

PM_{2.5} IN CAPE TOWN, SOUTH AFRICA: CHEMICAL CHARACTERIZATION AND SOURCE APPORTIONMENT USING DISPERSION-NORMALISED POSITIVE MATRIX FACTORIZATION

Anna Alfeus,^{1,2} Peter Molnar,³ Johan Boman,⁴ Philip K. Hopke,^{5,6} Janine Wichmann¹

¹School of Health Systems and Public Health, University of Pretoria, Private Bag X323, Pretoria,0001, South Africa

²Department of Public Health, School of Nursing and Public Health, University of Namibia, Eliander Mwatale Street, PO Box 2654, Oshakati, Namibia *Correspondence: aalfeus@unam.na; Tel.: +264 81 7361725

³Department of Occupational and Environmental Medicine, Institute of Medicine, Sahlgrenska Academy, University of Gothenburg, SE-405 30 Gothenburg, Sweden

⁴Department of Chemistry and Molecular Biology, University of Gothenburg, SE-405 30 Gothenburg, Sweden

⁵Institute for a Sustainable Environment, Clarkson University, Potsdam, NY 13699, USA

⁶Department of Public Health Sciences, University of Rochester School of Medicine and Dentistry, Rochester, NY 14642, USA

ABSTRACT

Understanding fine particulate matter (PM_{2.5}) composition and sources is beneficial to improving visibility, addressing climate change, and mitigating poor air quality and related public health effects. Source apportionment techniques have been instrumental in evaluating the impact of sources and secondary processes on the ambient PM_{2.5} concentrations in receptor areas. Positive Matrix Factorization (PMF) is now the most commonly used tool due to its ability to provide mixture resolution based on available PM_{2.5} compositional data. Sampling and analysis of PM_{2.5} was conducted in Cape Town, South Africa from April 2017 to April 2018. The resulting data were dispersion normalized to address the modifications of the source concentrations resulting from the varying dispersion conditions and thereby permit dispersion normalized PMF (DN-PMF) to be employed. DN-PMF quantified the 6 sources as 2-stroke vehicles/galvanizing industries (16.8%); soil/road dust (12.3%); sulphate/marine diesel (3.6%), traffic (15.7%), sea salt (21.8%), and heating/biomass burning/cooking (15.7%). In addition, air mass back trajectory analysis using the Hybrid Single Particle Lagrangian Trajectory (HYSPLIT) model identified long-range transport pathways to Cape Town. The HYSPLIT results showed air masses from the Atlantic SSW (6%), Atlantic SW (24%), Indian Ocean (31%), and Atlantic WSW (39%) influence air quality. The primary sources affected by the transport clusters were heating, 2-stroke vehicles/galvanizing, road and soil dust, and traffic emissions. These results show that reducing emissions from the local sources will improve air quality.

Keywords: Cape Town, Dispersion Normalized-Positive Matrix Factorization, PM_{2.5}, Source Apportionment, South Africa, Trace Elements

1. INTRODUCTION

Fine particulate matter (PM_{2.5}) is a major air pollutant. Globally, particles less than 2.5 microns in diameter have received particular attention due to their physicochemical properties (Orellano et al., 2020; WHO, 2021) and associated adverse health outcomes (Feigin et al., 2021; Soriano et al., 2020; WHO, 2021). Black carbon (BC) and sulphate (S) are strong climate forcings, both positive and negative (Bond et al., 2013; Dai et al., 2019). PM_{2.5} includes toxic elements and compounds. Black carbon is an indicator of combustion, including diesel engine emissions, residential wood burning, coal, heavy oil, and biomass burning from agricultural waste, forests, and vegetation fires that cause harmful effects to sensitive organs in the human body (Jacobson, 2001; Janssen et al., 2012; Wang et al., 2012), and is an important short-term climate forcer (Bond et al., 2013).

Serious air quality management efforts in South Africa began by enacting the National Air Quality Act in 2005 (Department of Planning, Monitoring and Evaluation, 2005). The daily and yearly South African air quality standard for PM_{2.5} only came into effect in June 2012, and there was a delay for the air pollutant to be monitored (Department of Environmental Affairs, 2012). PM_{2.5} was not monitored during the study period in Cape Town (Department of Environmental Affairs and Development Planning, 2021). Cape Town is a highly industrialised city with a variety of industries including metal recycling, production, and fabrication, cement production, and a port that handles both container and cruise ships. Recent studies indicated PM_{2.5} concentrations were sufficiently high to pose potential health risks in Cape Town (Alfeus et al., 2022; Williams et al., 2021). The PM_{2.5} concentrations in Cape Town were above the WHO guidelines with reported increased risk in adults, children, and infants (Alfeus et al., 2022; Williams et al., 2021). Identifying the sources and contributions could lower PM_{2.5} concentration and its associated effects (UNECE, 2010; WHO, 2013).

Emissions, dispersion, transport modelling, and source apportionment techniques are available to evaluate the impact of primary emitters and secondary processes on ambient PM_{2.5} loads (Cardoso et al., 2018). Source-oriented models require input data, including emission inventories, that is often difficult to develop and quantify the source contributions to ambient concentrations fully (JRC et al., 2014). Based on the available PM_{2.5} datasets, receptor-oriented models can provide resolutions of mixtures (JRC, 2014; Hopke, 2016). Thus, available compositional data are adequate for source apportionment studies applying the receptor models. Among the available data analysis methods, Positive Matrix Factorization (PMF) has become the most used receptor model (Hopke et al., 2020).

Hundreds of studies have been conducted worldwide (Hopke et al., 2022). However, there are very few source apportionment studies in Africa (Adeyemi et al., 2021; Benchrif et al., 2022; Cardoso et al., 2018; Doumbia et al., 2023; Gaita et al., 2014; Gatari et al., 2009; Klopper et al., 2020; Mmari et al., 2020; Muyemeki et al., 2021; Odediran et al., 2021; Orogade et al., 2016; Owoade et al., 2016; Sulaymon et al., 2020; Tefera et al., 2021; Tshehla and Djolov, 2018; Walton et al., 2021; Zhou et al., 2014). Some of the above studies used different methods (e.g., chemical mass balance or enrichment factors) (Cardoso et al., 2018; Gatari et al., 2009; Mmari et al., 2020; Tefera et al., 2021), shorter sampling periods (Owoade et al., 2016; Sulaymon et al., 2020; Walton et al., 2021), or focused on specific locations or situations (e.g., most polluted area, events or indoor environment) (Klopper et al., 2020; Odediran et al., 2021; Walton et al., 2021; Zhou et al., 2014), which may limit the representativeness and comparability of their findings. PMF studies conducted in African cities with similar sampling durations, such as Tetouan, Morocco (Benchrif et al., 2022), Nairobi, Kenya (Gaita et al., 2014), and Kaduna, Nigeria (Orogade et al., 2016), identified PM_{2.5} components such as particulate organic matters, black carbon, sulfate, nitrate, ammonia, vehicle emission, industrial emission, biomass burning, aged sea salt, mineral and soil dust.

In South Africa, PMF source apportionment studies have only been conducted in Pretoria (Adeyemi et al., 2021), the Vaal Triangle (Muyemeki et al., 2021), and Limpopo (Tshehla and Djolov, 2018). From the review of these source apportionment studies, a number of primary and secondary sources contribute to PM_{2.5} including on road transportation (exhaust emission, tire, and brake wear), residential space heating, biomass combustion (residential and agricultural wood burning), fossil fuel and coal combustion industries (base metals/pyrometallurgical, ferrochrome smelters), mineral or soil dust and secondary aerosols (Adeyemi et al., 2021; Muyemeki et al., 2021; Tshehla and Djolov, 2018).

This present study used dispersion normalized positive matrix factorization (DN-PMF) (Dai et al., 2020, 2021; Gu et al., 2022; Sofowote et al., 2021; Song et al., 2021; Chen et al., 2022) on data previously collected in Cape Town (Williams et al., 2021; Alfeus et al., 2022). DN-PMF provides improved results and reduces the influence of variable dispersion conditions that modify concentrations irrespective of emission rates (Chen et al., 2022). As done in these other studies, DN-PMF applied the ventilation coefficient (VC) on 24-h integrated filter-based sampling data from Cape Town, South Africa, during the April 2017–April 2018 sampling period to provide the first source apportionment results for Cape Town.

2. METHODS

2.1 Site description and measurements

Williams et al. (2021) and Alfeus et al. (2022) described the study setting in detail. 24-hour aerosol samples were collected at a sub-urban background site (3 m above the ground) in the residential area of the Kraaifontein suburb (Fig S1; coordinates: 33.8429°S, 18.7026°E). The Kraaifontein sampling site is 29 km from the city industries, 2 km from the N1 Freeway, and 30 km from the Cape Town International Airport (Williams et al., 2021). At the end of the sampling period, 121 exposed filters (37-mm PFTE, Zefon International, Inc., Ocala, FL34474, USA) were collected from 9:00 to 9:00 am on every third day from April 18, 2017 to April 18, 2018 using GilAir-5 personal air samplers. Detailed sampling information is available in studies conducted across South African cities by Adeyemi et al. (2022), Edlund et al. (2021), and Howlett-Downing et al. (2022).

2.2. Instrumentation and Data Analysis

Table S1 summarizes the methods and equipment used to analyse the PM_{2.5} species. Williams et al. (2021) performed the gravimetric analysis of PM_{2.5} at the School of Health Systems and Public Health (SHSPH), University of Pretoria (UP). As reported by other studies, the Department of Chemistry and Molecular Biology, Atmospheric Division, University of Gothenburg, analysed the trace elemental, black carbon, and organic carbon composition (Adeyemi et al., 2022; Howlett-Downing et al., 2022; Edlund et al., 2021).

2.2.1 Light-absorbing carbon

Light-absorbing carbon was measured at two different wavelengths, 880 and 370 nm, respectively, with a Model OT21 Optical Transmissometer. Delta-C, the difference between UVBC and BC, was determined as described by Wang et al. (2011). Delta-C helps differentiate combustion sources and is a known tracer for biomass burning (Wang et al., 2011; 2012). However, these absorption measurements only partially account for the carbonaceous components since there can be non-absorbing organic species. In addition, this study did not measure nitrate or non-light absorbing carbon. Thus, the measured data cannot provide mass closure for the samples.

2.2.2 Sulphate

Sulphate comprises primary and secondary sulphate (Dai et al., 2019). Secondary sulphate is a product of atmospheric chemical reactions of SO₂, oxygen, and ammonia. All elemental sulphur is assumed to be ammonia sulphate (NH₄)₂ SO₄ (Malm et al., 1994). The multiplicative molar conversion factor (mcf) for sulphur to ammonia sulphate is determined by multiplying the molecular mass of the ammonia sulphate molecule with the measured mass of sulphate. In this study, the mcf for ammonium sulphate is 4.125 (Malm et al., 1994).

$$\text{Sulfate} = S * 4.125 \quad (1)$$

2.2.3 Soil

The soil mass concentration was estimated by summing the masses of elemental oxides predominantly associated with soil (Cardoso et al., 2018; Malm et al., 1994). In this study, the elements associated with the soil were Si, Ca, Fe, and Ti (Cardoso et al., 2018; Malm et al., 1994). Since we had not measured Al, the silica-aluminium ratio (Si/Al = 2.7) derived the Al mass (Rahn, 1976). The elements were converted to their oxidized form using the following equation:

$$\text{Soil} = \frac{Si}{2.7} * 2.2 + Si * 2.49 + Ca * 1.63 + Fe * 2.42 + Ti * 1.94 \quad (2)$$

2.2.4. Sea Salt

In this study, chlorine measures sea salt (NaCl) and the molecular weight for NaCl is 58.5 (Cardoso et al., 2018; Malm et al., 1994). Hence the Cl is converted to NaCl by multiplying the Cl measured concentration with the molecular weight of Na divided by the molecular weight of Cl as demonstrated below:

$$\text{Sea Salt} = Cl * \left(1 + \frac{23}{35.5}\right) \quad (3)$$

2.2.5 Unmeasured Mass

Since the analytical results do not provide full mass closure, we incorporated the unmeasured mass (UMM) into the analysis (Hopke et al., 2003; Zhao et al., 2007; Anastasopoulos et al.,

2022). We subtracted the reconstructed mass from the measured mass on a sample-by-sample basis. The estimation of the reconstructed mass used the approach presented initially by Malm et al. (1994) that converts the measured elemental concentrations into species likely to be present in the PM samples. These species include sulphate, crustal species described as soil, and sea salt.

