UNIVERSITY OF GOTHENBURG

DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL SCIENCES

PATHWAYS TOWARDS SUSTAINABLE DEVELOPMENT:

Environmental diagnostics and air pollution mitigation in Lagos, Nigeria

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Abstract

The pathway towards sustainable development for any city must involve knowledge of the pollution problems and finding ways to limit or eliminate such problems. It is essential to find a pathway for Lagos to be sustainable as it is one of the most populated cities in Africa vested in creating a safe and sustainable environment for its people. Air pollution is a very serious problem that is not given enough significance in Africa due to the developing nature of countries on the continent.

To find out the air pollution problems of Lagos, Nigeria, the meteorological factors that influence air pollution in the city were observed and their extent was determined. A particle size distribution of particulate matter (PM) distribution in the air was also obtained using the optical aerosol spectrometer (Grimm), while various low-cost sensors were used to compare the concentrations at various places in Lagos. The pollution volume of different areas in the city was analyzed to know how much long-range transport had on particle movement and how much local pollution had on those areas. The Chemical ionization method spectroscopy (CIMS) was applied to analyze the organic components of the particulate matter in Lagos. Using energy-dispersive X-ray fluorescence (EDXRF) in conjunction with positive matrix factorization (PMF), the location of the various sources of pollution in the city was done which helped us to advise on possible mitigation methods to curb air pollution in Lagos. If these mitigation methods are introduced we believe that air pollution will be reduced by more than half its current levels.

Keywords: Pollution, Lagos, Particulate matter (PM), Sensor, Environment, Meteorology, Nigeria.

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1. Introduction

Air pollution is the presence of one or more contaminants in the atmosphere in a quantity and for a duration as to be harmful, or tending to be harmful, to human health, animal, or plant life. World Health Organization (WHO) identified four pollutants for which there is strong evidence of health effects on humans. They are particulate matter (PM), ozone (O_3), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) (WHO 2005).

In 2019, 99% of the world population was living in places where the WHO's strictest 2021 air quality guideline levels were not met (UNEP 2022). There are various sources of air pollution and they include; agriculture, industrialization, transport, waste, energy, marine aerosol from the sea, and residential and windblown dust sources. In Africa, the major source of air pollution is windblown dust contributing to 22.57 µg/m3 of the average total of Africa which is 43.29 µg/m3 (UNEP 2022).

Around the world, air pollution is responsible for an estimated 7 million premature deaths per year (UNEP, 2022). Nigeria is adjudged to be the country with the highest number of premature deaths (68,533 deaths in 2019) due to air pollution in West Africa and the second largest only to Egypt in Africa (UNEP, 2019), making it a severe situation. Lagos City accounts for about 11,200 of these deaths. People living in Nigeria are also exposed to 70 µg/m3 of air pollution concentration annually, which is 14 times the acceptable concentration according to WHO guidelines (UNEP, 2022). Lagos is a coastal city of about 24 million people and can be used to show how air quality is upending African megacities' growth, health and livelihoods. In spite of growing concern about air pollution, there is currently no reliable estimate of the impact of ambient air pollution, nor a comprehensive air pollution control plan (LASEPA, 2014).

There are negative effects on air quality in Lagos metropolis caused by the rapid growth in industries, motorized transport, and consumption of energy (Nkashi, 2019). In developing countries like Nigeria (Manucci PM, Franchini, 2017), the problem is more serious due to overpopulation and uncontrolled urbanization along with the development of industrialization. This leads to poor air quality, especially in countries with social disparities and a lack of information on sustainable management of the environment. The use of fuels such as wood fuel or other solid fuels for domestic needs due to low incomes exposes people to polluted air at home. It is of note that three billion people around the world are using the above sources of energy for their daily heating and cooking needs (WHO 2017).

This study aims to characterize the air pollution situation in Lagos, Nigeria, and also to suggest mitigation methods that may improve air quality by carrying out a source apportionment for inhalable particles ($PM_{2.5}$) based on data from analyses of filter samples, characterization of the temporal and spatial variations in air pollution in Lagos using multiple sensors for $PM_{2.5}$, and lastly evaluate air quality management methods that may reduce air pollution levels

1.1. Background

When we breathe, we take in tiny particles that can cause severe damage to our organs and lead to various health problems (UNEP, 2022). These particles which may include soot, soil dust, sulphates and other types of particles are called particulate matter (PM). These inhalable particles are a complex mixture consisting of organic and inorganic components that are either natural or anthropogenic in origin (Hinds 1998).

