GÖTEBORGS UNIVERSITET

INSTITUTIONEN FÖR BIOLOGI OCH MILJÖVETENSKAP

SOURCE APPORTIONMENT OF PM2.5 POLLUTION IN LAGOS, NIGERIA

Johanna Olsson

Degree of Bachelor of Science with a Major in Environmental Science

ES1505, Examination Course in Environmental Science, 15 hec

Basic level

Term/year: Spring 2025

Supervisor: Jan Pettersson, Department of Chemistry and Molecular Biology

Examiner: Erik Thomson, Department of Chemistry and Molecular Biology

ABSTRACT

This study presents a source apportionment of fine particulate matter (PM2.5) in the megacity of Lagos, Nigeria. The study took place from the beginning of January to the middle of March 2025, encompassing air pollution during the months of the dry season, characterised by Harmattan winds. The aim was to explore the level of PM2.5 and to better understand the air pollution in Lagos by doing source apportionment. A total of sixty 24-hour filters were collected by people at the University of Lagos and sent to Gothenburg. The PM2.5 was determined gravimetrically, and the elemental composition was analysed using an optical transmissometer and an Energy Dispersive X-Ray Fluorescence (EDXRF) instrument. The resulting data were then analysed through correlation analysis and by performing Positive Matrix Factorisation on the data for the source apportionment.

Twenty-two elements were detected and quantified: Al, P, S, Cl, K Ca, Ti, V, Mn, Fe, Cu, Zn, Ga, As, Se, Br, Sr, Y, Ba, Hg, Pb, and Si, along with black carbon (BC) and ultraviolet-absorbing particulate matter (UVPM). The average PM2.5 level was found to be 37 ± 24 μg/m³, exceeding the WHO 24-hour guideline of 15 μg/m³. Identified sources included mineral dust, combustion of petroleum products and vehicular emissions, biomass burning, sea salt, steel industry, and a V-rich source. Among these, mineral dust and the factor for combustion of petroleum products + vehicular emissions were the dominant contributors to PM2.5 mass. There was a discrepancy between the reconstructed mass and the total mass of PM2.5, suggesting that additional PM2.5 components not detectable by the instruments used may also be present. Improvements for further studies would be to have a larger data set, include meteorological data, and a broader range of chemical species to improve source identification and mass reconstruction.

ABSTRAKT (SE)

Denna studie presenterar en källfördelningsanalys för fina partiklar (PM2.5) i megastaden Lagos, Nigeria. Insamlingen av prover pågick från början av januari till mitten på mars 2025, och omfattar undersökning av luftkvalitet under den torra säsongen som karaktäriseras av Harmattan vind. Syftet var att undersöka nivåer av PM2.5 och skapa bättre förståelse för förorenad luft i Lagos genom att göra källfördelningsanalys. Totalt samlades 60st 24-timmars filter in av personer vid University of Lagos som sedan skickades till Göteborg. PM2.5 bestämdes gravimetriskt och den grundämnessammansättningen analyserades med en optisk transmissometer och energidispersiv röntgenfluorescensspektrometri (EDXRF). Datan analyserades sedan med korrelationsanalys och med Positive Matrix Factorisation (PMF) för att göra själva källfördelningsanalysen.

Tjugotvå grundämnen detekterades och kvantifierades: Al, P, S, Cl, K Ca, Ti, V, Mn, Fe, Cu, Zn, Ga, As, Se, Br, Sr, Y, Ba, Hg, Pb, och Si, tillsammans med svart kol (BC) och ultraviolett-absorberande partiklar (UVPM). Den genomsnittliga halten av PM2.5 uppmättes till 37 ± 24 $\mu g/m^3$, vilket överskrider WHO:s riktlinje för dygnsmedelvärde på 15 $\mu g/m^3$. Identifierade källor inkluderade mineraldamm, förbränning av petroleumprodukter och trafikrelaterade utsläpp, biomassaeldning, havssalt, stålindustri, samt en V-rik källa. Bland dessa var mineraldamm samt faktorn för förbränning av petroleumprodukter och trafikrelaterade utsläpp de dominerande bidragsgivarna till det insamlade PM2.5. Det fanns en diskrepans mellan den rekonstruerade massan och den totala uppmätta PM2.5-massan, vilket tyder på att ytterligare komponenter som inte kunde detekteras med de använda analysmetoderna kan förekomma. Förbättringar i framtida studier bör omfatta ett större datamaterial, inkludering av meteorologiska data samt ett bredare spektrum av kemiska ämnen för att förbättra källidentifiering och rekonstruktion av partikelmassa.

Innehållsförteckning

1. INTRODUCTION 1

1.1 BACKGROUND 1
1.1.1 PM2.5 1
1.1.2 The city of Lagos and major contributing sources to PM2.5 pollution 2
1.2 AIM 3

2. MATERIALS AND METHODS 4

2.1 SITE AND SAMPLE COLLECTION 4
2.2 MASS DETERMINATION OF PM2.5 4
2.3 ELEMENTAL ANALYSIS 5
2.3.1 Soot analysis 5
2.3.2 Elemental composition analysis with EDXRF 5
2.4 DATA ANALYSIS 5
2.4.1 Data preparation 5
2.4.2 Correlation 6
2.5 POSITIVE MATRIX FACTORIZATION (PMF) 6
2.5.1 About PMF 6
2.5.2 Execution of PMF 7
2.5.3 Analysis of PMF results 8

3. RESULTS 9

3.1 PM2.5 TREND 9
3.2 ELEMENTAL COMPOSITION 9
AND CORRELATION 9
3.3 SOURCE APPORTIONMENT 11

4. DISCUSSION 14

4.1 PM2.5 14
4.2 CORRELATION FIGURES 14
4.3 PMF – SOURCE APPORTIONMENT 14
Deciding number of factors 14
Source apportionment 14
4.5 IMPROVEMENTS FOR FURTHER STUDIES 17

5. CONCLUSION 18

6. REFERENCES 19

1. INTRODUCTION

Air pollution poses a significant threat to human health and was in 2021 estimated to be the second leading risk factor for death globally. The largest driver of air pollution's disease burden worldwide is fine particulate matter, which is particles with a diameter smaller than 2.5 μm (PM2.5). Long-term exposure to PM2.5 is associated with diseases such as ischemic heart disease, lung cancer, lower respiratory infections, stroke, and premature death. Specifically, outdoor pollution was in 2021 estimated to be responsible for 4.7 million deaths globally (Health Effects Institute, 2024). Besides inducing adverse health effects on humans, PM2.5 is also an important factor in causing smog, being a contributor to global warming, and has an impact on atmospheric chemistry (Ezeh et al., 2018). The World Health Organization has issued Air Quality Guidelines (AQG) to support policymakers and society in reducing human exposure to air pollutants (World Health Organization, 2021). The problem of air pollution is more serious in developing countries due to rapid population growth, uncontrolled urbanisation, and development of industrialisation (Manisalidis et al., 2020). At present time Africa is a continent with many developing countries, and many people are exposed to PM2.5 levels exceeding the Air Quality Guidelines. Eight of the ten countries with the highest exposure of PM2.5 are in Africa (Health Effects Institute, 2024). To combat the problems with air pollution and reduce the disease burden, knowledge about air pollution sources is important. With this knowledge, appropriate actions and policies can be implemented. In this study, the focus is turned towards the city that is predicted to be the world's most populated city in 2100 (Hoornweg & Pope, 2017): the megacity Lagos in Nigeria.

1.1 BACKGROUND

1.1.1 PM2.5

Particulate matter (PM) suspended in the atmosphere consists of solid particles and liquid droplets composed of organic and inorganic substances, generally in the size range 0,01-10 μm. Fine PM refers to the particles that have an aerodynamic diameter less than 2.5 μm and are, in shorter terms, called PM2.5. These particles are either emitted directly to the atmosphere as primary pollutants or formed through chemical reactions as secondary pollutants. They have a typical lifetime of 1-2 weeks in the atmosphere due to inefficient removal by rainwater scavenging or dry deposition to surfaces and can therefore be transported long distances (Harrison, 2014). Their small size makes them a great threat to human health since they can travel past the barriers of the lungs and into the bloodstream, increasing the risk for respiratory and cardiovascular disease and contributing to premature mortality (Brook et al., 2010).

PM2.5 in the atmosphere originates from both anthropogenic and natural sources. Major anthropogenic PM2.5 sources include fuel combustion (emissions from vehicles, residential use of fuel, coal-burning power plants), industrial activities, agriculture, construction projects, and biomass and waste burning. Some examples of natural sources include wildfires, windblown dust, and sea spray (Health Effects Institute, 2022).

Air Quality Guidelines are health-based guidelines set to provide evidence-informed recommendations for air quality management (World Health Organization, 2021). The World Health Organization also provides interim targets that are levels higher than the AQG levels. Their purpose is to guide authorities in highly polluted areas to develop pollution reduction policies that are more realistic and achievable, as steps towards the end goal of reaching the AQG levels. The AQG level for PM2.5 with a 24-hour averaging time was in 2021 set to 15 $\mu g/m^3$, and the following interim targets: (1) to 75 $\mu g/m^3$, (2) to 50 $\mu g/m^3$, (3) to 37.7 $\mu g/m^3$, and (4) to 25 $\mu g/m^3$.

1.1.2 The city of Lagos and major contributing sources to PM2.5 pollution

Lagos, Nigeria is one of the most densely populated cities in Africa with an estimated population of 16 million people in 2023 (Sheposh, 2024). It is a city going through rapid urbanization, is one of the world's fastest growing megacities and is predicted to become the world's largest city by year 2100. Lagos has a large immigration contributing to its increasing population, and the city's rapid growth has outpaced infrastructure, resulting in the around 100 informal settlements located around the city. While facing these challenges, the concern of air pollution is a pressing environmental concern. The energy situation, road transport, informal settlements, poor waste management, on-going construction projects, and climate are all many important factors playing a part in polluting the air (Croitoru et al., 2020). By the year 2020 there was no operational air quality monitoring stations, since the air quality monitoring station owned by the Nigerian Metrological Agency was not operational due to power unavailability, poor maintenance and lack of human, technical and financial resources to sustain the monitoring program (Croitoru et al., 2020). According to studies of PM2.5 performed in Lagos, the air pollution is well exceeding the AQG levels recommended by the World Health Organization (Croitoru et al., 2020).

1.1.2.1 The energy situation

Lagos accounts for 40% of Nigeria's electricity demand. The city has over half of the country's industrial and manufacturing activities. Nigeria is the richest oil resource centre of the African continent, and the largest gas consumer and producer of West Africa. The energy supply therefore largely consists of oil, natural gas, biofuels, and waste. According to Resilient City Network (2023), Lagos only receives 24-26% of the grid's total power capacity, about 1 000 MW, which is far below the required amount for guaranteed uninterrupted energy supply which is estimated to 9 000 MW. This has led to that residents and businesses must use back-up generators instead to meet their demand (Resilient Cities Network, 2023). The generators are often diesel- or petrol-powered. Power sector reforms are in motion along with plans for electrification (International Energy Agency, n.d).