The unmeasured mass (UMM) was then estimated by:

$$UMM_i = Mass_i - Sulfate_i - Soil_i - Sea\ Salt_i - BC_i - DC_i \quad (4)$$

Where i is the index for a given sample. The likely major components in the unmeasured mass are nitrate and non-light absorbing organic carbon.

2.3 Dispersion-Normalized Source Apportionment

The U.S. Environmental Protection Agency Positive Matrix Factorization (EPA-PMF) software, version 5.0, was employed. PMF estimates the source profiles and their contributions from the available concentrations and associated uncertainties (Hopke, 2016; Paatero, 1997; Paatero and Tapper, 1994). The species included in the analysis were BC, Delta-C, S, Cl, Si, K, Ca, Ti, Fe, Ni, Cu, Zn, As, Br, Sr, Sb, and Pb. Uncertainties were calculated as per Polissar et al. (1998). The geometric concentration means, and 5/6 DL were used for species with multiple missing data and concentrations below the detection limit (Polissar et al., 1998). Bootstrapping (BS), displacement (DISP), and bootstrap displacement (BS-DISP) analyses were performed to assess the uncertainties and rotational ambiguity (Paatero et al., 2014; Brown et al., 2015).

This study used DN-PMF, a recently developed approach to reduce the meteorological influence on PMF analysis by incorporating the ventilation coefficient (VC) as calculated below (Dai et al., 2020, 2021; Chen et al., 2022):

$$VC_i = BLH_i \times u_i \quad (5)$$

BLH_i is the boundary layer height for time period i , and u_i is the mean wind speed for time period i .

$$CVC_{ij} = C_{ij} \frac{VC_i}{\overline{VC}} \quad (6)$$

where \overline{VC} is the average VC over the whole sampling period, C_{ij} is the measured concentrations of species j in sample i , and CVC_{ij} is the corresponding dispersion normalized concentration.

Equation 6 normalized the concentrations to that it would be for the average VC for the whole sampling period and thereby reduced the influence of period-specific dispersion. The hourly BLH values were obtained from the website for ERA5 hourly data on single levels from 1940 to the present (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form>). Local hourly wind data from the Cape Town International Airport were obtained from the South African Weather Service. Hourly VC values were then calculated using Equation 5. Average 24-hour DN coefficients were obtained from the 24 one-hour values for a given sample and were applied to both measurements and error matrices. The final DN concentrations and uncertainties were input data in the PMF model. They provided the results in this study after unnormalisation by multiplying the resolved contributions with the inverse of the normalisation ratio.

2.4 Conditional Bivariate Probability Function

The seasonal conditional bivariate probability function (CBPF) values were calculated for each resolved factor to explore the location of the local sources relative to the monitoring sites (Uria-Tellaetxe and Carslaw, 2014; Begum and Hopke, 2019). The CBPF is defined by:

$$CBPF = \frac{m_{\Delta\theta\Delta u}}{n_{\Delta\theta\Delta u}} \quad (7)$$

Where $m_{\Delta\theta\Delta u}$ is the number of samples where the wind direction falls within the $\Delta\theta$ directions interval and the Δu speed interval, and the contributions from the factor that was greater than the 75th percentile; while $n_{\Delta\theta\Delta u}$ is the number of samples where the wind direction falls within the $\Delta\theta$ and Δu intervals.

2.5 HYSPLIT and Transport Clusters

Williams et al. (2021) identified a surrogate of long-range transport passing through Cape Town using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Using the trajectories shown in Figure 2 of Williams et al. (2021), this study investigated the influence of air masses from 4 directions; 1) Indian Ocean, 2) Atlantic Ocean-WSW, 3) Atlantic Ocean-SW, and 4) Atlantic Ocean-SSW on the modelled factors similar to what has been done in earlier studies (Adeyemi et al., 2021; Molnár et al., 2017; Muyemeki et al., 2021; Novela et al., 2020; Tshehla and Djolov, 2018)

2.6 Statistical Analyses

We used SAS version 9.3 to perform the statistical analysis (Alfeus et al., 2022; Williams et al., 2021). PMF sources did not have normal distributions. Thus, Kruskal-Wallis ANOVA on Ranks (Kruskal and Wallis, 1952) and Wilcoxon's rank sum tests (Wilcoxon, 1945) were applied to test whether PMF sources differed across seasons: Autumn (March-April); Winter (June-August); Spring (September-November) and Summer (December -February), and transport clusters. Studies from Pretoria and Gothenburg used similar tests (Adeyemi et al., 2021; Molnár et al., 2017).

3. RESULTS AND DISCUSSION

3.1. Overview of the measurements

Table S2 provides a summary of PM_{2.5} annual, seasonal, weekdays and weekends descriptive statistics. The mean daily concentration in this study was $13.4 \pm 8.2 \mu\text{g}/\text{m}^3$, exceeding the yearly WHO air quality guideline of $5 \mu\text{g}/\text{m}^3$, but not the yearly South African air quality standard of $20 \mu\text{g}/\text{m}^3$ (Alfeus et al., 2022; Williams et al., 2021). PM_{2.5} mass concentration reported in our study was lower than the mean concentration observed by Benchrif et al.(2022), at a coastal urban area in Tetouan, Morocco, ($17.96 \mu\text{g}/\text{m}^3$), and those reported by Owoade et al.(2016) at an urban industrial site in Kaduna, north western Nigeria ($37.2 \mu\text{g}/\text{m}^3$), but higher than those obtained by Anastasopoulos et al. (2022) at an urban city centre in Calgary, Canada ($7.45 \mu\text{g}/\text{m}^3$). Locally, the mean concentration reported in this study were lower than those observed by Adeyemi et al. (2021) at an urban industrial site in Pretoria ($21.1 \mu\text{g}/\text{m}^3$), but higher than those observed by Novela et al.(2020) at a rural site in Thohoyandou ($11 \mu\text{g}/\text{m}^3$) and Van der Westhuizen et al. (2022) at a sub-urban site in Bloemfontein ($11 \mu\text{g}/\text{m}^3$). It is expected that PM_{2.5} levels at sub-urban sites are lower than those at urban sites, as sub-urban sites usually further away from larger industries, busy roads and out of airmass trajectories pathways (Benchrif et al., 2022).

The measured PM_{2.5} data exceeded the daily WHO guideline ($15 \mu\text{g}/\text{m}^3$) on seventeen days in spring, thirteen in winter, seven in autumn and once in summer (equivalent to an average of 3 exceedance days per year) (Table S3). Cape Town experiences dry, warm summers resulting in few settling particles due to increased temperature, humidity, and wind speed, wet cold winters with more frequent inversions that lead to poor dispersion of particles (Williams et al.,

2021). These seasonal patterns were confirmed by the results in this study, as the lowest PM_{2.5} concentrations (9.1 µg/m³) and highest temperature (21.5°C) and windspeed (5.0 m/s) were reported in summer compared to other seasons (Table S4). The highest relative humidity was reported in winter (Table S4).

The annual mean BC concentration was 2.4 ± 1.5 µg/m³, accounting for 18% of the PM_{2.5} mass (Table S6). Studies from some African cities support our findings that PM_{2.5} is mainly made up of BC, e.g. in Pretoria, South Africa (Adeyemi et al., 2022), Kaduna, Nigeria (Orogade et al., 2016); Kenya (Gaita et al., 2014). Contrastingly, studies conducted in Thohoyandou, South Africa and Tetouan, Morocco found that PM_{2.5} mainly comprises of organic carbon (Benchrif et al., 2022; Novela et al., 2020). PM_{2.5} and BC showed a significant positive correlation (Table S5), which means controlling the sources of BC could result in PM_{2.5} reduction. A study conducted in Dakar; Bangladesh indicates that reducing BC concentration by a factor of 2.5 results in the reduction of PM_{2.5} concentration by a factor of 2, following the establishment of national air quality standard, replacement of old 2-stroke engine, three wheelers to CNG four stroke three wheelers and banning of leaded gasoline (Begum and Hopke, 2019). South Africa phased out the leaded gasoline in 2006. The country's air quality standard for PM_{2.5} came into effect in 2012 (Adeyemi et al. 2021; Department of Environmental Affairs, 2012). South Africa introduced electrical vehicles in 2013, but switching over is very slow as in the rest of the world (Moeletsi, 2021). Thus, the continuous use of internal combustion engines in South Africa contributes to air pollution.

The mean sulphur concentration was 1.4 ± 0.9 µg/m³, accounting for 10% of the PM_{2.5} mass. Sulphur concentrations did not differ significantly across seasons, days of the week, or weekdays (Table S6). Sulphur is a significant secondary inorganic aerosol (SIA) component because it contributes to primary and secondary sulphate (Zhou et al., 2020). This study did not quantify the other major SIA species, e.g. nitrate. Primary sulphate is produced from diesel vehicles containing higher concentrations of sulphur in fuels that is oxidized at low temperatures, producing SO₃, which then reacts with water vapor to form primary sulphate (Agarwal et al. 2008a; 2008b; 2009; 2010; Begum and Hopke, 2019). In the expansion stroke of a diesel engine, adiabatic cooling results in sufficiently low temperatures that produce SO₃. Given high-sulphur diesel fuels, diesel engines like marine diesel engines (Agrawal et al., 2008a; 2008b; 2009; 2010), heavy-duty on- and off-road diesel vehicles (Santoso et al., 2008; Begum and Hopke, 2019) or coal combustion at low temperatures (Dai et al., 2019) can produce primary sulphate. Currently South Africans consume diesel fuel with maximum S

content of 500ppm and 50 ppm (Xie et al.,2022). New regulations that will limit diesel sulphur content are published and will be effective in 2027 (Turner and Malicier, 2022). Finally, the sea contributes to the primary sulphate in the atmosphere as part of the sea salt (Mason, 1966).

The formation of secondary sulphate is due to strong photochemistry between SO₂ emissions formed through various atmospheric processes. SO₂, the precursor gas for secondary sulphate, is emitted by diesel vehicles (Santoso et al., 2008), marine diesel vessels (Agrawal et al., 2008a, 2008b; 2009;2010; Anastasopoulos et al., 2023), and household heating (Alfeus et al., 2022; Gaita et al., 2014; Zhang et al., 2013). However, it takes hours to convert a significant fraction of the SO₂ to SO₃, so local SO₂ sources do not contribute significantly to local sulphate (Agrawal et al., 2008a, 2008b). However, the oxidation of methyl disulfide and dimethyl disulfide emitted from marine phytoplankton produces biogenic sulphate and methane sulfonic acid (MSA) (Charlson et al., 1987). Thus, biogenic sulphate likely contributed to the measured sulphate values.