Particulate matter is airborne and consists of particles of different sizes, compositions, and origins. These variables determine the characteristics and properties of PM. The most significant characteristic of particulate matter is often its diameter. This is because it determines transportation and removal from the atmosphere and it also governs its deposition within the respiratory system. Sampling and description of airborne PM are done based on their aerodynamic properties (Hinds 1998). Particulate matter is generally classified into two groups based on particle size; coarse fraction (from 2.5 to 10 µm) and fine fraction (below 2.5 µm). This classification is used in health-related studies, regulation, and formulation of policies. In some other studies, they may be divided into three groups PM_1 (all particles with a diameter below 1 µm); $PM_{2.5}$ (below 2.5 µm), and PM_{10} (below 10 µm).

The size, elemental, and chemical characteristics of PM are related to their sources (Hinds 1998, Lui et al. 2000, Gabriel et al. 2002). Fine particles are usually formed from gas-to-particle conversion through condensation and solidification and the resulting particles are referred to as secondary particles, while coarse particles are usually produced from agricultural processes, uncovered soils, road dust, evaporation of sea spray, and vegetation debris (Finalyson-Pitts and Pitts Jr 2000). In most urban areas in developing countries, the chemical and elemental composition of PM usually develops from vehicular emission, road dust, biomass burning, and industrial emissions (Hand et al. 2010, Kinney et al. 2011, Pektova et al. 2013). The major sources of air pollutants in the environment include emissions from vehicles, electricity generators and industries, road and building construction activities, as well as mining. Vehicular emissions constitute a main source of fine and ultrafine particles and have a serious impact on urban air quality and public health (Mohan et al; 2013).

According to the WHO data bank, it is estimated that complications from PM inhalation are the top cause of death in Africa between 2014-2016 resulting in 10% of global mortality, amounting to 7 million people, resulting from air pollution in 2012 (WHO 2014). In the 2016 WHO report, 2.9 million annual estimated deaths were reported, of which more than 85% occurred in low- and middle-income countries. PM particles can be carried over long distances by wind and then settle on ground or water and depending on their chemical composition, the effects of this deposition may include damage to crops and animals due to the acidity of the particles; soil nutrient depletion; affecting nutrient balance in coastal water and sometimes acid rain (US EPA, 2022).

Lagos is the commercial and economic hub of Nigeria and is also one of the world’s fastest-growing megacities, expected to become the largest city by 2100

(Hoornweg and Pope, 2016). It generated 25% of the country's Gross Domestic Product (GDP) in 2015 and is home to 70% of the country's industrial and commercial activities (Owoade et al. 2013; PwC 2015). Fast urbanization and industrialization have exposed the majority of the population to high levels of air pollution, with negative effects on human lives (Olowoporoku et al., 2012) and on changing climatic conditions (Komolafe et al., 2014). Rapid growth in vehicular traffic and industrialization contribute to high levels of urban air pollution (Mohan et al., 2013).

Lagos City, Nigeria, is in the southwestern part of the country bounded by the Ogun state to the North and East, the Bight of Benin to the South, and the Republic of Benin to the West. It is a coastal city with a coastline of approximately 180 km located between longitudes 2° 42′E and 4° 21′E and latitudes 6° 22′N and 6° 41′N (Odunuga et al. 2012; BRNCC 2012). The state's population which is mainly Yoruba has grown and is more heterogenous due to the massive migration of Nigerians and other West Africans to the state. Lagos is also a port city boasting one of the largest ports in West Africa and also a commercial centre of the country. The metropolitan area originated on islands, including Lagos Island which was protected from the Atlantic Ocean by sand spits, and includes places like Lekki, Epe, Victoria Island, and Ikoyi. The city has expanded onto the mainland west of the lagoon, however, with Ikeja, the capital of Lagos, and other places like Yaba, Oshodi, Festac, Badagry, and Agege over 25 miles northwest of Lagos Island.