1.1.2.2 Biomass burning

Nigeria is also a country that has reportedly significant biomass burning (BB). Solid fuels, such as wood, are still used in low-income households for cooking (Alani et al., 2019). Municipal solid waste combustion is also a major source of pollutants. Fakinle et al. (2020) state that it is a common practice in Lagos to burn municipal solid waste instead of landfilling. In large cities like Lagos, there is a lot of waste generated that needs to be managed in some way. Burning it is an efficient way to manage the large volumes, but the practice emits pollutants that worsen the air quality drastically. Another type of BB mentioned by Fakinle et al. (2020) is the burning sawdust from sawmills. These wastes are generated daily and burned in the open air at the bank of the lagoon of Lagos.

1.1.2.3 Traffic

Lagos has limited public transport options, leading to people having to rely on personal vehicles, commercial buses, tricycles and motorcycles, making Lagos a city famous for many vehicles (Croitoru et al., 2020). There are over five million vehicles on the roads daily, with an average of 227 vehicles per kilometer of road per day, compared to the national average, which is 11 vehicles per kilometer per day. This leads to frequent traffic congestion in Lagos and is a contributor to significant local air pollution. The majority of vehicles in the city are also believed to have old emission control technologies, and therefore, more emissions of PM and black carbon (BC). Other emissions from road vehicle traffic are secondary particles of ammonium sulphate, ammonium nitrate, and organic matter (Harrison, 2014). Nigeria has been importing diesel and petroleum products with high sulfur content, but the government has revised standards for the sulfur content to minimise sulfur emissions. In 2020, the 15 countries of the Economic Community of West African States (ECOWAS), of which Nigeria is a part, adopted regulations for introducing cleaner

fuels in the region. This included a sulfur fuel standard of 50 parts per million for petrol and diesel for all imported fuels, starting 1 January 2021, with local refineries having until 1 January 2025 to meet the new requirements. The regulations would have a notable impact on the ECOWAS region since 80 percent of the fuel is imported (UN environment programme, 2020). Additionally, the use of leaded gasoline was banned in Nigeria in 2004 (Ezeh et al., 2018).

1.1.2.4 Climate

The climate in Lagos is characterised by wet and dry seasons, which contribute to seasonal variations in ambient PM2.5. Lagos is in the part of Nigeria with a tropical savanna climate (Agbo et al., 2023) with heavy rainfall during the rainy season from April to October, and a dry season from November to March. The dry season is characterised by dry winds from the Sahara, called Harmattan, bringing with it a large amount of mineral dust. A study of PM2.5 in Lagos, done from December 2010 to November 2011, obtained maximum concentrations during the dry season months (Ezeh et al., 2018).

1.1.2.5 Previous studies of PM2.5 in Lagos

Olufemi et al. (2023) performed a study to monitor and quantify the spatial trends of air pollutants in Lagos between November 2018 to February 2019. The study had five sampling sites, where the University of Lagos was used as a background site. A range between 3.4 – 297.2 $\mu g/m^3$ with a mean of 60.5 and SD of 69.2 $\mu g/m^3$ was obtained. This study did not perform source apportionment analysis.

Ezeh et al. (2018) did a study over PM2.5 in three sites (Ikoyi, Mushin, and Ikeja) in Lagos between December 2010 to November 2011, with the main objectives to understand seasonal PM pollution levels and do source apportionment. They found overall annual mean mass concentrations at 91, 98 and 41 $\mu g/m^3$ for each site, which exceed the AQG. The study found that the mass concentrations were not normally distributed across the months, with higher mass loads in Harmattan months (November to March). Of the months that this presence study is interested in, January to March, their study showed that January generally had higher mass concentration, followed by February and then March. The study identified five sources: sea spray, industrial and tire wear emissions, soil/dust, biomass burning, and petroleum oil combustion.

Alani et al. (2019) did a study in three locations in Lagos (Agege, Oshodi and the University of Lagos) and found PM2.5 levels below 25 $\mu g/m^3$. This study was performed during the rainy season, and Alani et al. (2019) discuss that the low concentrations could be due to wash-out. This study did not perform source apportionment.

1.2 AIM

This study aims to explore and better understand PM2.5 pollution in the city of Lagos, Nigeria, during the period January to March 2025. PM2.5 is collected using filter sampling, and its elemental composition is analysed for source apportionment. As few studies have investigated PM2.5 pollution in Lagos, this study seeks to contribute and add to the current knowledge of PM2.5 levels, composition, and sources in the city.

To achieve these objectives, the following questions were posed:

- What are the PM2.5 levels in Lagos?
- What are the major sources of PM2.5 pollution in Lagos?
- What trends can be distinguished from the results?

2. MATERIALS AND METHODS

2.1 Site and sample collection

The sampling took place at the University of Lagos in Nigeria during the period January 9th to March 15th 2025. The specific months of January to March were chosen for this study primarily because they were suitable for the people working in Lagos, but also because they offer insight into the time of year when the air quality is expected to be at its worst due to the presence of the dry season. According to an earlier study in the same area (University of Lagos), the area has proximity to residential areas where biomass is burnt and wood is used for cooking, a campus gas plant, and high volumes of human and vehicular traffic (Alani et al., 2019).

Earlier last year PTFE (polytetrafluoroethylene) particle filters, with a filter collection area of 20.5 mm, were sent to the University of Lagos, Nigeria. The filters were weighed before being sent. The ambient air pollution was measured with a PM2.5 sampler in periods of 24 hours. The time when each measurement was started and ended was noted, along with the time the sampler had electricity. Lagos does not have a stable energy supply, and since the sampler uses energy to drive air through the filter, this is crucial information to know the actual time of the sampling. The air volume flow was around 3 L/min. When the sampling was completed, the filters were sent back to Gothenburg, Sweden and arrived on 7th April 2025.

When looking over the data, it was apparent that some samples had been collected over shorter or longer periods than intended. Six samples had been measured for double the time, the dates are 15/1, 3/2, 21/2, 23/2, 27/2 and 9/3. Additionally, one sample (from 28 January) had active sampling for only 4 hours. These seven samples were still analysed in further steps since they are still suitable for elemental composition analysis, since the collected mass is still sufficient and the relative elemental proportions are not significantly affected by variation in sampling duration.

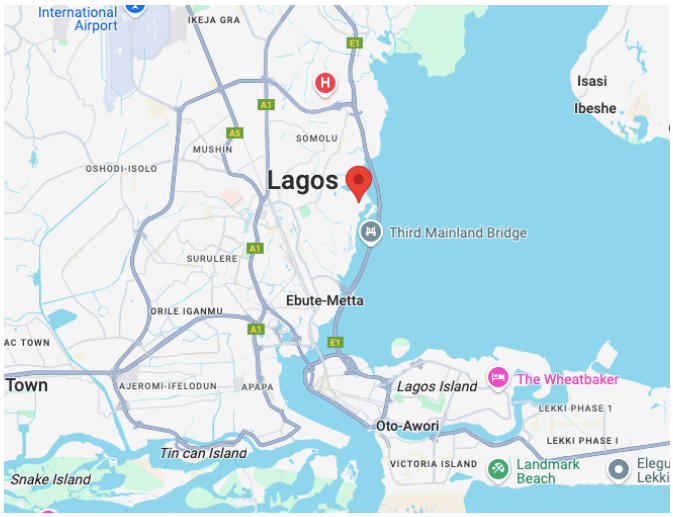

Figure 1 (left): Screenshot from Google Earth showing the location of Lagos (blue pinpoint) in Nigeria (the red borders) (Google Earth, 2025).
Figure 2 (right): Screenshot from Google Maps showing the sampling location (red pinpoint) with coordinates 6.517867° N, 3.398460° E (Google Maps, 2025).

2.2 Mass determination of PM2.5

The mass on the samples was decided gravimetrically using a microbalance (Mettler MT5 model). The filters were picked up using a metal tweezer to limit contamination. Each filter was weighed 3 times, and the average of the three measurements was calculated. This weight was then compared to the weight measured pre-sampling, and the difference between them was calculated, giving the

weight of PM2.5 captured on the filter. The weight difference, air volume, and measurement time were then used to calculate the PM2.5 on the filters.

2.3 Elemental Analysis

2.3.1 Soot analysis

Burning of biomass, biofuels, and similar sources contributes to soot in the air. This content was analysed with an optical transmissometer (SootScan Model OT21) that determines the optical attenuation and black carbon (BC) and brown carbon (BrC) mass results (Aerosol Magee Scientific, n.d). BC is part of elemental carbon and comprises graphitic particles from incomplete combustion, especially from diesel engines (Harrison, 2014). BrC is part of organic carbon and formed primary from fuel combustion and secondarily in the atmosphere, and high loadings of BrC has been reported in air with strong biomass burning influences (Xiong et al., 2022). The transmissometer uses wavelengths intensities at 880 nm in the infrared (IR) spectrum, and 370 nm in the UV-spectrum, where IR 880 nm is used to detect BC and UV at 370 nm detects both BC + BrC. Light attenuation is linearly related to BC mass loading. This method is non-contact, non-destructive and non-contaminating, which is important and a reason for choosing this method since additional analysis will be performed on the samples afterwards.

The samples were put on a glass fibre filter in the transmissometer which are used to improve the attenuation measurement. The samples were measured one time each and the data were then processed. The measured attenuation for BC and BrC was divided by the absorption cross section σ (for BC 16.6 and BrC 39.5), multiplied by the measuring area, multiplied by 1000 and lastly divided by the air volume, to get the concentrations in ng/m^3.

Brown carbon (BrC) will be further referred to as UVPM in the method and discussion.

2.3.2 Elemental composition analysis with EDXRF

Energy Dispersive X-Ray Fluorescence (EDXRF) was used to analyse the elemental composition of the particles on the samples. This was done by using a XRF instrument of the model SPECTRO XEPOS. The EDXRF technique uses x-ray radiation to simultaneously excite all elements in a sample. When the x-ray radiation hits an atom, the energy is absorbed by an inner-shell electron. With high enough energy, this electron will be released, and an electron from another shell will move to fill the empty spot. When the electron moves to the inner shell, it emits an X-ray fluorescence photon. An energy dispersive detector collects the fluorescence that is emitted. This emitted fluorescence is characteristic for each element. A multi-channel analyser separates the characteristic radiation. The EDXRF technique is non-destructive, easy to use, quick, reliable and an economical option. It provides multi-elemental analysis, which is beneficial for the following PMF analysis, since we need to know the concentrations of multiple elements in the sample to determine the PM (Spectro Analytical Instruments, n.d).