The correlations of PM_{2.5} and SO₂ from ambient air quality monitoring stations near our sampling location were significant (Williams et al., 2021). The highest correlation report was at Goodwood ($r^2=0.60$;14 km SWS of the study site), followed by Wallecedene ($r^2=0.31$; 3 km ESE of the study site), Table View ($r^2=0.24$; 18 km WNW of the site), Somerset West ($r^2=0.22$; 29 km SSE of the site) and Atlantis monitoring stations ($r^2=0.20$; 37 km NNW of the study site), which is a possible contribution from SO₂ local sources (Williams et al., 2021). The Somerset West monitoring station is 6 km SE of the Island harbour, a potential source of primary sulphate from heavy-duty diesel emissions from marine vessels (Williams et al., 2021). The Atlantis monitoring station is about 15 km E from the ocean which can be possible for biogenic SO₂ (Williams et al., 2021). The Goodwood monitoring station is approximately 16.5 km SE from the Cape Town international airport, potentially responsible for the primary sulphate from aircraft and associated vehicles in the airport (Williams et al., 2021).

Table S6 presents the summary statistics for annual values of the nineteen (19) elements (Si, S, Cl, K, Ca, Ti, Fe, Ni, Cu, Zn, U, Pb, Ba, As, Br, Se, Sb, Sr, V and Sr) essential for the source apportionment study. Overall, these trace elements account for 24.9% of the measured PM_{2.5}. S (1.4 µg/m³), Cl (0.5 µg/m³), Si (0.5 µg/m³), Ca (0.3 µg/m³), K (0.2 µg/m³), and Fe (0.2 µg/m³) had higher mean concentrations (Table S6). Studies from Pretoria and Bloemfontein reported similar elements (S, Si, Fe, K and Ca) that made up much of PM_{2.5} mass (Adeyemi et al., 2022; Van der Westhuizen et al., 2022), while Thohoyandou reported different elemental

concentration (Si, Mg, Al, Ti, Pb and Sb) (Novela et al., 2020). The observed abundance in the elemental concentrations across Cape Town, Bloemfontein and Pretoria is influenced by variety of sources in the vicinity and regional long- range transport (Adeyemi et al., 2021; Van der Westhuizen et al., 2022; Williams et al., 2021). The source apportionment study conducted in Pretoria and Vaal Triangle, South Africa identified S as a marker for coal combustion from industries (Adeyemi et al., 2021; Muyemeki et al., 2021). The source apportionment study conducted in Pretoria identified Si, Fe, K and Ca as markers of soil, road, mineral, or construction activities dust (Adeyemi et al., 2021). Some of the K and Fe emissions were attributed to biomass burning and traffic emission, respectively (Van der Westhuizen et al., 2022). S, Si, Ca, Ti, Ni, Cu, Zn, Sr, Sb and Pb mean concentrations did not vary significantly across seasons, days of the week, and weekends/weekdays (Table S6). This implies that these elements were emitted by constant sources with no significant influence of climatic condition or long-range transport (Adeyemi et al., 2021; Gaita et al., 2014; Molnár et al., 2017; Van der Westhuizen et al., 2022; Williams et al., 2021). As, Br, Cl, Fe, and K differed significantly across seasons ($p < 0.005$; Table S7), with high concentration of all metals observed in winter compared to spring, autumn and summer. In Pretoria, Br, Cl, As and K are coal burning markers, mainly used in electricity generation as well as cooking and space heating in household, hence high emission in winter due to more burning of coal/wood for space heating (Adeyemi et al., 2021; Muyemeki et al., 2021). For Cape Town, Cl is also a marker for sea salt emissions (Williams et al., 2021). Increased concentrations of Cl and K were observed in the weekend compared to weekdays ($p < 0.05$; Table S8), possibly attribute to increased usage of electricity or coal for domestic or recreational purposes (Adeyemi et al., 2021). While Fe concentrations differed significantly ($p < 0.05$) across the days of the week (Table S9), indicating that variety of sources contributes to Fe emissions on a daily basis. Fe is attributed to metal works in close vicinity of the study sampling site (Williams et al., 2021). Tshela and Djolov, 2018 identified agricultural or wood burning, ferrochrome smelter and vehicle emission as Fe sources.

3.2. Reconstructed Mass Results

Table 1 reports the annual and seasonal reconstructed mean concentration of PM_{2.5} and its identified chemical composition collected over the 12 months in Cape Town. This methodology reported a mean PM_{2.5} concentration of $13.4 \pm 16.9 \mu\text{g}/\text{m}^3$, like the gravimetric PM_{2.5} mean concentration, reflecting the reliability of the methodology (Benchrif et al., 2022). In the PM_{2.5}

fraction of this study, sulphate (44%; $5.9 \mu\text{g}/\text{m}^3$) contributed more than soil (20.1%; $2.7 \mu\text{g}/\text{m}^3$), light-absorbing carbon (18.7%; $2.5 \mu\text{g}/\text{m}^3$), unexplained particulate fine mass (10.4%; $1.4 \mu\text{g}/\text{m}^3$), sea salt (5.2%; $0.7 \mu\text{g}/\text{m}^3$), or other aerosols (3.7%; $0.5 \mu\text{g}/\text{m}^3$). Using the same methodology, Benchrif et al.(2022), reported particulate organic matter (33%), as the major aerosol component, followed by secondary inorganic aerosols (28%), black carbon (18%), sulphate (17%), mineral dust (9%), sea salt, ammonium, and nitrate (6%) as well as unexplained mass (4%) in Tetouan, Morocco. Spring and winter observed higher concentrations of unmeasured mass. The source apportionment study will clearly illustrate unmeasured mass sources and temporal variations.

Table 1: Mass closure and contributions of different components ($\mu\text{g}/\text{m}^3$) to the total $\text{PM}_{2.5}$ mass in Kraaifontein suburb, Cape Town from 18 April 2017- 16 April 2018

	Fine Mass	Light absorbing carbon	Soil	Ammonium Sulphate	Sea Salt	Other	Unexplained fine mass
Annual	13.4 ± 16.9	2.5 ± 1.9	2.7 ± 2.2	5.9 ± 3.8	0.8 ± 0.9	0.1 ± 0.2	1.4 ± 8.1
Autumn	11.2 ± 16.0	3.1 ± 1.7	3.4 ± 2.8	7.1 ± 4.6	0.5 ± 0.6	0.4 ± 0.2	-3.4 ± 6.2
Winter	16.3 ± 19.4	4.0 ± 2.4	2.9 ± 2.5	4.9 ± 3.3	0.6 ± 0.7	0.6 ± 0.4	3.3 ± 10.2
Spring	17.6 ± 13.7	1.6 ± 1.3	2.3 ± 1.6	5.3 ± 3.8	0.9 ± 0.8	0.3 ± 0.1	7.3 ± 6.1
Summer	9.1 ± 10.5	1.2 ± 0.7	2.1 ± 1.2	6.5 ± 3.4	1.4 ± 0.1	0.3 ± 0.1	-2.3 ± 4.2

3.3. Source identification and apportionment

We began the source apportionment analyses with the complete data set. However, after exploring many solutions between five and ten factors and then re-examined the data. We found that in period from mid-September to mid-November was qualitatively different from the rest of the study period. The unmeasured mass was larger in this period and it was not possible to get a PMF apportionment fit to the mass with an r^2 better than 0.6. There were several species (e.g., Ca, Cu, Fe) that appeared as unique factors, but did not contribute substantially to the mass fit. Thus, after considerable experimentation, we eliminated the data from 12 September 2017 to 14 November 2017. The statistics of the species from the remaining samples included in the analyses are provided in Table S10. The uncertainties for the species were derived from the tables provided by Kim et al. (2005) using the approach of Polissar et al. (1998).

We tested solutions from four to seven factors to determine the appropriate number of factors. The best solution included six factors based on the examination of the scaled residuals, the profiles' interpretability, the contribution time series, and the EPA PMF diagnostics. Table

S11 provides the diagnostics for the chosen 6 factor solution. The identified six source profiles (Figure 1) are traffic, sea salt, sulphate/marine diesel, 2-stroke vehicles/galvanizing, heating/biomass burning/ cooking, and soil/road dust. Figure 2 presents the time series of estimated daily contributions from each source. Figure 3 shows the fit of the PM_{2.5} concentrations derived from the PMF analysis against the measured PM_{2.5}. Figure 4 shows the fractional apportionment of PM_{2.5} mass concentrations to the identified sources. Figure 5 shows the CBPF plots demonstrating the relationships of source contributions with wind direction and wind speed. Table 2 provides the PMF daily mean contribution for PM_{2.5} and sources by trajectory cluster.

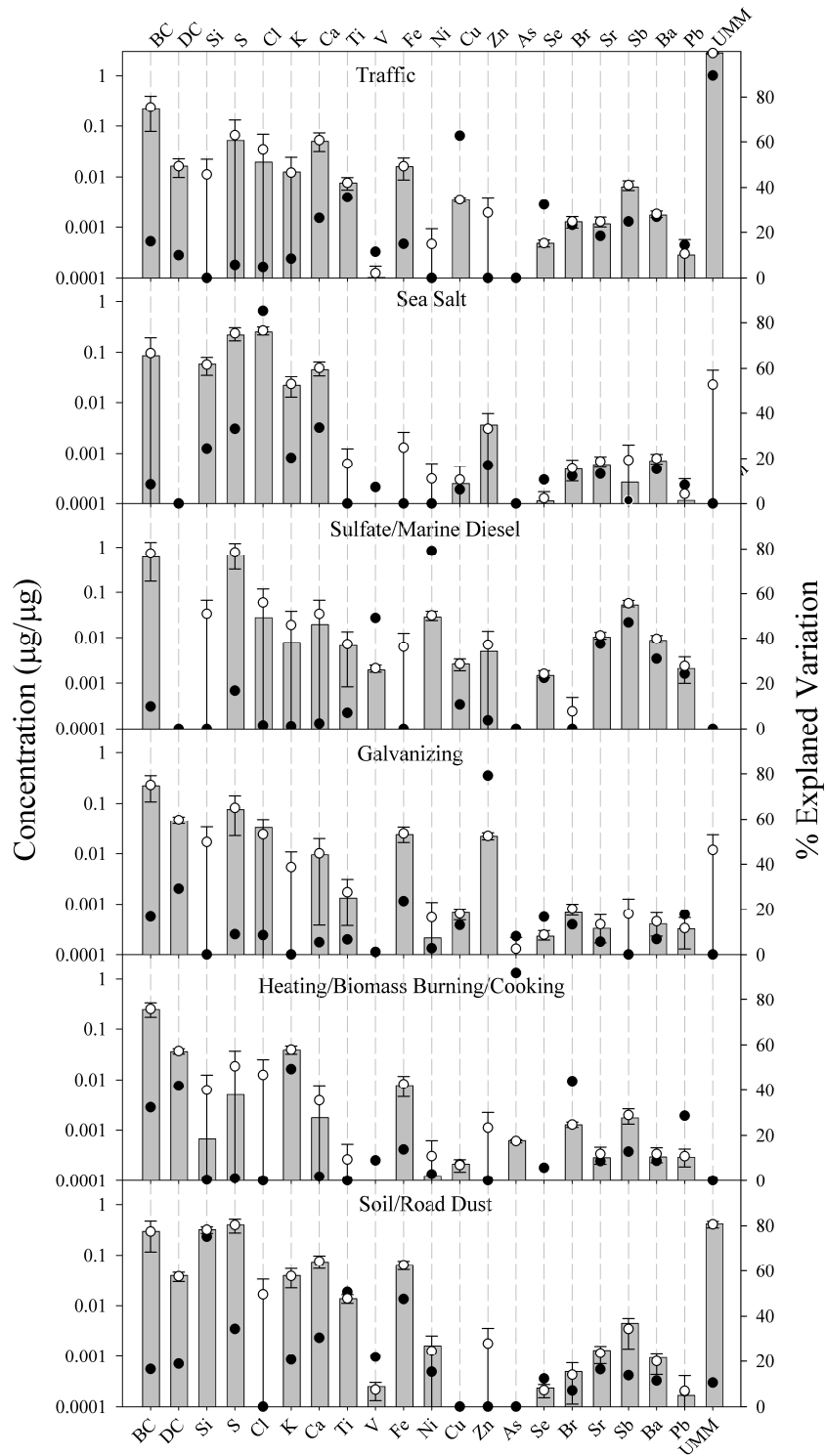


Figure 1: Six identified sources of PM_{2.5} measured at Kraaifontein suburb in Cape Town, South Africa, between 18 April 2017 and 16 April 2018.