Lagos city is one of the smallest cities in Nigeria covering a total land area of 3577.28 km^2, out of which 22 % is wetland, the population density is approximately 5926 persons per km^2 (Oshodi, 2013) and could be as high as 20,000 persons per km^2 in some built-up areas (BRNCC 2012). With a growth rate between 3.2 and 8 % per year (World Bank 2013; Oyegoke et al. 2012; United Nations Centre for Human Settlements, 1996), it was estimated to have a population of 24.5 million in 2015 (UN-Habitat, United Nations Human Settlements Programme, 2008) and 29 million by 2020 (George 2010). As a result of this high population, the peri-urban areas of the state have experienced growth of informal settlements, pollution, unregulated waste disposal, and other types of socio-environmental degradation.

Lagos has a low-lying topography of 1–4 % slopes, and an elevation of 0–2 m above sea level, which is characterized by a dendritic drainage system comprising Rivers Ogun, Adiyan, and Ossa (BRNCC 2012; Odunuga et al. 2012; Idowu and Martins, 2007). With 70 % of its population living in unplanned settlements such as slums (Adelekan 2010), it ranks 15th in the world in terms of population exposed to coastal flooding. The average temperature in Lagos is 26.7 ° C and 1783 mm of rainfall occurs yearly [Climate-Data.org]. The climate classification given by Balogun et al. (2016) shows the seasonal rainfall variability in Nigeria. The four seasons are spring which coincides with the March Equinox comprising February, March, and April (FMA), summer which coincides with the June Solstice consisting of May, June, and July (MJJ), autumn which streamlines with the September Equinox [August, September, October (ASO)] and, lastly winter which is described as December Solstice [November, December, January (NDJ)].

For this study, we tried to get samples from the two major divisions of Lagos which are Lagos Mainland and Lagos Island. For Lagos mainland, we studied Akoka, Bariga, Ilaje, and Makoko areas while for Lagos Island we covered the Lekki and Victoria Island axis.

2. Methodology

The methodology used in this paper to define this study was to focus on the particulate matter in the air, including characterization of the physical and chemical properties of PM using multiple methods. Meteorological data was also used to complement the PM properties studied in this thesis. This study paid special attention to the $PM_{2.5}$ concentration in a bid to evaluate the city's pollution levels.

This study aims to cover the two major divisions of Lagos which are Lagos Mainland and Lagos Island. For Lagos mainland, areas covered include; Akoka, Apapa, Bariga, Ikorodu, and Makoko areas while for Lagos Island we covered the Lekki and Victoria Island axis. Figure 1 shows the various parts of Lagos covered for this study. The studied areas are represented by the red dots on the map.

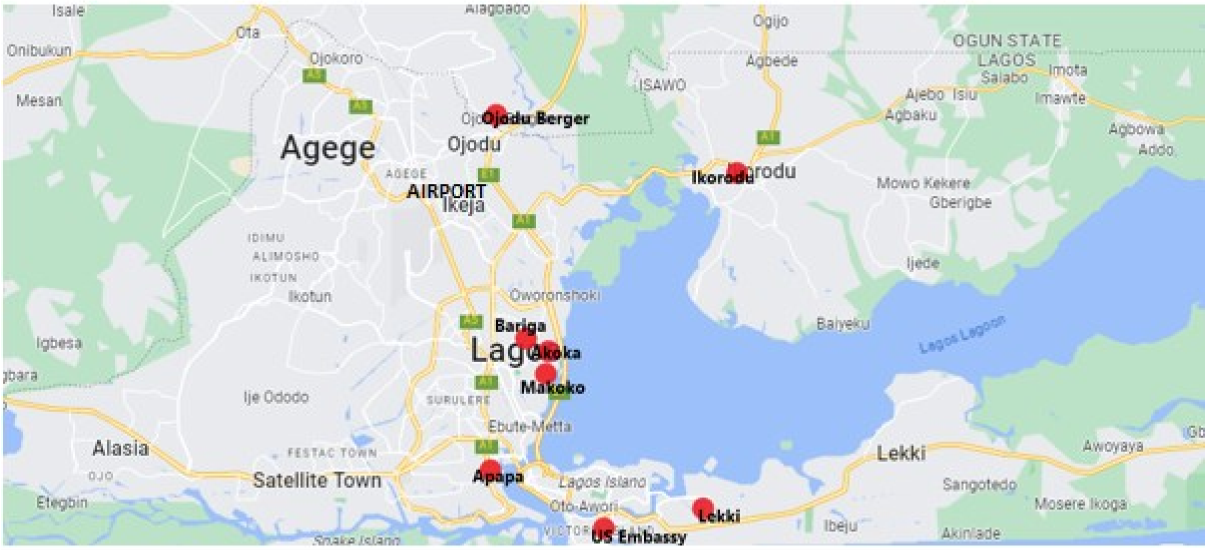


Figure 1. Map of Lagos showing the areas covered for this study.