The samples were measured in batches of eight. Each filter was put between Prolene thin-film to keep the filters flat in the holder, so that the X-rays can hit the sample evenly. Two blank filter samples were measured, one at the beginning of the analysis and one at the end. Blanks are necessary to extract the signals from the material of the filter.

2.4 Data Analysis

2.4.1 Data preparation

The data from the EDXRF analysis was opened in Excel for processing. The elements with only data under the detection limit (DL) were removed. This left the elements: Al, P, S, Cl, K, Ca, Ti, V, Mn, Fe, Ni, Cu, Zn, Ga, As, Se, Br, Sr, Y, Ba, Hg, Pb, and Si. The data points below the DL were substituted with 0. For the data of the blank samples, the data below DL was instead

substituted with half the DL value. For example, if <10, then it was changed to 5 ng/cm^2. If one of the blanks had a value under the DL and one above, DL/2 was chosen for both. An average value was then made for each element from the blank to give a representative blank, which was then subtracted from all the other samples to give representative values.

The data for Al, P, S, Cl, K, Ca, Ti, V, Mn, Fe, Ni, Cu, Zn, Ga, As, Se, Br, Sr, Y, Ba, Hg, Pb, and Si were put in a new table, multiplied by the filter sample area, and divided by the air volume to determine the elemental concentrations in the sampled air. Silicon had disproportionally large negative concentrations, indicating that the blank had been contaminated before measuring it. A probable cause of this is that it could have been contaminated with extra glass fibre. Before using the SootScan instrument, an old glass fibre filter had been stored in the measuring spot, which had started to fall apart on the edges. It is possible that small parts of this old paper could have been transferred onto the blank filter paper, even though caution was taken. To account for this, a blank value for Si from another study was used as a blank instead. The calculation for Si was done again with the new blank value, and more realistic concentrations were given.

Together with the determined concentrations of BC and UVPM, this finalised the input data for the subsequent PMF analysis. When carrying out the PMF analysis, an uncertainty data file is also necessary. This was prepared by taking the detection limit (DL) for each element. Some of the detection limits were present in the data from the EDXRF analysis. This was the case for Al, V, Mn, Ga, As, Y, Hg and Pb, with the DLs being 10, 0.6, 0.7, 1.2, 0.4, 0.6, 2 and 2, respectively. For the other elements, estimated detection limits from earlier studies using the same EDXRF instrument were used. These are presented in the Results section.

2.4.2 Correlation

To get a first preliminary overview of the data, binary correlations between pairs of element concentrations were calculated. This was put into a matrix and colour coordinated to symbolize stronger and weaker correlation.

2.5 Positive Matrix Factorization (PMF)

2.5.1 About PMF

The PMF analysis was performed with the EPA PMF 5.0 software provided by the US Environmental Protection Agency. PMF is a receptor modelling software that takes a mathematical approach to quantify the contribution of sources to samples. The software does this based on the composition of species, which is determined by using analytical methods, in this case EDXRF and optical transmission. A receptor model aims to solve the chemical mass balance between measured concentrations and source profiles, see Equation 1 below. X_{ij} is the input data matrix X of i by j dimensions, in which i is the number of samples and j is the number of chemical species measured (U.S. Environmental Protection Agency, 2014)

$$x_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij} \quad (1)$$

where p is the number of factors, f is the species profile of each source, g is the amount of mass contributed by each factor to each sample, and e_{ij} is the residual for each sample/species.

There are multiple types of models that can be used to solve the CMB equation, other examples than the one used here, PMF, are CMB and Unmix (U.S. Environmental Protection Agency, 2014). The latter two are similar to PMF but work with different mechanisms. Unmix does not allow

individual weighting of data points, as PMF does. In PMF, this allows for giving less weight to low-quality data and making it less sensitive to noise. PMF and Unmix generally give similar factors, but PMF can sometimes resolve more factors (Pekney et al., 2006). The difference between CMB and PMF is that for CMB, the user must additionally provide source profiles (measurement at receptor and source signature) for the model to use, while in PMF this is decided by the mathematical procedure. The advantage of using PMF modelling is thus that it only requires measured concentrations and uncertainties, and no other input data (U.S. Environmental Protection Agency, 2014).

PMF is a multivariate factor analysis tool, meaning that it finds patterns and relationships in data with many variables. It decomposes a matrix of speciated sample data into two matrices: factor contributions (G) and factor profiles (F). The factor profiles then need to be interpreted by the user to identify the source types. The interpretation is done by using measured source profile information and knowledge about the sampling location. The model uses the constraint that no sample can have significantly negative source contributions. To perform the PMF analysis, detection limits and user-provided uncertainty associated with the sample data are needed as input data. Uncertainty data is necessary to account for the confidence in the measurement, where data points with higher uncertainty have less influence on the solution. Small data sets pose an extra challenge in PMF. The solution is strongly affected by rotational ambiguity, and overall uncertainty is increased (Manousakas et al., 2017). The smaller the data set, the more limited the model will be when distinguishing between sources.

Q is a critical parameter in PMF and is called the goodness-of-fit parameter. Two versions of Q are given after running the model, Q(true) and Q(robust). The Q(true) is calculated including all data points, while Q(robust) is calculated excluding points not fit by the model (samples for which the uncertainty-scaled residual is greater than 4). When taking the difference between these two parameters, a measure of the impact of data points with high scaled residuals can be obtained**.**

2.5.2 Execution of PMF

To obtain the optimal number of sources, the model was used with factors ranging from 3 to 10, and with random seed values. The results from each case were analysed to see which factors could provide the fit of the experimental data.

In PMF, the data for each element can be categorised as “Strong”, “Weak” or “Bad”. A categorisation of “Weak” triples the provided uncertainty, and a categorisation of “Bad” excludes the species from the analysis. When deciding on the categorisation several approaches can be employed. The presence of sources based on measured profiles, tracer species, the number of samples that are missing or below the detection limit, known problems with sampling or analysis, and species reactivity should be considered (U.S. Environmental Protection Agency, 2014). It was discovered that the Ni concentration was dependent on which spot in the EDXRF plate the samples had been put in, so the values for Ni were categorised as “Bad” and excluded from the PMF analysis. The categorisation of Ni was hence due to analytical problems. Since no other problems were known for the other species, no more species were labelled as “Bad”. The U.S. Environmental Protection Agency (2014) also recommend that if detailed information about the data set is unavailable, the S/N ratio could be used to categorise some species. This strategy was used, categorising elements with S/N ratio <1 as “Weak”. The elements were P, Hg, Ba, Ga and Y. Additionally, Al was also changed to “Weak” since the PMF struggled with modelling peaks in the time series, and the EPA PMF Guide advised to exclude or change elements like this to “Weak”.
When the PMF had been performed for all the factors, the results were analysed. To help decide/determine the most suitable number of factors, Q values were examined. This was done by taking the lowest Q_{true} value from each run and dividing these with the calculated $Q_{expected}$ values,

$$Q_{expected} = Samples*Species - Factors*Samples - Factors*Species \quad (2)$$

The $Q_{true}/Q_{expected}$ ratio gives an indication of how good the solutions are for each factor. When the ratio does not get better (lower) for a higher number of factors, it is an indication that the quality of the solution does not improve (U.S. Environmental Protection Agency, 2014).

2.5.3 Analysis of PMF results

The analysis of the results from PMF was done by looking at the $Q_{true}/Q_{expected}$ ratio, and then the values from the produced base files, where the factor profiles with % of species were first compared between different runs. The case with the most identified and reasonable sources was used as the best fit. Then a time series for these factors was created by using the relative factor contribution.

To estimate the contribution of each factor to a certain species, the concentrations of elements from the factor profiles were multiplied by the molar ratios between each element and its likely oxide form (the compound it typically forms in the atmosphere, considering known sources). Many elements form oxides during combustion by reacting with oxygen. For example, sulfur (S) is emitted through combustion as sulfur dioxide SO_2, which can further oxidise to sulfur trioxide SO_3 and react with water to form H_2SO_4, a major contributor to acid rain. This approach does not account for all possible fine particulates that could be present on the sample, since not all possible elements and species could be measured by the EDXRF and transmissometer instruments. This means that there could be a difference between the reconstructed mass and the gravimetrically determined mass.

3. RESULTS

3.1 PM2.5 Trend

The measurement of PM2.5 showed a trend of higher concentrations at the beginning of January, with a peak between January 9th to 13th, and lower concentrations in March (Figure 3). The concentrations are quite similar from the second part of January and throughout February. For PM2.5 the Maximum value is 122 µg/m^3, the Minimum 4.7 µg/m^3, the Mean = 37 µg/m^3, and the SD = 24 µg/m^3. Some samples did not have any documented problems with the sampling but were very light in the amount of PM2.5 on them, almost empty. This could be from problems with the measuring device, but since no problems had been documented, they were still used in the study. The samples were from the dates: 6 February and 11-14 March.

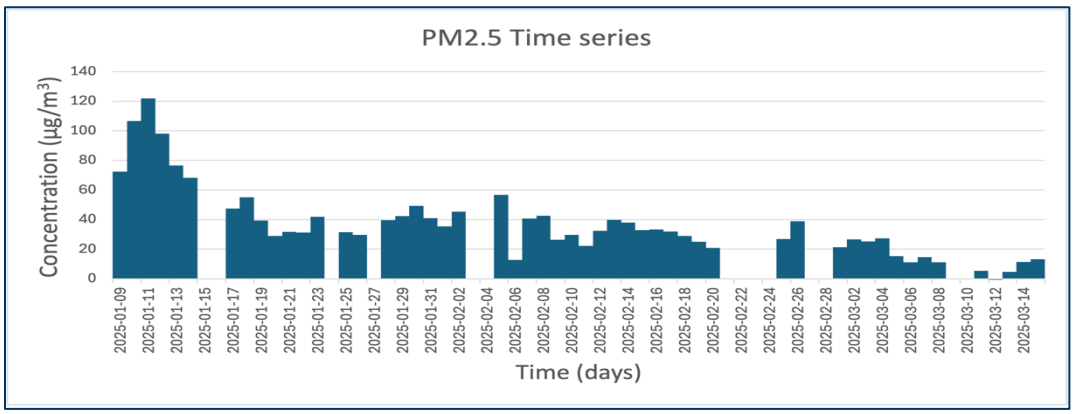

Figure 3: Bar chart of PM2.5. Samples that had been measured for double the time (i.e 48 hours instead of 24) are excluded. These dates are 15-16/1, 3-4/2, 21-22/2, 23-24/2, 27-28/2, and 9-10/3. The measurement for 27/1 had only been operative for 4 hours and is therefore also excluded from this figure.