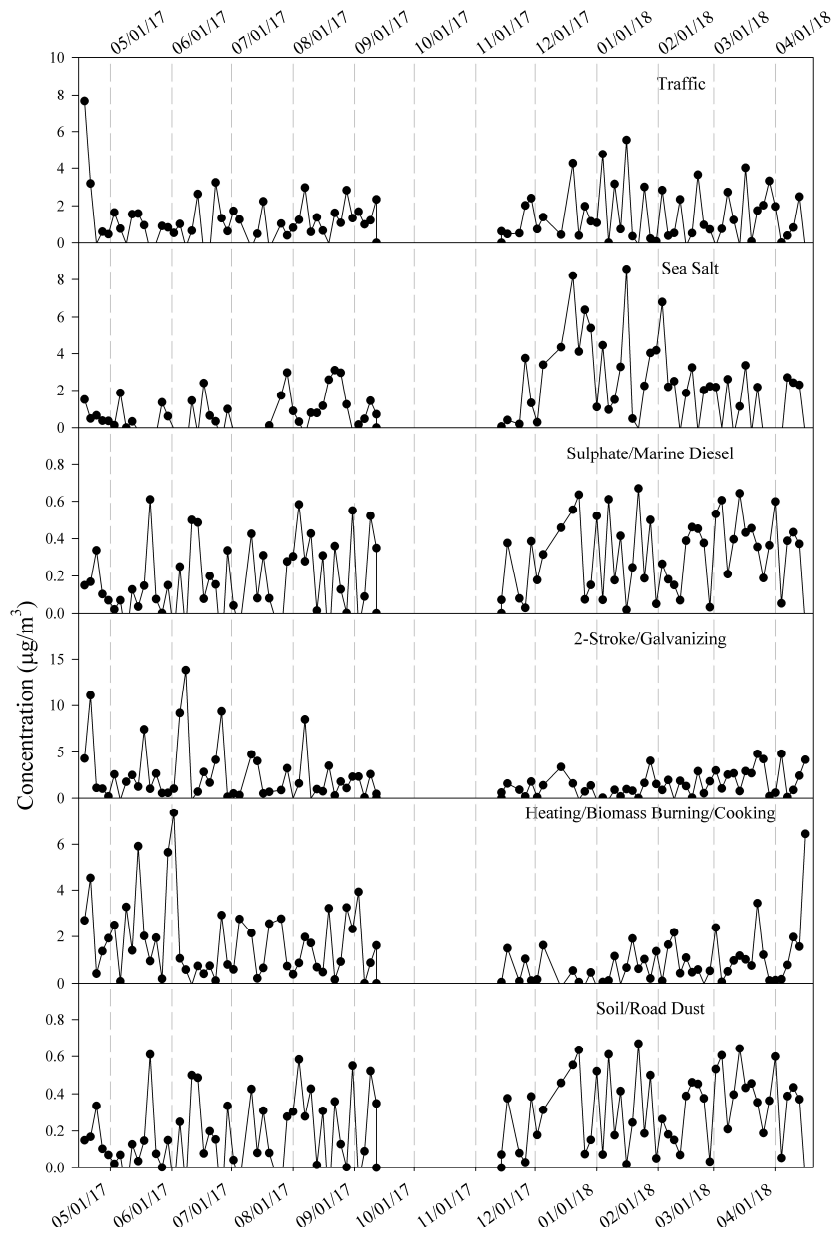


Figure 2: Time-series variations in PM_{2.5} levels of the six identified sources at Kraaifontein suburb in Cape Town, South Africa, between 18 April 2017 and 16 April 2018.

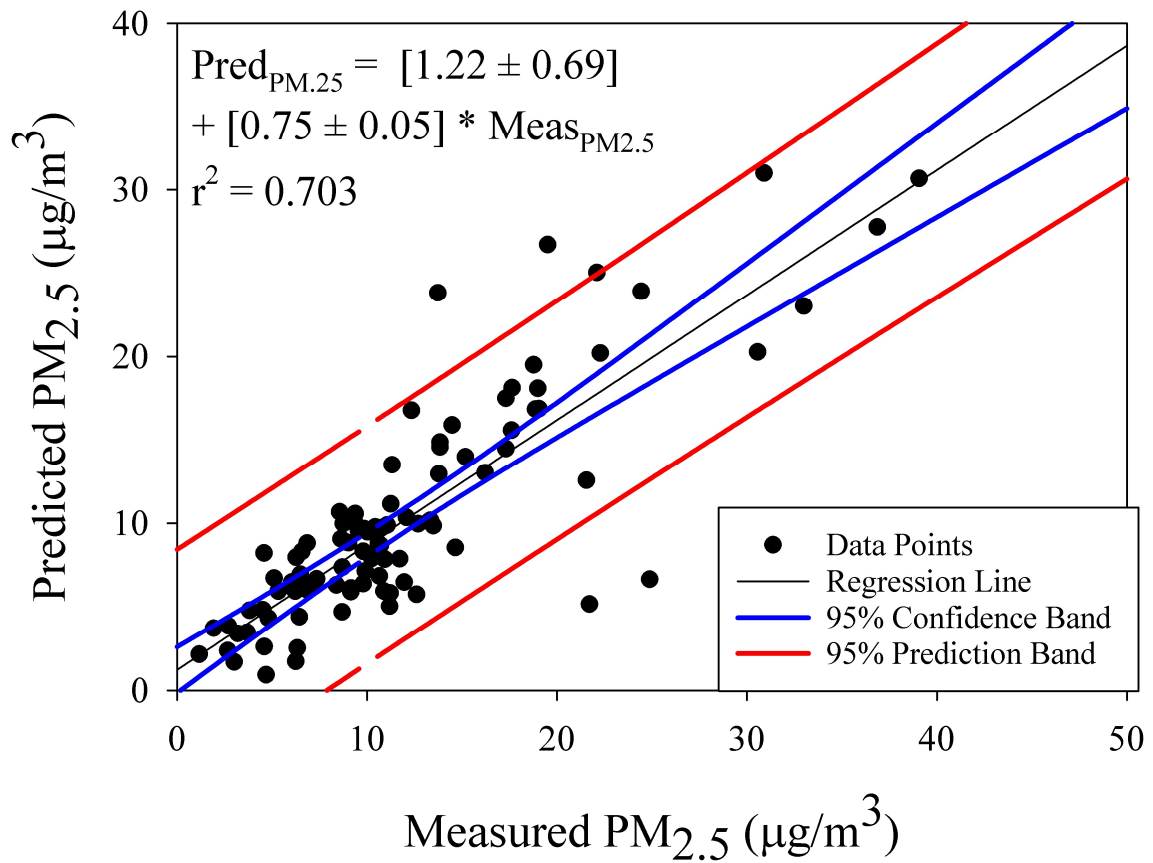


Figure 3. Predicted $\text{PM}_{2.5}$ versus Measured $\text{PM}_{2.5}$ at Kraaifontein suburb in Cape Town, South Africa, between 18 April 2017 and 16 April 2018.

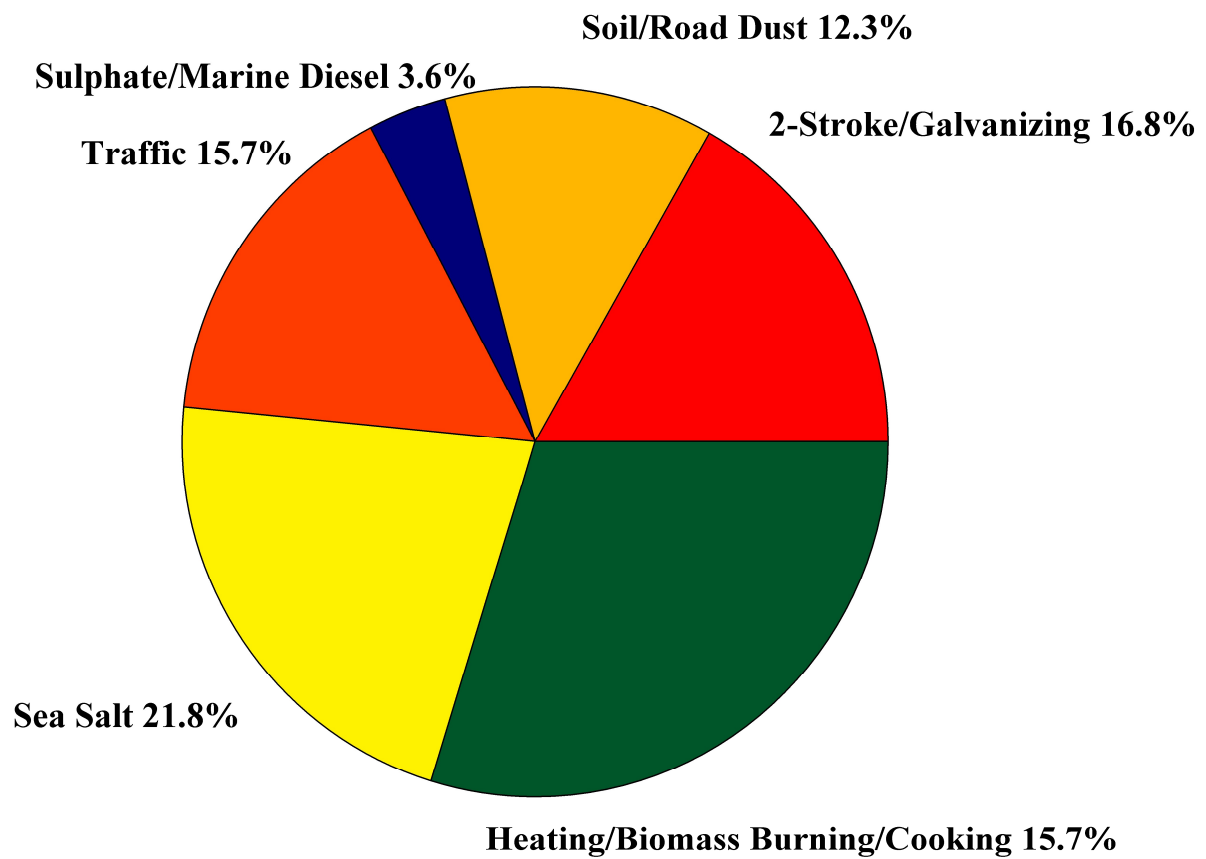


Figure 4: Percentage contribution of the six identified sources to PM_{2.5} at Kraaifontein suburb in Cape Town, South Africa, between 18 April 2017 and 16 April 2018.