The areas in this study are a representation of various zones and environments found in Lagos. Table 1 below shows the characteristics of the areas measured.

Study area	Zone	Environment(Others)
Akoka	Commercial	University environment
Apapa	Commercial	Harbour environment
Bariga	Commercial/Residential	Outskirts of University
Ojodu Berger	Industrial/Residential	Border area
Ikorodu	Commercial/Residential	Border area

Makoko	Residential/Slum zone	Lagoon environment
Lekki	Commercial/Residential	Close to the sea
Victoria Island	Commercial	Close to the sea

Table 1. Table showing study areas and their characteristics.

2.1. Meteorological measurements

To get the meteorological measurements of Lagos, I used the hourly meteorology results from Lagos International Airport [ASOS network (https://mesonet.agron.iastate.edu/)]. I focused on parameters like relative humidity, temperature, and visibility and plotted a rose diagram with the wind speed and direction to get where the wind is coming from and deduce its impact on PM spread and concentrations. This took into consideration the readings from January 1 to August 17, 2023.

2.2. Particulate matter measurement techniques

This study was carried out using different measurement techniques, which can be divided into online measurements and offline measurements. The online measurements were done using the low-cost monitoring sensor (PurpleAir), the aerosol spectrometer (Grimm), and online data obtained from a sensor at the US Embassy in Lagos. The offline measurements were done by initial sampling which involved pumping air through plastic cyclones to collect $PM_{2.5}$ on filters after which the filters were analyzed in the laboratory using Energy dispersive X-ray fluorescence spectrometer or Chemical ionization mass spectrometer.

2.2.1. Online measurements

Online measurements represent those measurements and data gotten from real-time sensors placed by me and those already in place in various parts of Lagos. They include;

2.2.1.1. PurpleAir sensor

PurpleAir sensors are low-cost monitoring sensors that are used to measure real-time PM concentrations of different sizes, temperatures, humidity, and pressure for residential, commercial, or industrial use and can be installed indoors or outdoors. Each sensor is connected to WiFi and a power source and the data can be obtained online [Purple air (https://community.purpleair.com/t/what-do-purpleair-sensors-measure-and-how-do-they-work/)]. PurpleAir sensors from Plantower counters to measure particulate matter in real time. Purpleair sensors are made up of two laser counters. Each laser counter within a pair alternates five-second readings averaged over two minutes. Each laser counter uses a fan to draw a sample of air past a laser beam. The laser beam is reflected off any present particles onto a detection plate. The reflection is measured as a pulse by the detection plate, and the length of this pulse determines the size of the particle. The number of pulses determines the particle count. These particle measurements are used to infer the mass concentrations PM_1, $PM_{2.5}$, and PM_{10} for standard indoor and outdoor atmospheric particles. PurpleAir sensors were deployed to the Lekki, Akoka, Apapa, Ikorodu, Ojodu Berger and Bariga areas where the PM measurements were read from the devices. For this study, the raw $PM_{2.5}$ concentration recorded was used for all analyses done with this device. The displayed data are raw data and corrections have been applied to correct the values. There are several corrections have been suggested in the options on the device but at present due to uncertainties with the various corrections and how they affect conditions prevailing in Lagos, the raw $PM_{2.5}$ concentration was used. Further studies will be required to recommend a correction of Purpleair data under these conditions.

2.2.1.2 Aerosol Spectrometer

This is an aerosol spectrometer (Dustmonitor Model 1.108, Grimm GmbH) built for continuous optical measurement of airborne particles as well as for measuring the particle number size distribution. It possesses an integrated gravimetric filter on which all particles are collected after the optical measurement and thus is available for further analysis. The data can be displayed as number concentration in the unit particle/liter and also as a mass concentration in the unit µg/m3. The Grimm Windows Software additionally shows different dust mass fractions which are displayed as well as the calculated particle surface area. The standardized dust mass fraction is in terms of occupational health respiratory, thoracic, and alveoli. A second dust mass fraction is named emissions PM_{10}, $PM_{2.5}$, and $PM_{1.0}$. The measuring principle of model 1.108 which was used for this study is the light scattering of single particles with a semiconductor laser as a light source and it possesses 15 size channels. This way the particle size distribution can be measured which provides the basis for the calculation of the dust mass. These devices are suitable for a variety of applications for instance the compilation of occupational health data, dust analysis, inhalation toxicology, aerosol research, or atmospheric research.