3.2 Elemental composition and Correlation

Twenty-two elements were detected and quantified: Al, P, S, Cl, K Ca, Ti, V, Mn, Fe, Cu, Zn, Ga, As, Se, Br, Sr, Y, Ba, Hg, Pb, and Si, along with BC and UVPM. Ni was also detected, but discarded due to earlier mentioned problem. The elements and the detection limit (DL), mean, standard deviation (SD), minimum, maximum, and number of valid samples (N^a) can be seen below in Table 1. The elements S, Cl, K, Ca, Ti, Mn, Fe, Cu, Zn, As, Se, Br, Sr, Si, and BC and UVPM were found in the majority of samples (see N^a in Table 1), meaning that they come from sources that had emissions during the majority of days from January to March. On the other side the elements Al, Ga, Y, Ba, and Hg were detected only for a few days, indicating that they were emitted from sources with less occurrence, or emitted in very small

Table 1: Elemental composition data for detected elements. ^aN is the number of valid samples.

Element	DL (ng m^{-3})	Mean (ng m^{-3})	SD (ng m^{-3})	Minimum (ng m^{-3})	Maximum (ng m^{-3})	N^a
Al	7.7	1420	1140	<DL	3810	*18*
P	62	<DL	-	<DL	<DL	*0*
S	15	830	389	<DL	1500	*57*
Cl	3.8	161	129	<DL	537	*56*
K	2.5	1203	747	<DL	3250	*57*
Ca	0.8	537	360	17.2	1360	*60*
Ti	0.8	127	83	<DL	352	*58*
V	0.5	3.7	1.6	<DL	7.1	*39*
Mn	0.5	12	9.2	<DL	47	*54*
Fe	2.3	443	311	11.7	1350	*60*
Cu	1.0	23	21.3	<DL	128	*58*
Zn	3.5	201	250	<DL	128	*59*
Ga	2.4	1.7	0.8	<DL	1570	*5*
As	0.9	4.5	7.0	<DL	3.2	*51*
Se	0.3	3.3	4.0	<DL	43	*53*
Br	0.3	63	192	0.3	21	*60*
Sr	0.3	2.5	1.4	<DL	1300	*55*
Y	0.8	0.8	0.5	<DL	6.0	*16*
Ba	0.5	7.6	0.7	<DL	2.4	*3*
Hg	6.3	4.5	3.8	<DL	8.4	*2*
Pb	1.5	32	55	<DL	7.2	*44*
Si	1.5	2710	1930	41	315	*60*
BC	6.3	1540	726	<DL	7580	*57*
UVPM	77	984	438	<DL	3480	*59*

amount, so that they in most days don't reach the detection limit (DL).

The Mean and N^a in Table 1 shows that the dominating elements were S, K, Ca, Fe, Si, BC and UVPM. This indicates, based on the elements measured in this study, that the air pollution during the period majorly comes from mineral dust and combustion processes (Kovacevik et al., 2011). Ca, Fe and Si are associated with mineral dust, and S, K, BC and UVPM with combustion or burning of biomass or waste.

Figure 4 shows the presence of the elements over time. It shows visually the dominating elements (Si, BC, K, S, UVPM, Ca, Fe).

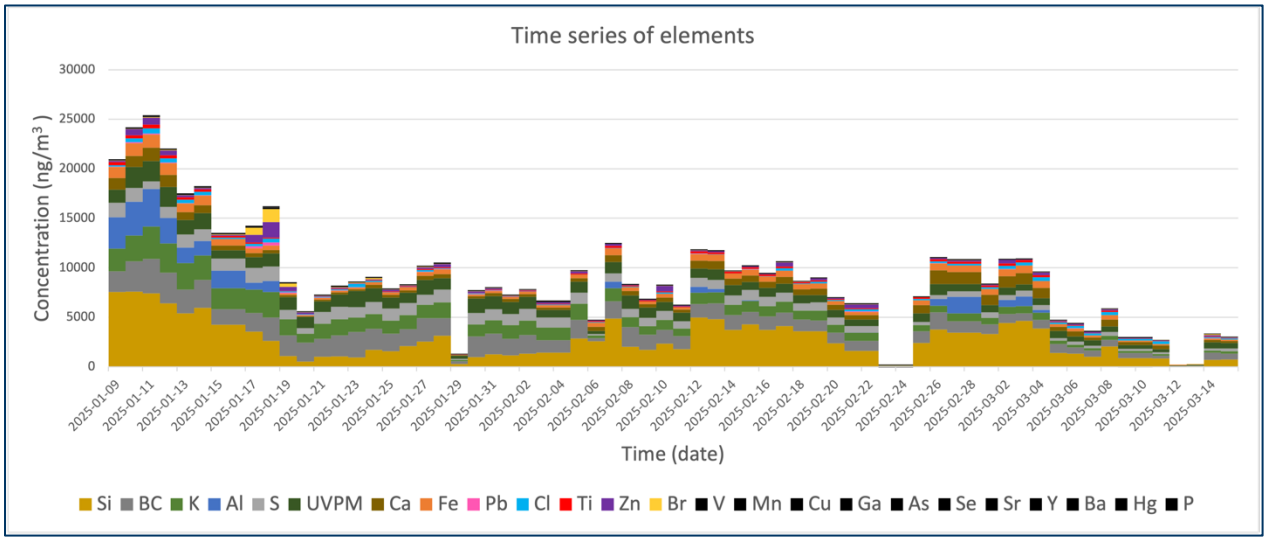

Figure 4: Visualisation of detected elements. Samples that had been measured for double the time (i.e 44 hrs instead of 24) are included. These dates are 15-16/1, 3-4/2, 21-22/2, 23-24/2, 27-28/2, and 9-10/3. The elements after Br are too small to see in the graph, therefore they were all assigned the black colour.

Figure 5 shows the binary correlation between all detected elements. The results were colour coded with green for symbolising stronger correlation and red for weaker. This made it easier to visually sort and group the rows to get elements with strong correlation next to each other. A strong correlation between elements means that they probably come from the same source, since they follow similar patterns. The green cluster in the upper left corner shows that Fe, Si, Ti, Ca, and Sr have a strong correlation with each other, which are common elements in mineral dust (Kovacevik et al., 2011). The cluster in the middle shows K, BC, UVPM, and S, these are related to emissions from combustion (Kovacevik et al., 2011). The bottom right shows a strong correlation between Zn, As, Pb, and Br, which are associated with traffic and industrial sources (Duan & Tan, 2013; Kovacevik et al., 2011).

	Al	Fe	Si	Ti	Ca	Sr	P	Mn	K	BC	UVPM	S	Cu	Zn	Ga	As	Pb	Br	Se	Y	Hg	Cl	V	Ba
Al	1,00	0,84	0,80	0,80	0,66	0,71	0,76	0,83	0,69	0,56	0,55	0,33	0,25	0,43	0,63	0,38	0,32	0,14	-0,02	0,36	0,05	0,59	0,32	0,46
Fe	0,84	1,00	0,98	0,99	0,89	0,93	0,87	0,81	0,65	0,55	0,56	0,37	0,16	0,36	0,44	0,23	0,18	0,02	-0,12	0,28	-0,05	0,61	0,37	0,48
Si	0,80	0,98	1,00	0,97	0,85	0,90	0,85	0,76	0,64	0,51	0,52	0,43	0,15	0,33	0,41	0,20	0,16	0,02	-0,11	0,29	-0,05	0,51	0,37	0,49
Ti	0,80	0,99	0,97	1,00	0,93	0,96	0,84	0,75	0,58	0,47	0,50	0,33	0,11	0,32	0,38	0,18	0,13	-0,01	-0,15	0,28	-0,07	0,60	0,37	0,46
Ca	0,66	0,89	0,85	0,93	1,00	0,95	0,68	0,58	0,34	0,30	0,34	0,12	-0,05	0,21	0,21	0,05	0,01	-0,09	-0,21	0,16	-0,10	0,58	0,34	0,35
Sr	0,71	0,93	0,90	0,96	0,95	1,00	0,76	0,66	0,47	0,38	0,41	0,24	0,07	0,29	0,30	0,14	0,10	-0,02	-0,14	0,26	-0,03	0,59	0,35	0,42
P	0,76	0,87	0,85	0,84	0,68	0,76	1,00	0,87	0,87	0,77	0,77	0,68	0,47	0,51	0,62	0,48	0,43	0,27	0,20	0,45	0,11	0,56	0,47	0,58
Mn	0,83	0,81	0,76	0,75	0,58	0,66	0,87	1,00	0,86	0,81	0,78	0,55	0,46	0,54	0,67	0,51	0,44	0,23	0,16	0,36	0,11	0,66	0,35	0,45
K	0,69	0,65	0,64	0,58	0,34	0,47	0,87	0,86	1,00	0,91	0,86	0,84	0,66	0,57	0,71	0,61	0,56	0,39	0,40	0,53	0,19	0,44	0,30	0,47
BC	0,56	0,55	0,51	0,47	0,30	0,38	0,77	0,81	0,91	1,00	0,99	0,80	0,55	0,44	0,53	0,50	0,43	0,25	0,35	0,33	0,07	0,37	0,22	0,34
UVPM	0,55	0,56	0,52	0,50	0,34	0,41	0,77	0,78	0,86	0,99	1,00	0,76	0,47	0,39	0,46	0,44	0,37	0,19	0,28	0,29	0,00	0,39	0,24	0,34
S	0,33	0,37	0,43	0,33	0,12	0,24	0,68	0,55	0,84	0,80	0,76	1,00	0,59	0,40	0,46	0,45	0,44	0,35	0,53	0,50	0,14	0,09	0,32	0,40
Cu	0,25	0,16	0,15	0,11	-0,05	0,07	0,47	0,46	0,66	0,55	0,47	0,59	1,00	0,73	0,75	0,83	0,82	0,81	0,75	0,66	0,63	0,34	0,14	0,24
Zn	0,43	0,36	0,33	0,32	0,21	0,29	0,51	0,54	0,57	0,44	0,39	0,40	0,73	1,00	0,82	0,92	0,92	0,81	0,56	0,60	0,61	0,55	0,17	0,25
Ga	0,63	0,44	0,41	0,38	0,21	0,30	0,62	0,67	0,71	0,53	0,46	0,46	0,75	0,82	1,00	0,88	0,85	0,72	0,52	0,72	0,52	0,50	0,26	0,35
As	0,38	0,23	0,20	0,18	0,05	0,14	0,48	0,51	0,61	0,50	0,44	0,45	0,83	0,92	0,88	1,00	0,99	0,92	0,71	0,70	0,69	0,44	0,18	0,25
Pb	0,32	0,18	0,16	0,13	0,01	0,10	0,43	0,44	0,56	0,43	0,37	0,44	0,82	0,92	0,85	0,99	1,00	0,95	0,73	0,70	0,69	0,40	0,17	0,22
Br	0,14	0,02	0,02	-0,01	-0,09	-0,02	0,27	0,23	0,39	0,25	0,19	0,35	0,81	0,81	0,72	0,92	0,95	1,00	0,75	0,69	0,80	0,27	0,13	0,16
Se	-0,02	-0,12	-0,11	-0,15	-0,21	-0,14	0,20	0,16	0,40	0,35	0,28	0,53	0,75	0,56	0,52	0,71	0,73	0,75	1,00	0,63	0,57	0,02	0,15	0,13
Y	0,36	0,28	0,29	0,28	0,16	0,26	0,45	0,36	0,53	0,33	0,29	0,50	0,66	0,60	0,72	0,70	0,70	0,69	0,63	1,00	0,52	0,28	0,31	0,29
Hg	0,05	-0,05	-0,05	-0,07	-0,10	-0,03	0,11	0,11	0,19	0,07	0,00	0,14	0,63	0,61	0,52	0,69	0,69	0,80	0,57	0,52	1,00	0,18	0,04	0,09
Cl	0,59	0,61	0,51	0,60	0,58	0,59	0,56	0,66	0,44	0,37	0,39	0,09	0,34	0,55	0,50	0,44	0,40	0,27	0,02	0,28	0,18	1,00	0,22	0,23
V	0,32	0,37	0,37	0,37	0,34	0,35	0,47	0,35	0,30	0,22	0,24	0,32	0,14	0,17	0,26	0,18	0,17	0,13	0,15	0,31	0,04	0,22	1,00	0,58
Ba	0,46	0,48	0,49	0,46	0,35	0,42	0,58	0,45	0,47	0,34	0,34	0,40	0,24	0,25	0,35	0,25	0,22	0,16	0,13	0,29	0,09	0,23	0,58	1,00