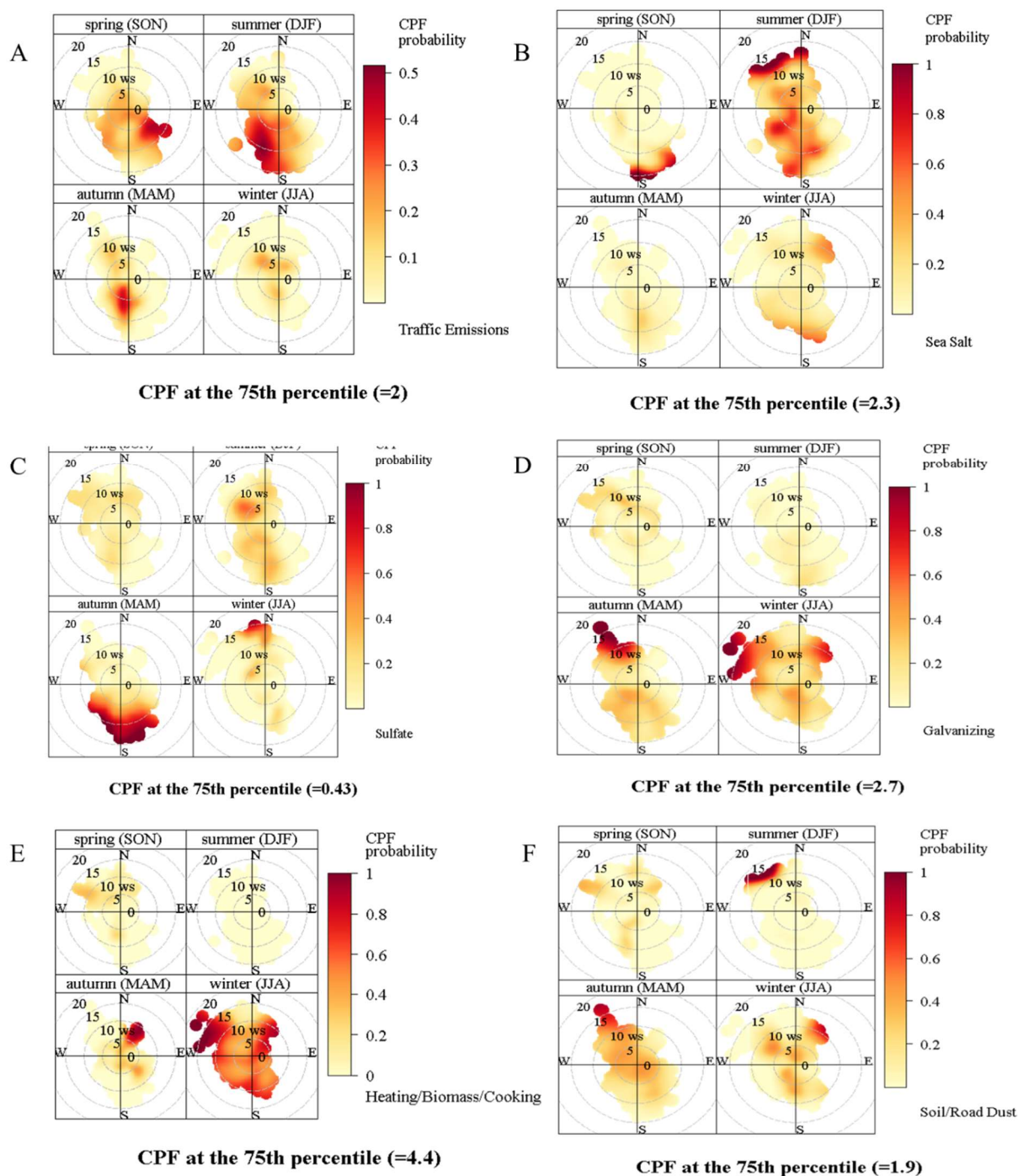


Figure 5: CBPF analysis of seasonal relationships between the six identified source contributions and wind direction to $PM_{2.5}$ at Kraaifontein suburb in Cape Town, South Africa, between 18 April 2017 and 16 April 2018: A) Traffic; B) Sea Salt; C) Sulphate/Marine Diesel; D) 2-Stroke Vehicles/Galvanizing; E) Heating/Biomass/Cooking; F) Soil/Road Dust.

Table 2. Positive Matrix Factorization estimated daily mean concentration for PM_{2.5} and sources by four long-range transport clusters at Kraaifontein suburb in Cape Town, South Africa, between 18 April 2017 and 16 April 2018

Cluster	Traffic	Sea Salt	Sulphate/ Marine Diesel	2-Stroke Vehicles/Galvanizing	Heating	Soil
Indian Ocean	1.22	0.74	0.20	2.29	3.25	2.15
Atlantic WSW	1.22	1.20	0.30	1.78	3.74	1.03
Atlantic SW	1.48	2.42	0.20	1.97	5.06	0.69
Atlantic SSW	1.63	1.16	0.24	2.21	5.71	1.08

3.3.1 Traffic Emissions

The first factor was traffic emission, contributing 15.7% to PM_{2.5} (Fig 4). Traffic emission is a known contributor to PM_{2.5} globally (Anastasopoulos et al., 2022; Benchrif et al., 2022; Kim and Hopke, 2009) and in South Africa (Adeyemi et al., 2021, Muyemeki et al., 2021; Tshela and Djolov., 2018). The traffic factor is characterized by high values of unmeasured mass likely representing nitrate and organic carbon, BC, Fe, Delta-C, and moderate amounts of multiple elements that are associated with tailpipe and non-tailpipe emissions from both light- and heavy-duty vehicles (Fig 1). The presence of high BC and Delta-C are characteristic of diesel and gasoline vehicles (Kim and Hopke, 2004). Delta-C is normally considered as an indicator of biomass burning. However, diesels used to emit considerable OC (Watson et al., 1994) and thus, would have emitted significant amounts of PAH that would contribute to 370 nm BC. The factor also had a high value for unmeasured mass with a small DISP interval, suggesting majority of organic carbonaceous material and nitrate associated with vehicular combustion emissions (Anastasopoulos et al., 2022). Fe suggests brake wear or rail steel abrasion particles (Anastasopoulos et al., 2022; Dai et al., 2023), and Ni, Pb and Ti in this factor suggest the resuspension of contaminated road traffic dust by on road moving vehicles, (Anastasopoulos et al., 2022; Kim and Hopke, 2004). There is no Zn since there is the separate 2-stroke vehicles/galvanizing factor that has most of the explained variation of Zn.

The time series shows that this source portrayed a mild seasonal trend, with slightly elevated contribution to PM_{2.5} in summer (Fig 2), likely due to increased exhaust emission (Anastasopoulos et al., 2022). CBPF plots indicate a local source region to the SW and SE at low windspeed (<15km/h) in summer and spring (Fig 5). The sampling site location was 1km away from the busy N1 freeway road, that could be the nearby source (William et al., 2021). In addition, higher concentration of traffic emission in warmer months could be due to the increase in traffic use, higher volatility of volatile organic compounds and increased photochemical activities leading to more secondary organic aerosol formation (Chen et al.,

2022). Atlantic SSW trajectories transport more traffic emission (Table 2), that is, the direction of downtown Cape Town and Island Harbour to the sampling site.

3.3.2 Sea Salt

The second factor is assigned as sea salt, accounts for 21.8% of PM_{2.5} mass (Fig 4), with high explained variations for Cl, S, Si, K and Ca (Fig 1). It is noteworthy that the sampling site location, somewhat far from the coast (within 25 km from the Atlantic and Indian Oceans) is likely to receive fresh marine sprays that explains the increased Cl concentrations (Williams et al., 2021). This factor showed a consistent moderate seasonality with slightly higher mean contributions to PM_{2.5} in summer (Fig 2). Similarly, the CBPF plots identified a local sources region across seasons, and particularly the summer CBPF plots indicate a local source region at low windspeed (<15 km/hour) to the NW, SW, and SE (Fig 5), attributing to the sea sprays from Atlantic ocean and Indian ocean, respectively (William et al., 2021). Table 2 shows that long range transported air mass from Atlantic ocean SW moderately contributes to this factor more than those from the Indian ocean, Atlantic WSW and Atlantic SSW.

3.3.3 Sulphate/Marine Diesel

This factor is identified as sulphate/marine diesel comprised of primary sulphate from land and marine diesel vehicles (Agarwal et al., 2008a; 2008b; 2009; 2010; Begum and Hopke, 2019) and biogenic sulphate from oxidation of dimethyl sulphide and dimethyl disulphide emitted from marine phytoplankton (Charlson et al., 1987; Sanchez et al., 2021), contributing 3.6% of ambient PM_{2.5} in Cape Town (Fig 4). The sulphate factor is characterized by high loads of S, BC and some V, Ni, Cu, Sr, Sb, Ba and Pb, all with a small DISP interval (Fig 1). BC has a relatively high concentration likely due to the emissions from the ships in port and the heavy-duty diesel engines on the highways between the coast and the sampling site with the winds from the ocean producing the observed covariance. Ni in this factor could be a tracer for residual oil combustion from ships in the harbour (Belis et al., 2013; Anastasopoulos et al., 2023). The time series plot (Fig 2) indicates little seasonal difference, implying active sources contributing to this factor throughout the year. The autumn CBPF plot (Fig 5) identified contributions from SW/SE direction at low-to-high windspeed (5-15 km/h) in autumn. Cape Town experiences nothing to very little SE/SW winds in autumn, possibly negatively impacting the local air transport contributing to this source (William et al., 2021).

Regarding air mass transport, none of the four trajectory clusters (See Figure 2 in Williams et al., 2021) had substantial influence on the sulphate concentrations since all 4 values are very

similar (Table 2). Coal-fired power plants in South Africa are primarily in the northeastern part of the country. Thus, they are in an area where long-range transport to Cape Town has low probabilities. It is likely that the observed sulphate is largely local in origin coming from heavy-duty diesel vehicles on the roads and from emissions from ships entering the port and running their engines while they unload/load passengers or goods as discussed above.

3.3.4 2-Stroke Vehicles/Galvanizing

The factor contributes 16.8% of PM_{2.5} mass (Fig 4). The factor is dominated by Zn, a known marker for 2-stroke vehicles (Chueinta et al., 2000) and galvanizing industries (Begum and Hopke, 2019; Dai et al., 2023). There are also BC and Delta-C concentrations with small DISP intervals and S, Fe, Br, Sr and Ba (Fig 1). The observed Pb is commonly added in the zinc alloy to coat and make galvanized products shiny (Begum and Hopke, 2019; Dai et al., 2023; Kania et al., 2020). Two-stroke vehicles are potential sources of extra BC, Delta-C and Zn appearing in this factor (Chueinta et al., 2000). South Africa is one of the few countries where 2-stroke engines remain in widespread use. This factor showed increased contribution to PM_{2.5} in winter compared to autumn, spring, and summer (Fig 2). The CBPF plot indicates a more distant source region at moderate to high windspeed (10-19 km/h) in the NW direction in winter and autumn (Fig 5).

