concentrations in Almaty (35.6 μg m^{-3}) and Astana (19.4 μg m^{-3}) substantially exceeded WHO limits, indicating persistent urban air quality challenges. $PM_{2.5}$ in both cities is predominantly composed of organic carbon, elemental carbon, ions (notably nitrate and sulfate), and metals (such as iron, calcium, and aluminum), with distinct inter-city variations reflecting differences in emission sources, meteorological conditions, and urban structure. Source apportionment revealed city-specific patterns. In Almaty, the valley topography amplified contributions from resuspended urban road dust (32 %), urban atmosphere (20 %), power plants (18 %), residential heating (16 %), and exhaust emissions (14 %). Conversely, in Astana's steppe landscape, residential heating, regional and local power plants, and traffic emissions (exhaust and non-exhaust) each contributed 20 %, with resuspended urban road dust and industrial emissions accounting for 22 % and 18 %, respectively. Despite these distributional differences, coal and biomass combustion emerged as dominant contributors to $PM_{2.5}$ in both cities, highlighting the persistent impact of fossil fuel dependence on urban air quality.

The HYSPLIT-based cluster analysis in Almaty confirmed the pronounced contribution of urban road dust, particularly from slow-moving air masses. In Astana, air mass trajectory analysis revealed the impact of industrial emissions originating in neighboring regions, such as Karagandy and Pavlodar, with considerable atmospheric pollutant enrichment along transport pathways. Additionally, CPF analysis corroborated the impact of local emission sources and facilitated the identification of their potential locations.

These findings emphasize the importance of implementing targeted emission control strategies and air quality management reforms to reduce regional and transboundary air pollution. Key measures include transitioning from coal to natural gas, strengthening industrial and vehicle emission controls, enhancing air quality monitoring systems, and promoting cleaner residential heating. Additionally, implementing science-based interim $PM_{2.5}$ targets (15 μg m^{-3} for Astana and 35 μg m^{-3} for Almaty) would provide a structured pathway toward improved air quality. Aligning policies with international air quality standards and raising public awareness is critical for long-term sustainability.

Furthermore, future PMF analysis should be extended to additional pollution sources and other highly polluted cities in Kazakhstan, particularly those with extensive heavy and petroleum industries, as well as mining activities. The findings from this study provide evidence-based recommendations for policymakers to develop and implement effective mitigation strategies for $PM_{2.5}$ in Almaty, Astana, and other Central Asian cities facing similar issues. Future research should focus on evaluating the long-term health impacts of $PM_{2.5}$ exposure and the effectiveness of policy interventions in protecting public health and reducing the disease burden associated with ambient air pollution.

CRediT authorship contribution statement

Kazbek Tursun: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anara Omarova:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Olga P. Ibragimova:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Bauyrzhan Bukenov:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Madina Tursumbayeva:** Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Ravkat Mukhtarov:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ivan Radelyuk:** Writing – original draft, Validation, Methodology, Investigation. **Serpil Yenisoy:** Writing – review & editing, Methodology, Conceptualization. **Duran Karakaş:** Writing – review & editing, Methodology, Conceptualization. **Hatice Ergin:** Writing – review & editing, Methodology, Conceptualization. **Ferhat Karaca:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Nassiba Baimatova:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2025.102706.

Data availability

All data presented in this paper are available upon request.

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