Figure 5: Correlation matrix for measured elements. Colour grading where green equals stronger correlation.

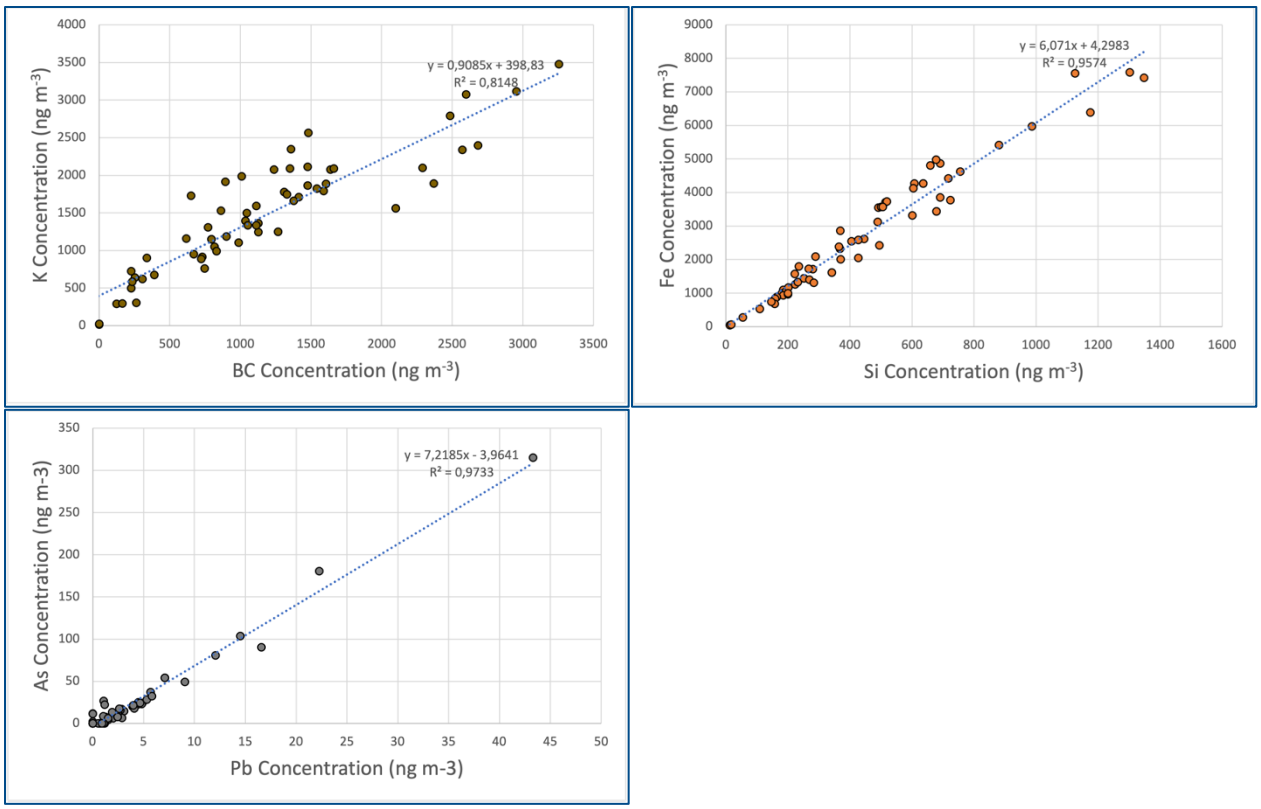

Figure 6: Relationships between measured concentrations of selected pairs of species. The top left shows relationship between K and BC, the top right shows As and Pb, and the bottom shows between Fe and Si.

3.3 Source apportionment

Figure 7 shows how the $Q_{true}/Q_{expected}$ ratio changes for different amounts of factors (factors 3-10). The figure shows that the line becomes flat after 8 factors, suggesting that the usage of more than eight factors in the PMF gives less robust solutions, as mentioned in the Background section.

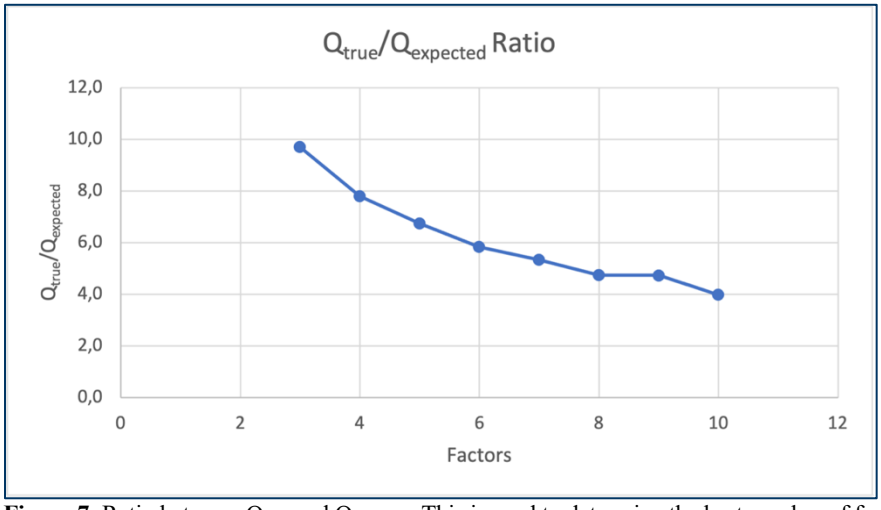

Figure 7: Ratio between Q_{true} and $Q_{expected}$. This is used to determine the best number of factors for the PMF model.

The Q ratio suggested that one of the solutions for 6 to 8 factors would be the best. Based on this the factors 6 to 8 were especially further analyzed to see which sources could be identified, where 6 factors were chosen as the one to go further with. The most sources could be identified here, for higher number of factors the sources seemed to be splitting into individual sources for some elements, and the traffic source were split into two separate factors.

The factor profiles from PMF consists of concentration of elements assigned to each factor, and % of species sum. The % of species sum describes how much the factor contributes to that element. The six factors can be seen to the left in Figure 8. The identified factors were named “Mineral dust”, “Combustion of petroleum-products + vehicles”, “Biomass burning”, “Sea salt”, “Steel industry emissions”, and “V-rich”. How these were identified is discussed in the Discussion section. The time series for the factors can be seen in Figure 9. The “Diesel combustion + vehicles” can be seen throughout the sampling period, with generally stable levels, but higher levels in the middle of January and February. The “Mineral dust” and “Sea salt” factors do not have stable levels, instead, they have higher levels in episodes. “Biomass burning” is seen mostly in January, but is low in the other months. The “V-rich” factor is seen throughout the sampling period, but with varying levels. The “Steel industry emissions” factor has one large peak and two smaller ones, otherwise, the levels are low.

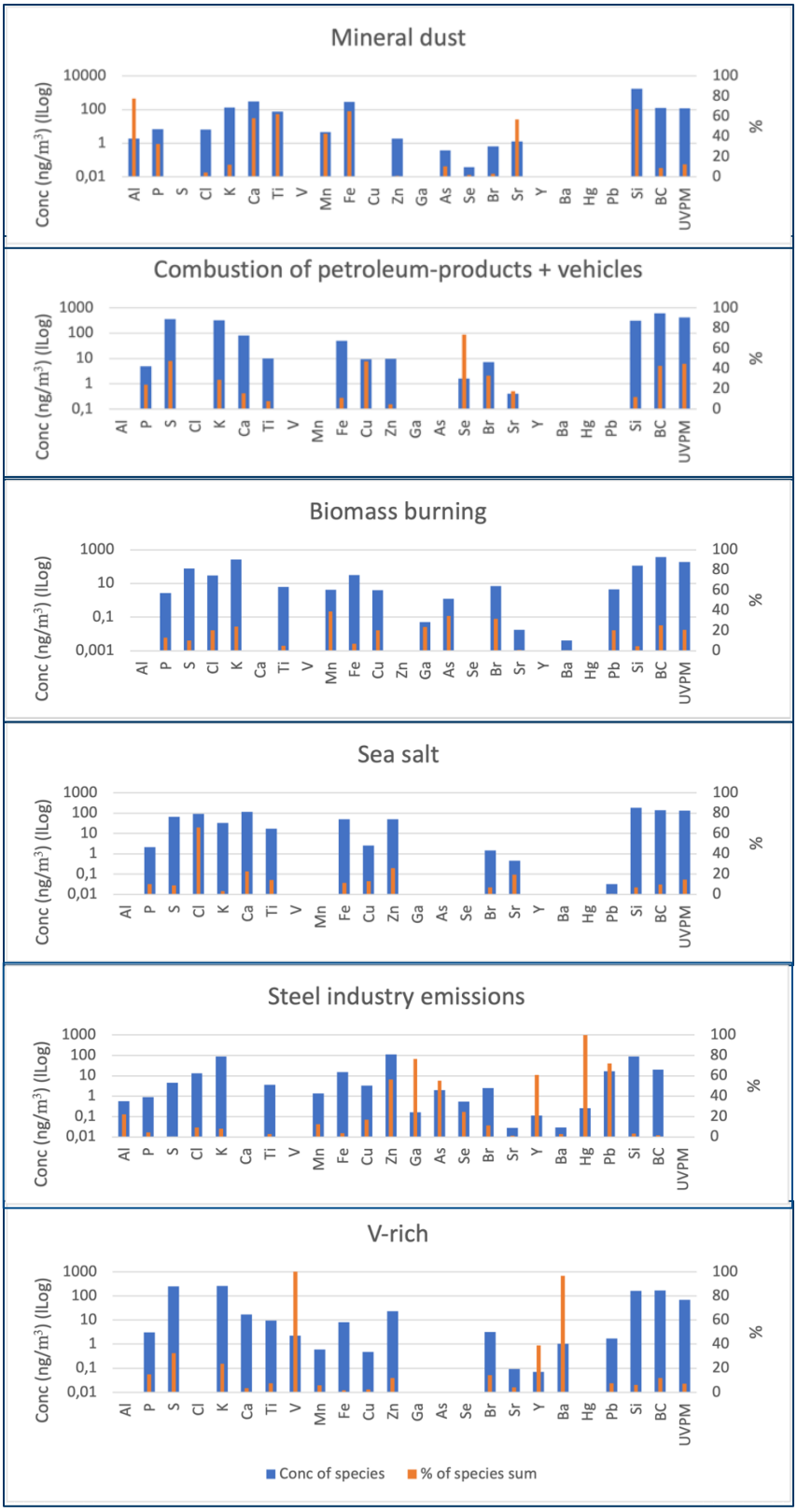

Figure 8: Factor profiles for each source. The left y-axis shows concentration on a log scale, and the right axis shows % of species sum.