3.3.5 Heating/Biomass Burning/Cooking

This factor was a major contributor to the modelled mass providing 15.7 % of the average ambient PM_{2.5} concentration (Fig 4). Because of the mild climate, central heating is not commonly present in homes. Thus, solid fuel combustion of wood and/or coal might be used for room heating during the winter. Potassium can also be emitted by cooking. The factor is characterised by the enrichment of K, a marker for biomass combustion, and As and Br species, markers for coal combustion (Adeyemi et al., 2021; Anastasopoulos et al., 2022, Belis et al., 2013; Hopke et al., 2020; Williams et al., 2021), a primary source of energy in South Africa (Adeyemi et al., 2021; Muyemeki et al., 2021). In addition, BC, DC, Fe, Sb, and Pb exhibited a small DISP interval and thus contributed to this factor (Fig 1). As expected, Delta-C, a tracer for residential wood burning, has observed contribution to this source. The substantial proportion of BC implies origins from solid fuel (coal or charcoal) combustion (Benchrif et al., 2022). This factor showed a clear seasonality with much higher mean contributions to PM_{2.5} in winter than all other seasons (Fig 2). This seasonal pattern is

consistent with increased use of coal/wood burning in cold months for indoor residential space heating (Adeyemi et al., 2021; Anastasopoulos et al., 2022; Benchrif et al., 2022). Peak events were observed in winter (Fig 2), that likely reflects local or regional recreational activities (i.e., barbecuing) (Adeyemi et al., 2021; Chen et al., 2022; William et al., 2021), commercial coal burning for industrial energy production and agricultural burning (Adeyemi et al., 2021). The CBPF plots (Fig 5) identified a nearby to distance local source contributing to winter (N/S/E/W, 0-20km/h). The enhancement of biomass burning in winter can be attributed to domestic heating: winter generally experiences poorer dispersion of pollutants due to a low mixing height (Anastasopoulos et al., 2022; Benchrif et al., 2022). Biomass burning was enhanced by long range transport of particles by airmasses from the Atlantic SSW and SW (5.71 and $5.06 \mu\text{g}/\text{m}^3$), Atlantic WSW ($3.74 \mu\text{g}/\text{m}^3$) and Indian ocean ($3.25 \mu\text{g}/\text{m}^3$), that pass-through areas with coal or charcoal burning, making them heavy transporter of biomass burning markers to the receptor site (Tshehla and Djolov, 2018).

3.3.6 Soil and Road Dust

The final factor is labelled as dust, contributing 12.3% of $\text{PM}_{2.5}$ mass (Fig 4). Dust is highly loaded with BC, DC, Si, S, Fe, K, Ca, Ti, UMM and moderate Pb and Sr (Fig 1). Local studies have noted the contribution of soil dust to $\text{PM}_{2.5}$ (Adeyemi et al., 2021; Tshehla and Djolov., 2018). These elements are traditional markers for resuspended or transported crustal soil (Anastasopoulos et al., 2022), mineral dust (Gaita et al., 2014), or road dust (Anastasopoulos et al., 2022; Gaita et al., 2014). The contribution to $\text{PM}_{2.5}$ of 12.3% could be due to non-tailpipe vehicular emissions since soil is generally being observed in coarse particles (Benchrif et al., 2022). The time series plot (Fig 2) shows consistent moderate contribution of this source to $\text{PM}_{2.5}$ throughout the year. Anastasopoulos et al., (2022), observed lower contribution of this source in winter compared to other seasons, attributing it to easier transport and resuspension of soil or road dust particles in warmer and dry months compared to wet and weather. The CBPF plots identified a more distant source region in the NNW/NW at a moderate to high speed (10-19 km/h) in summer and autumn, respectively (Fig 5). Regional transported soil contributions are related to higher windspeeds in this factor with strong north/northwest winds. Long range transport clusters from the Indian ocean ($2.15 \mu\text{g}/\text{m}^3$), Atlantic SSW ($1.08 \mu\text{g}/\text{m}^3$) and Atlantic WSW ($1.03 \mu\text{g}/\text{m}^3$) contribute greatly to this factor (Table 2). This flow likely reflects circulation from the Kalahari Desert in neighbouring Namibia (Bhattachan et al., 2012; 2013).

4. CONCLUSIONS

PM_{2.5} chemical characterization and source apportionment study were carried out in the Kraaifontein sub-urban area of Cape Town city, South Africa using 2017-2018 data. Chemical characterization was achieved using chemical mass closure calculations for the fine size fraction. The PM_{2.5} chemical components were categorized into sulphate, light absorbing carbon, soil dust, and sea salt. The findings of the mass closure method reveal that sulphate (44%), soil (20.1%), light-absorbing carbon (18.7%), unexplained particulate fine mass (11.2%), sea salt (5.2%), and other aerosols (3.7%; 0.5 µg/m³) contribute to PM_{2.5}.

The paper demonstrated that useful source apportionment results could be obtained in the absence of complete chemical composition data with the Positive Matrix Factorization model. The PMF analysis identified primary and secondary sources contributing to observed ambient PM_{2.5} concentrations in Cape Town. Identified source types and average PM_{2.5} contribution were traffic emissions (15.7%), sea salt (21.8%), sulphate/Marine diesel (3.6%), 2-stroke vehicles/galvanizing (16.8%), heating/ biomass burning/cooking (15.7%), and soil/road dust (12.3%).

Biomass burning were consistent with other south African cities and confirmed that coal combustion was the main ingredient for residential cooking, heating, or recreational barbequing events, hence the high winter contribution from this source. Sulphate in Cape Town was mainly associated with primary sulphate from diesel vehicle and biogenic sulphate and methane sulfonic acid from marine phytoplankton, than photochemical reaction of SO₂ from coal combustion industries. Soil and road dust transport and re-suspension, and sea sprays were also important local PM_{2.5} sources in this mediterranean climate city.

Most of the aerosol factors were largely depending on local source (biomass burning/cooking/heating, sea salt, traffic emissions, 2-stroke vehicles/galvanizing industries, and sulphate) with episodic regional source contributions. Thus, combining model indicate that both local and long-range transport strongly influence air quality in Cape Town.

The findings present opportunities for air quality management and source mitigation strategies at different levels of operations. Best practices can be implemented locally to reduce local sources and episodic regional levels of biomass burning, traffic emission, precursor emission of sulphate. Furthermore, recognition and collaboration are needed to address the long-range transport sources of soil and road dust.

Credit Author Statement

Anna Alfeus: Writing- Original draft preparation, Methodology, Formal analysis, Visualisation, Writing- Reviewing and Editing. **Peter Molnar and Johan Boman:** Experimental activity, Data Analysis, Visualization, Writing- Reviewing and Editing. **Phillip Hopke;** Original draft preparation; methodology design, Formal analysis, Validation, Supervision, and Mentoring; Reviewing and Editing; **Janine Wichmann-**Conceptualisation, Methodology design, Financial funding, Supervision, and Mentoring, Reviewing and Editing.

Declaration of 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.

Acknowledgment

This paper results from the PhD thesis of Anna Alfeus. The authors acknowledge the National Research Foundation for South Africa (NRF Grant Ref No.36/2017), University of Namibia Staff Development Office, AGNES grant office for supporting this study. We thank Dr. Joyce Shirinde for the co-supervision of the corresponding author during the Ph.D. studies.

Appendix A. Supplementary data

REFERENCES

- Adeyemi, A., Molnar, P., Boman, J. 2021. Source apportionment of fine atmospheric particles using positive matrix factorization in Pretoria, South Africa. *Environ Monit. Assess.* 193, 716. <https://doi.org/10.1007/s10661-021-09483-3>
- Adeyemi, A., Molnar, P., Boman, J., Wichmann, J. 2022. Particulate matter characterization, air quality level and origin of air masses in an urban background in Pretoria. *Arch Environ Contam Toxicol.* 83, 77–94. <https://doi.org/10.1007/s00244-022-00937-4>
- Agrawal, H., Malloy, Q., Welch, W.A., Miller, J.W., Cocker, D.R., 2008a. In-use gaseous and particulate matter emissions from a modern oceangoing container vessel. *Atmos. Environ.* 42, 5504–5510. <https://doi.org/10.1016/j.atmosenv.2008.02.053>.
- Agrawal, H., Welch, W.A., Miller, J.W., Cocker, D.R., 2008b. Emission measurements from a crude oil tanker at sea. *Environ. Sci. Technol.* 42, 7098–7103.

<https://doi.org/10.1021/es703102y>.

- Agrawal, H., Eden, R., Zhang, X., Fine, P.M., Katzenstein, A., Miller, J.W., Ospital, J., Teffera, S., Cocker III, D.R., 2009. Primary particulate matter from ocean-going engines in the Southern California air basin. *Environ. Sci. Technol.* 43, 5398–5402. <https://doi.org/10.1021/es8035016>.
- Agrawal, H., Welch, W.A., Henningsen, S., Miller, J.W., Cocker III, D.R., 2010. Emissions from main propulsion engine on container ship at sea. *J. Geophys. Res.* 115, D23205. <https://doi.org/10.1029/2009JD013346>.
- Alfeus, A., Molnar, P., Boman, J., Shirinde, J., Wichmann, J. 2022. Inhalation health risk assessment of ambient PM_{2.5} and associated trace elements in Cape Town, South Africa. *Human.Ecol. Risk. Assess. Intern. J.* 28, 917–929. <https://doi.org/10.1080/10807039.2022.2110449>
- Anastasopoulos, A.T., Hopke, P.K., Sofowote, U.M., Zhang, J.J.Y., Johnson, M. 2022. Local and regional sources of urban ambient PM_{2.5} exposures in Calgary, Canada. *Atmos. Environ.* 290, 119383. <https://doi.org/10.1016/j.atmosenv.2022.119383>.
- Anastasopoulos, A.T., Hopke, P.K., Sofowote, U.M., Mooibroek, D., Zhang, J.J.Y., Rouleau, M., Peng, H., Sundar, N., 2023. Evaluating the effectiveness of low-sulphur marine fuel regulations at improving urban ambient PM_{2.5} air quality: Source apportionment of PM_{2.5} at Canadian Atlantic and Pacific coast cities with implementation of the North American Emissions Control Area. *Sci. Total Environ.* 904, 166965. <https://doi.org/10.1016/j.scitotenv.2023.166965>.
- Bhattachan, A., D'Odorico, P., Baddock, M.C., Zobeck, T.M., Okin, G.S., Cassar, N. 2012. The Southern Kalahari: a potential new dust source in the Southern Hemisphere? *Environ. Res. Lett.* 7, 024001
- Bhattachan, A., D'Odorico, P., Okin, G. S., Dintwe, K., 2013. Potential dust emissions from the southern Kalahari's dunelands, *J. Geophys. Res. Earth Surf.* 118, 307– 314, doi:[10.1002/jgrf.20043](https://doi.org/10.1002/jgrf.20043).
- Begum, B. A., Hopke, P. K., 2019. Identification of sources from chemical characterization of fine particulate matter and assessment of ambient air quality in Dhaka, Bangladesh. *Aerosol Air Qual. Res.* 19(1), 118–128. <https://doi.org/10.4209/aaqr.2017.12.0604>
- Belis, C. A., Karagulian, F., Larsen, B. R., Hopke, P. K., 2013. Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe. *Atmos Environ.* 69, 94-108. <https://doi.org/10.1016/j.atmosenv.2012.11.009>
- Benchrif, A., Tahri, M., Guinot, B., Chakir, E. M., Zahry, F., Bagdhad, B., Bounakhla, M., Cachier, H., Costabile, F., 2022. Aerosols in Northern Morocco-2: Chemical Characterization and PMF Source Apportionment of Ambient PM_{2.5}. *Atmos*, 13, 1701.
- Bond, T. C., Doherty, S. J., Fahey, D.W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C.M., Schultz, G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., Zender, C. S., 2013. Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res. Atmos.* 118, 1-173. <https://doi.org/10.1002/jgrd.50171>