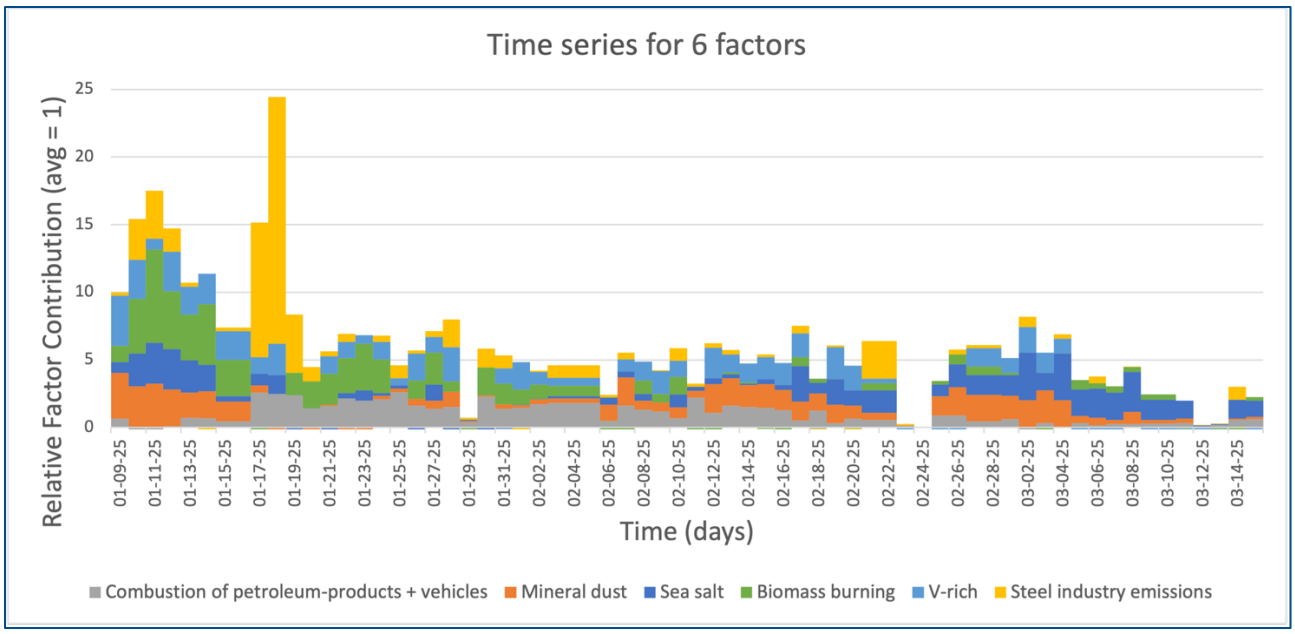

Figure 9: Time series for all six factors. The y-axis shows relative factor contribution (average = 1).

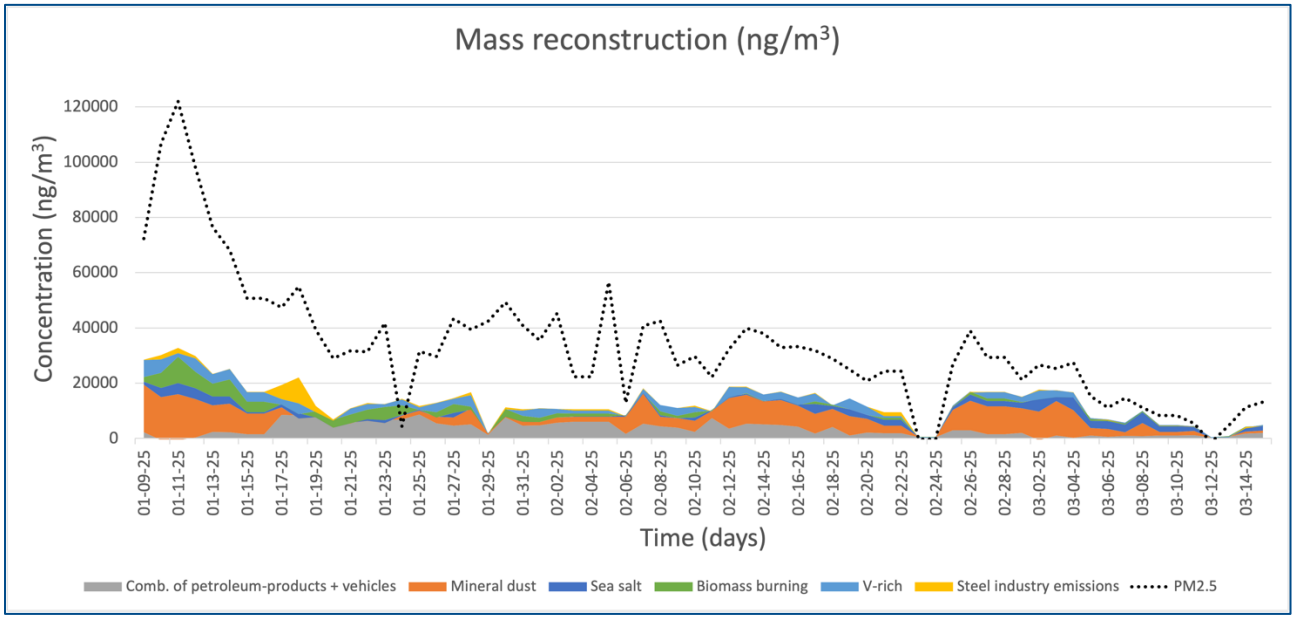

Figure 10: Estimated mass reconstruction using common oxides for each element. It does not match the PM2.5 time series, which is the dotted line. This is because not everything can be measured by the methods used in this study. For example, nitrate, organic compounds, and ammonium ions are not accounted for.

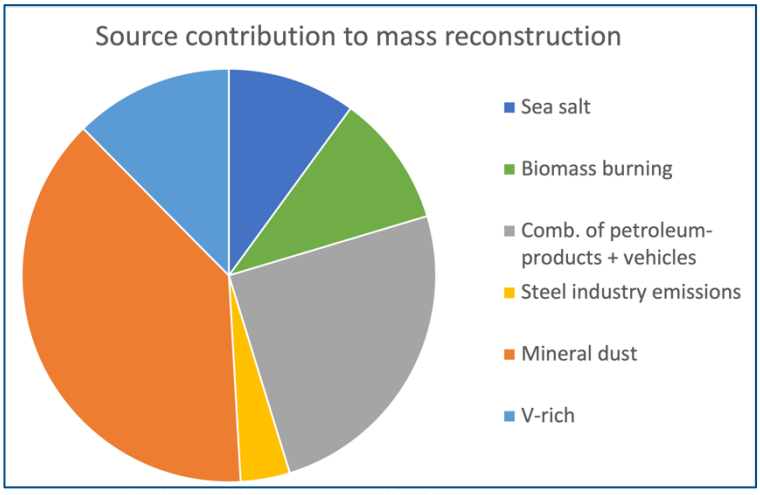

Figure 11: Pie chart of the source contributions.

The reconstructed mass does not fully match with the measured mass of PM2.5 (Figure 10). This is further discussed in the Discussion section.

The factors that contributed the most to the mass are mineral dust and diesel combustion + vehicles (Figure 11).

4. DISCUSSION

4.1 PM2.5

The maximum PM2.5 measured were 122 μg/m^3, and the mean value was 37 μg/m^3. The SD = 24 μg/m^3 indicates that the data is quite spread out, meaning that the results from this study show that the PM2.5 levels varied over the sample period. The average PM2.5 level of 37 ± 24 μg/m³ is well exceeding the AQG of 15 μg/m³, and the mean is right at the interim Target 3 at 37 μg/m^3 (World Health Organization, 2021). Since the studies mentioned in the Background section do not have the same duration or measurements during the same months, they can't be compared directly without taking this into account. Compared to the study by Olufemi et al. (2023), the mean from this present study is lower. The study by Olufemi includes more months of the Harmattan season, which could be an explanation for this. Compared to the study by Ezeh et al. (2018), they obtained the data for a whole year, which is not comparable since they have data from both the wet and dry seasons. Though their results showed that generally January had higher PM2.5 levels than February and March, which is similar to the results in this study. This indicates that the temporal trend seen between the months in Figure 3 could be due to seasonal patterns. The study by Alani et al. (2019) was performed during the wet season, which is most likely the reason for having lower concentrations than the present study, since periods with heavy rainfall might contribute to wash-out of particles as Alani et al. discuss in their report.

4.2 Correlation figures

Correlations found between elements can indicate a common source or similarity in chemical properties. The correlation matrix (see Figure 5 in results) gives a first visible overview of how the elements from the samples correlate with each other, and an indication of what sources the analysis with PMF will find. The results of this showed a strong correlation between elements indicating mineral dust (Al, Fe, Si, Ti, Ca, and Sr), combustion (K, BC, UVPM, and S), and traffic/industrial (Pb, Zn, and As).

4.3 PMF – Source apportionment

Deciding number of factors

To determine what number of factors that gave the most suitable solution, two approaches were taken. The first approach, to investigate the $Q_{true}/Q_{expected}$, can be seen in Figure 7. In the figure, its apparent that the slope straightens from factor 6 to 7, and then even more after factor 8. This indicates that the most fitted solution would be in the range of 6-8 factors, which was considered in further steps.

The next approach was to compare the percentage of species for each number of factors, to see similarities and distinguish source profiles. If the PMF can distinguish a similar factor for different runs, it indicates that it is a robust solution. The characteristic profiles of Mineral dust, Traffic, BB, Sea salt, and steel industry emissions were recurring through all the runs with different numbers of factors. These sources could be identified at the number of 5 factors, but having few factors can show mixed factors, which can become more distinct by using more factors. The risk of adding more factors could, however, also result in the splitting of sources. This seemed to be happening for 9 and 10 factors, where Zn seemed to be divided into its own source. The PMF solution for 7 factors was less clear to interpret, and the solution for 8 factors split the traffic factor into two different. The PMF solution with 6 factors was therefore decided as the most fitting solution. The reasoning behind the identification of the sources is described below.

Source apportionment

The first factor to be identified was of crustal origin and had high contents of Ca (58%), Ti (62%), Fe (65%), Sr (57%), and Si (67%), where percentage is the % of species sum (meaning that if = 100% then all contribution of the element is modelled from only one source). Sources of crustal

origin are in literature typically identified by Si, K, Ca, Ti, Fe, Br, Rb, and Sr (Kovacevik et al., 2011). This matches well with this factor and will here be called **Mineral dust**. It was visible as a source in all the cases for factors 3 to 10, which confirms its significance as a source and as a robust solution. Mineral dust usually has peaks during the dry season, as seen in a study by Owoade et al. (2016) in South West Nigeria, since influence from the Harmattan season brings winds with dust from Sahara. In the time series (see Figure 9), this factor has a higher loading in episodes. This could be because of meteorological conditions, as wind patterns and wind strength vary.

Mineral dust can also come from construction activities and road dust. Construction activities can contribute dust from gypsum, silt and gravel to the atmosphere. Rai et al. (2020) discuss that the absence of S from a mineral dust profile and weak correlation between S and Ca suggest an insignificant contribution from construction activities with gypsum dust. This factor has an absence of S (0%), and the samples generally have a low correlation between S and Ca (see Figure 5), therefore indicating a low contribution from construction activities with gypsum. Silt and gravel are recognised by Si and Ca, which are hard to differentiate from natural sources of mineral dust so therefore, the mineral dust in this factor could still have a contribution from anthropogenic sources.

It would be expected to see a factor/factors for combustion and traffic-related emissions based on the correlation figures. BC is emitted from sources such as combustion of fossil fuels and burning of wood, biomass fuels, and waste (Climate and Clean Air Coalition, n.d), and is especially known for being a marker for diesel exhaust (Owoade et al., 2016). Two factors were shown to contribute a lot to the BC content, and one of these significantly more at 43%. This factor also contributed much of the elements S (48%), P (24%), K (29%), Cu (47%), Se (74%), Br (33%) and Zn (5%) (see the orange bars in Figure 8), and additionally high content of Fe, Zn and Br (see the blue bars in Figure 8). According to Owoade et al. (2016), major elemental markers for vehicle emissions are Cu, Zn, Pb, Ni, and Mn. Additionally this factor also shows a quite similar profile as the "Exhaust traffic" profile in Rys et al. (2022) study of PM2.5 in Krakow. Cu content is associated with brake abrasion and fuel/lubricant combustion (Li et al., 2020). These observations motivate that this factor is traffic related. The time series (Figure 9) shows that this source is present throughout the entire sampling period and does not have drastic fluctuations, supporting the interpretation that it may originate from traffic. This factor could also have additional contributions from other petroleum-products combustion sources, such as the diesel generators used to provide extra energy supply. A study about diesel generators in Cambodia by Sothea and Kim Oanh (2019) conclude that the elements Fe, Ca, Zn, Mg, Al and Cr can be used as signatures for diesel generator emissions in PM apportionment studies, although they also state that emissions can vary between different generators and fuel content. The factor in this study had content of Fe (11%), Ca (16%), and Zn (5%). Based on the above discussion, this factor was called **Combustion of petroleum-products + vehicular emissions**.

The other factor with high contribution to the BC content (at 25%) also had high contribution to Cl (20%), K (24%), Mn (39%), Cu (20%), Ga (23%), As (34%), Br (31%), and UVPM (21%). This suggests that this factor could be identified as **biomass burning (BB)**. BB is mostly identified by organic and elemental carbon, K, and traces of Na, Cl, Cu, and Br (Ofosu et al., 2013). Cl can be both from BB since the compound and from burning of plastic, which happens during waste incineration. This also means that there is a possibility that emissions from waste incineration are contributing to this factor. The time series (Figure 9) for this factor shows that emissions are more present during January and almost not at all in February and March, indicating that more BB and/or waste incineration occurred in January. The fourth factor is majorly dominated by Cl (66%), suggesting that this is a source for **sea salt**. Since Lagos is a coastal city, it is reasonable that sea

salt would be found in the air. The time series (Figure 9) shows that this factor is present throughout the measuring period and has higher content in episodes.

The fifth factor contributed to Ga (77%), As (55%), Pb (72%), Hg (100%), Y (61%), Cu (17%), Zn (56%), Se (25%), Al (22%), and Mn (13%). While analysing the time series (Figure 9) for this source, it is visible that the factor is present in small amounts throughout all three months but has three peaks, one between 10-12 January, the largest between 17-19 January, and the third between 21-22 February. This indicates that this source might have regular emissions in small amounts, and on rare occasions, larger emissions. A longer sampling period would have been interesting to investigate this further, to see if the peaks are recurring. This type of trend also indicates that it is not a traffic related source. Looking at the present elements, Ga was only identified in 5 samples, Y in 15, and Hg only in 2 samples. These elements had in common that they were mostly detected in the earliest samples of the study, between the dates 9-21 January, where two of the peaks are. Though when examining the concentrations of these elements, it's evident that they are still very low in concentrations, implying that they were detected in these samples probably because they were emitted in slightly larger amounts than usual and therefore could be detected.

With a focus on the other elements instead, the presence of Zn, As, Pb, and Cu could be interpreted as coming from a type of industrial source. In the studies Kovacevik et al. (2011) and Owoade et al. (2016), it is motivated that Zn and Pb, among other elements, can be from either traffic or industry emissions. Since there is very little BC (1.4%) and S (0,6%) contribution modelled in this factor, which combustion sources like traffic would have high of, industrial emissions are more likely. A study by Duan and Tan (2013) linked As, Zn and Pb to steel industries (As from smelting furnaces, Zn from steel smelting, and Pb from steel production). Given this, and the episodic peaks seen in the timeseries, this factor is identified as a **steel industry source**.

The sixth factor accounts for the following % of the species sum: S (32%), K (24%), Zn (12%), Y (39%), V (100%) and Ba (97%). Some BC content at 12% (UVPM at 7%). The source is present almost throughout the measuring period, see Figure 9, and has a few days scattered across the period with no contribution. V is known to be emitted from industry and the combustion of fossil fuels. Even though the % of species sum is seemingly low for BC in this factor, BC is together with S and K contributing the most mass to this factor. This indicates combustion, but that this source is a smaller contributor to the BC and UVPM emissions than the other sources mentioned above. In order to more confidently call this factor an oil-combustion source it would have been preferred to have Ni also, since V and Ni are used in multiple studies for this identification (Kovacevik et al., 2011), (Li et al., 2020). It is also questionable that if V were from oil combustion, it only showed in 39 samples, and not more. Also, the element Y is not commonly used as a tracer for oil-combustion emissions and is primarily found in industrial emissions instead.

To analyse this deeper, extra attention was put on the concentration time series for each of these elements. V was found in 39 samples, Ba in 3, and Y in 16. V was found in samples across the measuring period, with slightly higher concentrations in the beginning. The three samples with Ba were detected across January, at the dates 12/1, 24/ and 29/1. Y, on the other hand, was mostly found at the beginning of January (dates 9th to 22nd January, similar to the factor discussed above). This indicates that Y could be from industrial emissions, and since Y is not known to be in oil combustion emissions, this source probably has influence from both industrial emissions and some oil combustion. Another thing to consider is that since multiple elements in this factor were only detected a few times, the PMF could have a harder time connecting these elements to the other, which means that the solution could be somewhat unreliable. With this in mind, the factor will be called **V-rich** and not be identified as a specific source.

To summarize, the factors were identified as: Mineral dust, Combustion of petroleum-products + vehicle emissions, Biomass burning, Sea salt, Steel industry, and lastly a V-rich source. The identified sources in this study are similar to the sources found in Ezeh et al. (2018). Ezeh et al. found sea spray, industrial and tire wear emissions, soil/dust, biomass burning, and petroleum oil combustion. The additional source in this present study is the V-rich source. The pie chart (Figure 11) shows that mineral dust and traffic emissions are the sources contributing the most to the mass of PM2.5 pollution. Figure 10 shows however that there is a significant part of the PM2.5 mass that was not measured by the method in this study, meaning that other sources with content that could not be identified by this study (for example nitrate, organic compounds, and ammonium ions) also could have significant contribution to the air pollution of PM2.5 in the area.

4.5 Improvements for further studies

- Having a larger data set by extending the measuring period, which would make the PMF analysis more robust and could improve source resolution. A larger number of data points increases statistical reliability of the PMF model and improves the separation of overlapping sources. Including hourly measurements to enable analysis of diurnal trends could also be interesting, since it could help in identifying sources like traffic emissions, since traffic usually follows a pattern during the day.
- Include techniques that could measure the elements/compounds that could not be accounted for, such as nitrate, organic compounds, and ammonium ions.
- Include meteorological data to assess the influence of meteorological factors. For example, it would have been interesting to perform a back trajectory analysis with wind data to investigate the influence of wind patterns. Such an analysis could indicate which regions emissions come from, which could have strengthened the identification of certain sources, for example the Harmattan winds or specific industries.

5. CONCLUSION

This study investigated PM2.5 pollution in Lagos, Nigeria, through source apportionment using sixty 24-hour filter samples collected from the University of Lagos. The average PM2.5 level was 37 ± 24 μg/m³, greatly exceeding the WHO 24-hour guideline of 15 μg/m³. The results showed that levels were highest in January and then declined towards March, which agreed with a seasonal trend of the months, seen in a previous study also done in Lagos. Twenty-two elements were detected, and six sources were identified: mineral dust, combustion of petroleum products and traffic-related emissions, biomass burning, sea salt, steel industry, and lastly, a V-rich source. Mineral dust and the traffic-related source were found to be the dominant contributors to the overall mass. However, the mass reconstruction showed a discrepancy with the overall PM2.5 mass, suggesting the presence of additional PM2.5 constituents. Such other constituents could be organic compounds, nitrates, and ammonium, which were not accounted for by using the methods in this study.