- Brown, S. G., Eberly, S., Paatero, P., Norris, G. A., 2015. Methods for estimating uncertainty in PMF solutions: Examples with ambient air and water quality data and guidance on reporting PMF results. *Sci. Total Environ*, 518, 626-635. <https://doi.org/10.1016/j.scitotenv.2015.01.022>
- Cardoso, J., Almeida, S. M., Nunes, T., Almeida-Silva, M., Cerqueira, M., Alves, C., Rocha, F., Chaves, P., Reis, M., Salvador, P., Artiñano, B., Pio, C., 2018. Source apportionment of atmospheric aerosol in a marine dusty environment by ionic/composition mass balance (IMB). *Atmos. Chem. Phys.* 18(17), 13215–13230. [10.5194/acp-18-13215-2018](https://doi.org/10.5194/acp-18-13215-2018)
- Charlson, R. J., Lovelock, J. E., Andreae, M. O., Warren, S.G. 1987., Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature*. 326, 655–661. <https://doi.org/10.1038/326655a0>
- Chen, Y., Rich, D. Q., Hopke, P. K., 2022. Long-term PM_{2.5} source analyses in New York City from the perspective of dispersion normalized PMF. *Atmos. Environ.* 272, 118949. <https://doi.org/10.1016/j.atmosenv.2022.118949>
- Chueinta, W., Hopke, P.K., Paatero, P., 2000. Investigation of sources of atmospheric aerosol at urban and suburban residential areas in Thailand by positive matrix factorization. *Atmos Environ.* 34, 3319–3329. [https://doi.org/10.1016/S1352-2310\(99\)00433-1](https://doi.org/10.1016/S1352-2310(99)00433-1)
- Dai, Q., Bi, X., Song, W., Li, T., Liu, B., Ding, J., Xu, J., Song, C., Yang, N., Schulze, B. C., 2019. Residential coal combustion as a source of primary sulphate in Xi'an, China. *Atmos Environ.* 196, 66–76. <https://doi.org/10.1016/j.atmosenv.2018.10.002>
- Dai, Q., Liu, B., Bi, X., Wu, J., Liang, D., Zhang, Y., Feng, Y., Hopke, P. K., 2020. Dispersion normalized PMF provides insights into the significant changes in source contributions to PM_{2.5} after the COVID-19 outbreak. *Environ Sci Technol.* 54, 9917–9927. <https://doi.org/10.1021/acs.est.0c02776>
- Dai, Q., Ding, J., Song, C., Liu, B., Bi, X., Wu, J., Zhang, Y., Feng, Y., Hopke, P. K., 2021. Changes in source contributions to particle number concentrations after the COVID-19 outbreak: Insights from a dispersion normalized PMF. *Sci. Total Environ.* 759, 143548. <https://doi.org/10.1016/j.scitotenv.2020.143548>
- Dai, Q.L., Chen, J.J., Wang, X.H., Dai, T.J., Tian, T.Z., Bi, X.H., Shi, G.L., Wu, J.H., Liu, B.S., Zhang, Y.F., Yan, B.Z., Kinney, P.L., Feng, Y.C., Hopke, P.K., 2023. Trends of source apportioned PM_{2.5} in Tianjin over 2013–2019: impacts of clean air actions. *Environ. Pollut.* 325, 121344. <https://doi.org/10.1016/j.envpol.2023.121344>
- Department of Environmental Affairs, 2012. National ambient air quality standard for particulate matter with aerodynamic diameter less than 2.5 micron metres (PM_{2.5}). *Gov Gazette*, GN35463(NN486), 7–9.
- Department of Environmental Affairs and Development Planning, 2021. Western Cape Air Quality Management Plan. https://www.westerncape.gov.za/eadp/sites/eadp.westerncape.gov.za/files/atoms/files/AQMP%202021_Web_1.pdf
- Department of Planning, Monitoring and Evaluation, State of Air Report 2005. 1–249. <https://evaluations.dpme.gov.za/evaluations/102>
- Doumbia, T., Liousse, C., Ouafou-Leumbe, M. R., Ndiaye, S. A., Gardrat, E., Galy-Lacaux,

- C., Zouiten, C., Yoboué, V., Granier, C., 2023. Source Apportionment of Ambient Particulate Matter (PM) in Two Western African Urban Sites (Dakar in Senegal and Bamako in Mali). *Atmos.* 14, 684. <https://doi.org/10.3390/atmos14040684>
- Du Venage, G., 2019. Vedanta Zinc Starts Gamsberg Mine. *Engin. Min J.* 220(4), 18-18.
- Edlund, K. K., Killman, F., Molnár, P., Boman, J., Stockfelt, L., Wichmann, J. 2021., Health risk assessment of PM_{2.5} and PM_{2.5}-bound trace elements in Thohoyandou, South Africa. *Int. J. Environ. Res. Public Health.* 18, 1–12. <https://doi.org/10.3390/ijerph18031359>
- Feigin, V. L., Stark, B. A., Johnson, C. O., Roth, G. A., Bisignano, C., Abady, G. G., Abbasifard, M., Abbasi-Kangevari, M., Abd-Allah, F., Abedi, V. and Abualhasan, A., 2021. Global, regional, and national burden of stroke and its risk factors, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet Neurology*, 20, 795-820. [https://doi.org/10.1016/S1474-4422\(21\)00252-0](https://doi.org/10.1016/S1474-4422(21)00252-0)
- Gaita, S. M., Boman, J., Gatari, M. J., Pettersson, J. B. C., Janhäll, S., 2014. Source apportionment and seasonal variation of PM_{2.5} in a sub-Saharan African city: Nairobi, Kenya. 14, 9977–9991. *Atmos. Chem. Phys.* <https://doi.org/10.5194/acp-14-9977-2014>
- Gatari, M. J., Boman, J., Wagner, A., 2009. Characterization of aerosol particles at an industrial background site in Nairobi, Kenya. *X-Ray. Spectro. Intern. J.* 38, 37–44. <https://doi.org/10.1002/xrs.1097>
- Gu, Y., Liu, B., Dai, Q., Zhang, Y., Zhou, M., Feng, Y., Hopke, P. K., 2022. Multiply improved positive matrix factorization for source apportionment of volatile organic compounds during the COVID-19 shutdown in Tianjin, China. *Environ Intern*, 158, 106979. <https://doi.org/https://doi.org/10.1016/j.envint.2021.106979>
- Hopke, P. K., 2016. Review of receptor modeling methods for source apportionment. *J. Air Waste Manage. Assoc.* 66, 237–259. <https://doi.org/10.1080/10962247.2016.1140693>
- Hopke, P.K., Ramadan, Z., Paatero, P., Norris, G.A., Landis, M.S., Williams, R.W., Lewis, C.W., 2003. Receptor modeling of ambient and personal exposure samples: 1998 Baltimore Particulate Matter Epidemiology-Exposure Study. *Atmos. Environ.* 37, 3289–3302. [https://doi.org/10.1016/S1352-2310\(03\)00331-5](https://doi.org/10.1016/S1352-2310(03)00331-5)
- Hopke, P. K., Dai, Q., Li, L., Feng, Y., 2020. Global review of recent source apportionments for airborne particulate matter. *Sci. Total Environ.* 740, 140091. <https://doi.org/10.1016/j.scitotenv.2020.140091>
- Hopke, P. K., Feng, Y., Dai, Q., 2022. Source apportionment of particle number concentrations: A global review. *Sci. Total Environ.* 819, 153104. <https://doi.org/10.1016/j.scitotenv.2022.153104>
- Howlett-Downing, C., Boman, J., Molnár, P., Shirinde, J., Wichmann, J., 2022. PM_{2.5} chemical composition and geographical origin of air masses in Pretoria, South Africa. *Water Air Soil Pollut.* 233, 271. <https://doi.org/10.1007/s11270-022-05746-y>
- Jacobson, M. Z., 2001. Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature.* 409, 695–697. <https://doi.org/10.1038/35055518>
- Janssen, N. A. H., Gerlofs-Nijland, M. E., Lanki, T., Salonen, R. O., Cassee, F., Hoek, G., Fischer, P., Brunekreef, B., Krzyzanowski, M., 2012. Health effects of black carbon. World Health Organization. Regional Office for Europe. <https://www.who.int/europe/publications/i/item/9789289002653>.

- Joint Research Centre (JRC), 2014. Institute for Environment and Sustainability, Viana, M., Belis, C., Vecchi, R. et al., *European guide on air pollution source apportionment with receptor models*, Publications Office, <https://data.europa.eu/doi/10.2788/9307>
- Kania H, Mendala J, Kozuba J, Saternus M., 2020. Development of Bath Chemical Composition for Batch Hot-Dip Galvanizing—A Review. *Materials*. 13, 4168. <https://doi.org/10.3390/ma13184168>
- Kalenga, J., & Akande, J. M., 2021. Determination of Airways Resistance, Volumetric Efficiency and Development of Ventilation Model of Rosh Pinah Zinc Mine Namibia. *J. Miner. Mater. Charact. Engin.* 9(2), 194-205. <https://doi.org/10.4236/jmmce.2021.92014>
- Kim, E., Hopke, P.K., 2004. Source apportionment of fine particles at Washington, DC, utilizing temperature-resolved carbon fractions. *J. Air Waste Manage. Assoc.* 54, 773–785. <https://doi.org/10.1080/10473289.2004.10470948>.
- Kim, E., Hopke, P.K., Qin, Y., 2005. Estimation of Organic Carbon Blank Values and Error Structures of the Speciation Trends Network Data for Source Apportionments; *J. Air & Waste Manage. Assoc.* 55, 1190-1199.
- Klopper, D., Formenti, P., Namwoonde, A., Cazaunau, M., Chevaillier, S., Feron, A., Gaimoz, C., Hease, P., Lahmidi, F., Mirande-Bret, C., Triquet, S., Zeng, Z., Piketh, S.J., 2020. Chemical composition and source apportionment of atmospheric aerosols on the Namibian coast. *Atmos. Chem. Phys.* 20, 15811–15833. <https://doi.org/10.5194/acp-20-15811-2020>
- Kruskal, W.H., Wallis, W.A., 1952. Use of ranks in one-criterion variance analysis. *J. Am. Stat. Assoc.* 47, 583–621. <https://doi.org/10.1080/01621459.1952.10483441>
- Maenhaut, W., Salma, I., Cafmeyer, J., Annegarn, H.J., Andreae, M.O., 1996. Regional atmospheric aerosol composition and sources in the eastern Transvaal, South Africa, and impact of biomass burning. *J Geophys Res* 101, 23,632-23,650. <https://doi.org/10.1029/95JD02930>
- Malm, W. C., Sisler, J. F., Huffman, D., Eldred, R. A., Cahill, T. A., 1994. Spatial and seasonal trends in particle concentration and optical extinction in the United States. *J. Geophys. Res. Atmos.* 99(D1), 1347–1370. <https://doi.org/10.1029/93JD02916>
- Mason, B.H., 1966. *Principles of Geochemistry*, 3rd Edition, J. Wiley & Sons, New York, pp. 329.
- Mmari, A. G., Hassan, H. A., Bencs, L., 2020. Daytime concentrations of minor and trace elements in atmospheric aerosols at four sampling sites of Dar es Salaam, Tanzania. *Air. Qual. Atmos. Health.* 13, 739–750. <https://doi.org/10.1007/s11869-020-00832-8>
- Moeletsi, M. E. 2021., Socio-economic barriers to adoption of electric vehicles in South Africa: Case study of the Gauteng province. *World Elec Veh J.*12, 167.
- Molnár, P., Tang, L., Sjöberg, K., Wichmann, J., 2017. Long-range transport clusters and positive matrix factorization source apportionment for investigating transboundary PM_{2.5} in Gothenburg, Sweden. *Environ. Sci. Processes. Impacts.* 19, 1270-1277. <https://doi.org/10.1039/c7em00122c>
- Muyemeki, L., Burger, R., Piketh, S. J., Language, B., Beukes, J. P., Van Zyl, P. G., 2021. Source apportionment of ambient PM_{10-2.5} and PM_{2.5} for the Vaal Triangle, South Africa. *S. Afr. j. Sci.*117, 1–11. <https://doi.org/10.17159/SAJS.2021/8617>