Improvements could be made by having a larger data set, either by conducting the study over a longer period or by taking hourly measurements. A larger data set would improve the robustness of the PMF. Hourly measurements would help capture diurnal patterns, which could help the identification of traffic-related sources. Including meteorological data such as wind direction, wind speed, and precipitation would also provide a valuable context for interpreting pollution trends and to better understand the impacts these have on PM2.5 pollution.

Lagos faces critically high levels of PM2.5, which pose a significant health risk to its population. Based on the findings of this study, emissions reductions should prioritise the traffic and transport sector, which appears to be the major anthropogenic contributor to urban air pollution.

Acknowledgements

I would like to sincerely thank my supervisor, Jan Pettersson, for guiding me and supporting me through the entire project. I would also like to thank Rose Alani and Fatimoh Afolabi at University of Lagos who carried out the sampling of the filters. Without their efforts, this study would not have been possible.

6. REFERENCES

Aerosol Magee Scientific. (n.d). *SootScan OT21*. Retrieved 2 May 2025 from https://www.aerosolmageesci.com/products/sootscan-model-ot21-optical-transmissometer/

Agbo, E. P., Nkajoe, U., & Edet, C. O. (2023). Comparison of Mann–Kendall and Şen's innovative trend method for climatic parameters over Nigeria's climatic zones [Article]. *Climate Dynamics*, *60*(11-12), 3385-3401. https://doi.org/10.1007/s00382-022-06521-9

Alani, R. A., Ayejuyo, O. O., Akinrinade, O. E., Badmus, G. O., Festus, C. J., Ogunnaike, B. A., & Alo, B. I. (2019). The level PM2.5 and the elemental compositions of some potential receptor locations in Lagos, Nigeria. *Air Quality, Atmosphere & Health*, *12*(10), 1251-1258. https://doi.org/10.1007/s11869-019-00743-3

Brook, R. D., Rajagopalan, S., Pope, C. A., 3rd, Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin, F., Hong, Y., Luepker, R. V., Mittleman, M. A., Peters, A., Siscovick, D., Smith, S. C., Jr., Whitsel, L., & Kaufman, J. D. (2010). Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation*, *121*(21), 2331-2378. https://doi.org/10.1161/CIR.0b013e3181dbece1

Climate and Clean Air Coalition. (n.d). *Black Carbon*. Retrieved 14 May 2025 from https://www.ccacoalition.org/short-lived-climate-pollutants/black-carbon

Croitoru, L., Chang, J. C., & Kelly, A. (2020). *The Cost of Air Pollution in Lagos*. World Bank. http://hdl.handle.net/10986/33038

Duan, J., & Tan, J. (2013). Atmospheric heavy metals and Arsenic in China: Situation, sources and control policies. *Atmospheric Environment*, *74*, 93-101. https://doi.org/https://doi.org/10.1016/j.atmosenv.2013.03.031

Ezeh, G. C., Obioh, I. B., Asubiojo, O. I., Onwudiegwu, C. A., Nuviadenu, C. K., & Ayinla, S. B. (2018). Airborne fine particulate matter (PM2.5) at industrial, high- and low-density residential sites in a Nigerian megacity [Article]. *Toxicological and Environmental Chemistry*, *100*(3), 326-333. https://doi.org/10.1080/02772248.2018.1485924

Fakinle, B., Odekanle, E., Olalekan, A., Ije, H., Olawale, O., & Sonibare, J. (2020). Air pollutant emissions by anthropogenic combustion processes in Lagos, Nigeria. *Cogent Engineering*, *7*, 1808285. https://doi.org/10.1080/23311916.2020.1808285

Google Earth. (2025). *Location of Lagos in Nigeria [Map]*. Google. Retrieved 22 May from https://earth.google.com/web/search/Nigeria/@9.03378421,8.67726514,446.00032553a,2350965.78480121d,35y,0h,0t,0r/data=CiwiJgokCbaX8vQkCBtAER9BMnUKWhlAGYO3zDqI-gxAIVh5ffCQkAdAQgIIAToDCgEwQgIIAEoNCP_____wEQAA

Google Maps. (2025). *Location in Lagos [Map]*. Google. Retrieved 23 May from https://www.google.com/maps/place//@6.4992704,3.3953001,13.34z/data=!4m6!1m5!3m4!2zNsKwMzEnMDQuMyJOIDPCsDIzJzU0LjUiRQ!8m2!3d6.517867!4d3.39846?entry=ttu&g_ep=EgoyMDI1MDYwMi4wIKXMDSoASAFQAw%3D%3D

Harrison, R. M. (2014). *Pollution : causes, effects and control* (5th ed.). The Royal Society of Chemistry.

Health Effects Institute. (2022). *The State of Air Quality and Health Impacts in Africa. A Report from the State of Global Air Initiative.* https://www.stateofglobalair.org/sites/default/files/documents/2022-10/soga-africa-report.pdf

Health Effects Institute. (2024). *State of Global Air. Special report*. https://www.stateofglobalair.org/resources/report/state-global-air-report-2024

Hoornweg, D., & Pope, K. (2017). Population predictions for the world's largest cities in the 21st century. *Environment & Urbanization*, *29*(1), 195-216. https://doi.org/10.1177/0956247816663557

International Energy Agency. (n.d). *Nigeria*. Retrieved 12 May 2025 from https://www.iea.org/countries/nigeria

Kovacevik, B., Wagner, A., Boman, J., Laursen, J., & Pettersson, J. B. C. (2011). Elemental composition of fine particulate matter (PM2.5) in Skopje, FYR of Macedonia. *X-Ray Spectrometry*, *40*(4), 280-288. https://doi.org/https://doi.org/10.1002/xrs.1337

Li, R., Wang, Q., He, X., Zhu, S., Zhang, K., Duan, Y., Fu, Q., Qiao, L., Wang, Y., Huang, L., Li, L., & Yu, J. Z. (2020). Source apportionment of PM2.5 in Shanghai based on hourly organic molecular markers and other source tracers. *Atmos. Chem. Phys.*, *20*(20), 12047-12061. https://doi.org/10.5194/acp-20-12047-2020

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and Health Impacts of Air Pollution: A Review [Review]. *Frontiers in Public Health*, *Volume 8 - 2020*. https://doi.org/10.3389/fpubh.2020.00014

Manousakas, M., Papaefthymiou, H., Diapouli, E., Migliori, A., Karydas, A. G., Bogdanovic-Radovic, I., & Eleftheriadis, K. (2017). Assessment of PM2.5 sources and their corresponding level of uncertainty in a coastal urban area using EPA PMF 5.0 enhanced diagnostics. *Science of The Total Environment*, *574*, 155-164. https://doi.org/https://doi.org/10.1016/j.scitotenv.2016.09.047

Ofosu, F. G., K., H. P., K., A. I. J., & and Bamford, S. A. (2013). Biomass burning contribution to ambient air particulate levels at Navrongo in the Savannah zone of Ghana. *Journal of the Air & Waste Management Association*, *63*(9), 1036-1045. https://doi.org/10.1080/10962247.2013.783888

Olufemi, A. P., Fawole, O. G., Owoade, O. K., Popoola, O. A. M., Jones, R. L., Toyeje, A. B., Abiodun, P. O., Omokungbe, O. R., Abiye, O. E., & Sunmonu, L. A. (2023). Spatiotemporal distribution of pollutants and impact of local meteorology on source influence on pollutants' level in a traffic air-shed in Lagos megacity, Nigeria [Article]. *Environmental Monitoring and Assessment*, *195*(9), Article 1126. https://doi.org/10.1007/s10661-023-11757-x

Owoade, K. O., Hopke, P. K., Olise, F. S., Adewole, O. O., Ogundele, L. T., & Fawole, O. G. (2016). Source apportionment analyses for fine (PM2.5) and coarse (PM2.5–10) mode particulate matter (PM) measured in an urban area in southwestern Nigeria. *Atmospheric Pollution Research*, *7*(5), 843-857. https://doi.org/https://doi.org/10.1016/j.apr.2016.04.006

Pekney, N. J., I., D. C., Allen, R., Liming, Z., Philip, H., Delbert, E., & and Rogge, W. F. (2006). Major Source Categories for PM2.5 in Pittsburgh using PMF and UNMIX. *Aerosol Science and Technology*, *40*(10), 910-924. https://doi.org/10.1080/02786820500380271

Rai, P., Furger, M., El Haddad, I., Kumar, V., Wang, L., Singh, A., Dixit, K., Bhattu, D., Petit, J.-E., Ganguly, D., Rastogi, N., Baltensperger, U., Tripathi, S. N., Slowik, J. G., & Prévôt, A. S. H. (2020). Real-time measurement and source apportionment of elements in Delhi's atmosphere. *Science of The Total Environment*, *742*, 140332. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.140332

Resilient Cities Network. (2023). *Lagos Urban Power Profile: Power System and Urban Resilience*. R. C. Network. https://resilientcitiesnetwork.org/urban-power-lagos/

Rys, A., Samek, L., Stegowski, Z., & Styszko, K. (2022). Comparison of concentrations of chemical species and emission sources PM2.5 before pandemic and during pandemic in Krakow, Poland. *Scientific Reports*, *12*(1), 16481. https://doi.org/10.1038/s41598-022-21012-x

Sheposh, R. (2024). *Lagos, Nigeria*. EBSCO. Retrieved 22 May 2025 from https://www.ebsco.com/research-starters/history/lagos-nigeria

Sothea, K., & Kim Oanh, N. T. (2019). Characterization of emissions from diesel backup generators in Cambodia. *Atmospheric Pollution Research*, *10*(2), 345-354. https://www.sciencedirect.com/science/article/pii/S1309104218302824

Spectro Analytical Instruments. (n.d). *The fundamentals of energy dispersive X-ray fluorescence technology [PDF].* Spectro Analytical Instruments. https://extranet.spectro.com/-/media/8CC93043-2863-489F-806E-98EF775948B7.pdf

U.S. Environmental Protection Agency. (2014). *Positive Matrix Factorization (PMF) 5.0 Fundamentals and User Guide*. U. S. E. P. Agency. https://www.epa.gov/sites/default/files/2015-02/documents/pmf_5.0_user_guide.pdf

UN environment programme. (2020). *West African Ministers adopt cleaner fuels and vehicles standards*. Retrieved 20 May 2025 from https://www.unep.org/news-and-stories/story/west-african-ministers-adopt-cleaner-fuels-and-vehicles-standards

World Health Organization. (2021). *WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Executive summary*. https://iris.who.int/bitstream/handle/10665/345334/9789240034433-eng.pdf?sequence=1

Xiong, R., Li, J., Zhang, Y., Zhang, L., Jiang, K., Zheng, H., Kong, S., Shen, H., Cheng, H., Shen, G., & Tao, S. (2022). Global brown carbon emissions from combustion sources. *Environmental Science and Ecotechnology*, *12*, 100201. https://doi.org/https://doi.org/10.1016/j.ese.2022.100201