- Novela, R. J., Gitari, W. M., Chikoore, H., Molnar, P., Mudzielwana, R., Wichmann, J., 2020. Chemical characterization of fine particulate matter, source apportionment and long-range transport clusters in Thohoyandou, South Africa. *Clean Air J.* 30, 1–12 <http://dx.doi.org/10.17159/caj/2020/30/2.8735>.
- Odediran, E. T., Adeniran, J. A., Yusuf, R. O., Abdulraheem, K. A., Adesina, O. A., Sonibare, J. A., Du, M., 2021. Contamination levels, health risks and source apportionment of potentially toxic elements in road dusts of a densely populated African City. *Environ. Nanotechnol. Monit. Manag.* 15, 100445. <https://doi.org/10.1016/j.enmm.2021.100445>
- Orellano, P., Reynoso, J., Quaranta, N., Bardach, A., Ciapponi, A., 2020. Short-term exposure to particulate matter (PM₁₀ and PM_{2.5}), nitrogen dioxide (NO₂), and ozone (O₃) and all-cause and cause-specific mortality: Systematic review and meta-analysis. *Environ. Int.* 142, 105876. <https://doi.org/10.1016/j.envint.2020.105876>
- Orogade, S. A., Owoade, K. O., Hopke, P. K., Adie, D. B., Ismail, A., Okuofu, C. A., 2016. Source apportionment of fine and coarse particulate matter in industrial areas of Kaduna, Northern Nigeria. *Aerosol Air Qual. Res.* 16, 1179–1190. <https://doi.org/10.4209/aaqr.2015.11.0636>
- Owoade, K. O., Hopke, P. K., Olise, F. S., Adewole, O. O., Ogundele, L. T., Fawole, O. G., (2016). Source apportionment analyses for fine (PM_{2.5}) and coarse (PM_{2.5-10}) mode particulate matter (PM) measured in an urban area in southwestern Nigeria. *Atmos. Pollut. Res.* 7, 843–857. <https://doi.org/10.1016/j.apr.2016.04.006>
- Paatero, P., 1997. Least squares formulation of robust non-negative factor analysis. *Chemom. Intell. Lab. Syst.* 37, 23–35. [https://doi.org/10.1016/S0169-7439\(96\)00044-5](https://doi.org/10.1016/S0169-7439(96)00044-5)
- Paatero, P., Eberly, S., Brown, S.G., Norris, G.A., 2014. Methods for estimating uncertainty in factor analytic solutions. *Atmos. Meas. Tech.* 7, 781–797. <https://doi.org/10.5194/amt-7-781-2014>
- Paatero, P., Tapper, U., 1994. Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values. *Environmetrics.* 5, 111–126. <https://doi.org/10.1002/env.3170050203>
- Polissar, A.V., Hopke, P.K., Paatero, P., Malm, W.C., Sisler, J.F., 1998. Atmospheric aerosol over Alaska 2. Elemental composition and sources. *J. Geophys. Res.* 103, 19045–19057. <https://doi.org/10.1029/98JD01212>
- Rahn, K.A., 1976. Silicon and aluminum in atmospheric aerosols: crust-air fractionation? *Atmos. Environ.* (1967), 10, 597–601. [https://doi.org/10.1016/0004-6981\(76\)90044-5](https://doi.org/10.1016/0004-6981(76)90044-5).
- Sanchez, K. J., Zhang, B., Liu, H., Saliba, G., Chen, C.-L., Lewis, S. L., Russell, L. M., Shook, M. A., Crosbie, E. C., Ziemba, L. D., Brown, M. D., Shingler, T. J., Robinson, C. E., Wiggins, E. B., Thornhill, K. L., Winstead, E. L., Jordan, C., Quinn, P. K., Bates, T. S., Porter, J., Bell, T. G., Saltzman, E. S., Behrenfeld, M. J., and Moore, R. H., 2021, Linking marine phytoplankton emissions, meteorological processes, and downwind particle properties with FLEXPART, *Atmos. Chem. Phys.*, 21, 831–851. <https://doi.org/10.5194/acp-21-831-2021>
- Santoso, M., P.K. Hopke, A. Hidayat, and L.D. Dwiana., 2008. Sources identification of the atmospheric aerosol at urban and suburban sites in Indonesia by positive matrix factorization. *Sci Total Environ.* 397, 229–38. doi:10.1016/j.scitotenv.2008.01.057

- Sofowote, U. M., Healy, R. M., Su, Y., Deboasz, J., Noble, M., Munoz, A., Jeong, C.-H., Wang, J. M., Hilker, N., Evans, G. J., Brook, J. R., Lu, G., Hopke, P. K., 2021. Sources, variability and parameterizations of intra-city factors obtained from dispersion-normalized multi-time resolution factor analyses of PM_{2.5} in an urban environment. *Sci. Total Environ.* 761, 143225. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.143225>
- Song, L., Dai, Q., Feng, Y., Hopke, P. K., 2021. Estimating uncertainties of source contributions to PM_{2.5} using moving window evolving dispersion normalized PMF. *Environ. Pollut.* 286, 117576. <https://doi.org/https://doi.org/10.1016/j.envpol.2021.117576>
- Soriano, J. B., Kendrick, P. J., Paulson, K. R., Gupta, V., Abrams, E. M., Adedoyin, R. A., Adhikari, T.B., Advani, S.M., Agrawal, A., Ahmadian, E., Alahdab, F and the GBD Chronic Respiratory Disease Collaborators., 2020. Prevalence and attributable health burden of chronic respiratory diseases, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet Respir Med.* 8, 585-596. [https://doi.org/10.1016/S2213-2600\(20\)30105-3](https://doi.org/10.1016/S2213-2600(20)30105-3)
- Sulaymon, I.D., Mei, X., Yang, S., Chen, S., Zhang, Y., Hopke, P.K., Schauer, J.J., Zhang, Y., 2020. PM_{2.5} in Abuja, Nigeria: chemical characterization, source apportionment, temporal variations, transport pathways and the health risks assessment. *Atmos. Res.* 237, 104833. <https://doi.org/10.1016/j.atmosres.2019.104833>
- Tefera, W., Kumie, A., Berhane, K., Gilliland, F., Lai, A., Sricharoenvech, P., Patz, J., Samet, J., Schauer, J. J., 2021. Source Apportionment of Fine Organic Particulate Matter (PM_{2.5}) in Central Addis Ababa, Ethiopia. *Int. J. Environ. Res. Public Health.* 18, 11608. <https://doi.org/10.3390/ijerph182111608>
- Tshehla, C., Djolov, G., 2018. Source profiling, source apportionment and cluster transport analysis to identify the sources of PM and the origin of air masses to an industrialised rural area in Limpopo. *Clean Air J.* 28, 54–66. <https://doi.org/10.17159/2410-972X/2018/v28n2a18> <http://ojs.uj.ac.za/index.php/CAJ/article/view/11980>
- Turner, E., Malicier, V., 2022. *South Africa deferring tighter fuel specs could prop up refineries.* S&P Global commodity insight (Accessed November 2023). <https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/petrochemicals/071222-south-africa-deferring-tighter-fuel-specs-could-prop-up-refineries>
- Walton, N.M., Piketh, S.J., Zyl, P., Maenhaut, W., Burger, R., Formenti, P., 2021. Source apportionment of ambient fine and coarse aerosols in Embalenhle and Kinross, South Africa. *Clean Air J.* 31, 1-13. <http://dx.doi.org/10.17159/caj/2020/31/2.11980>
- Wang, Y., Hopke, P.K., Rattigan, O.V., Xia, X., 2011. Characterization of residential wood combustion particles using the two-wavelength aethalometer. *Environ. Sci. Technol.* 45, 7387-7393. <https://doi.org/10.1021/es2013984>
- Wang, Y., Hopke, P. K., Rattigan, O. V, Chalupa, D. C., Utell, M. J., 2012. Multiple-year black carbon measurements and source apportionment using Delta-C in Rochester, New York. *J. Air Waste Manage. Assoc.* 62, 880–887. <https://doi.org/10.1080/10962247.2012.671792>
- Watson, J.G.; Chow, J.C.; Lowenthal, D.H.; Pritchett, L.C.; Frazier, C.A.; Neuroth, G.R.; and Robbins, R., 1994. Differences in the carbon composition of source profiles for

- diesel- and gasoline-powered vehicles. *Atmos. Environ.*, 28, 2493-2505.
- WHO, 2013. Review of evidence on health aspects of air pollution – REVIHAAP Project: Technical Report. World Health Organization. <https://doi.org/10.1007/BF00379640>
- WHO, 2021. WHO Global Air Quality Guidelines. Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulphur dioxide and carbon monoxide. World Health Organization
- Wilcoxon, F., 1945. Individual comparisons by ranking methods. *Biometrics Bull.* 1, 80–83. <https://cir.nii.ac.jp/crid/1571980074214430976>
- Williams, J., Petrik, L., Wichmann, J., 2021. PM_{2.5} chemical composition and geographical origin of air masses in Cape Town, South Africa. *Air Qual Atmos Health.* 14, 431–442. <https://doi.org/10.1007/s11869-020-00947-y>
- Xie, Y., Posada, F., & Sen, A., 2022. Soot-free Road transport in South Africa: A cost-benefit analysis of Euro VI heavy-duty vehicle standards.
- Zhao, W., Hopke, P.K., Zhou, L., 2007. Spatial distribution of source locations for particulate nitrate and sulphate in the upper-midwestern United States. *Atmos. Environ.* 41, 1831–1847. <https://doi.org/10.1016/j.atmosenv.2006.10.060>
- Zhou, C., Liu, P., Huang, G., Lin, J., Hu, K., Chen, L., Wang, J., Li, S., Wang, S., Ni, R., 2020. The impact of secondary inorganic aerosol emissions change on surface air temperature in the Northern Hemisphere. *Theor Appl Climatol.* 141, 857–868. <https://doi.org/10.1007/s00704-020-03249-6>
- Zhou, Z., Dionisio, K. L., Verissimo, T. G., Kerr, A. S., Coull, B., Howie, S., Arku, R. E., Koutrakis, P., Spengler, J. D., Fornace, K., 2014. Chemical characterization and source apportionment of household fine particulate matter in rural, peri-urban, and urban West Africa. *Environ. Sci. Technol.* 48(2), 1343–1351. <https://doi.org/10.1021/es404185m>