In the instrument, the sample air is sucked through the measuring cell and a gravimetric filter utilizing an internal volume flow-controlled pump. This filter serves as a dust collector and can be used for gravimetric control of the optical gained measurement results. The pump also conveys the rinsing air, which is gained out of the pump's exhaust air via a zero filter and is held constant by a rinsing air control. The rinsing air protects the laser optics just as other components of the optical measuring cell from pollution and serves during the self-test as particle-free reference air. The device was used in Lekki and Akoka areas to measure particulate matter

2.2.2. Offline measurements

Offline measurements represent measurements that were obtained from several samples collected from the study areas and taken back to the laboratory for analysis. They include;

2.2.2.1. EDXRF Spectroscopy Analysis

Energy Dispersive X-ray fluorescence spectroscopy (EDXRF) uses a Philips diffraction X-ray Tube and a Mo secondary target. Fluoresced X-rays were propagated through two Ag collimators giving a relatively focused beam of near monochromatic X-ray for sample excitation. The samples (filter papers) were collected using plastic cyclone samplers and a pump calibrated with a flow rate of 3 litres per second or approximately 24 hours each. The spectrometer uses an optimized three-axial geometry that gives good signal-to-noise ratios for the measured elements on the filter papers (Boman 1991). A calibration file was created using single-element standards which were run and evaluated for elements' net peak area (P_A) and associated background area (B_A). The obtained P_A and B_A together with the known concentration (C_A) of the elements were used to calculate the detection limit (DL_A). This technique was used to analyse the inorganic components of the particulate matter.

2.2.2.2. CIMS Analysis

In chemical ionization mass spectrometry (CIMS), ionization of the gaseous analyte occurs via gas-phase reactions rather than by direct electron impact (EI), photon impact, or field ionization (Harrison, 2017). EI ionization of a reagent gas (present in large excess) is usually followed by ion–molecule reactions involving the initially formed ions and the reagent gas neutrals to produce the chemical ionization (CI) reagent ion or reagent ion array. Collision of the reagent ion(s) with the analyte (usually present at 1% of the reagent gas pressure) produces one or more ions characteristic of the analyte. These initial analyte ions may undergo fragmentation or, infrequently, react further with the reagent gas to produce a final array of ions representing the CI mass spectrum of the analyte as produced by the specific reagent gas. To a considerable extent, the usefulness of CIMS arises from a soft ionization method that limits the fragmentation of the original molecules. The size of molecules can be determined. Combined with a high-resolution mass spectrometer, the exact composition of the molecule can be determined. Problems that can be solved by chemical ionization include molecular mass determination, structure elucidation, identification, and quantification. In many instances, CI provides information that is complementary rather than supplementary to that obtained by EI, and often both approaches are used.

2.3 Statistical Analysis of Data

Positive Matrix Factorization (PMF) is an advanced algorithm analysis method that is used in receptor modelling by decomposing a bilinear matrix problem of type X= GF+E into factor contributions and profiles (Pateero 1997).

In the above equation, X is the matrix of observed data, G is the unknown factor matrix of scores, F is the unknown factor matrix of loadings and E is the matrix of residuals. The PMF is used to identify the sources of respirable suspended particles and it is unique in the sense that it guarantees non-negative results unlike the factor analysis or the principal component analysis.

The PMF was applied to data obtained from the EDXRF spectrometer analysis and analysed in a bid to identify the sources contributing to the pollution in Lagos.

3. Results and discussion

The results of all the analyses done both during online and offline measurements will be shown and discussed below.

3.1. Meteorology

For the meteorology of this study, we are going to be focusing on the temperature, relative humidity, wind speed and wind direction. The data was collected using January 2023 to August 2023 as a time series for evaluation. Figure 2 shows the hourly data (blue) and 24-hour average (orange) values for the months.

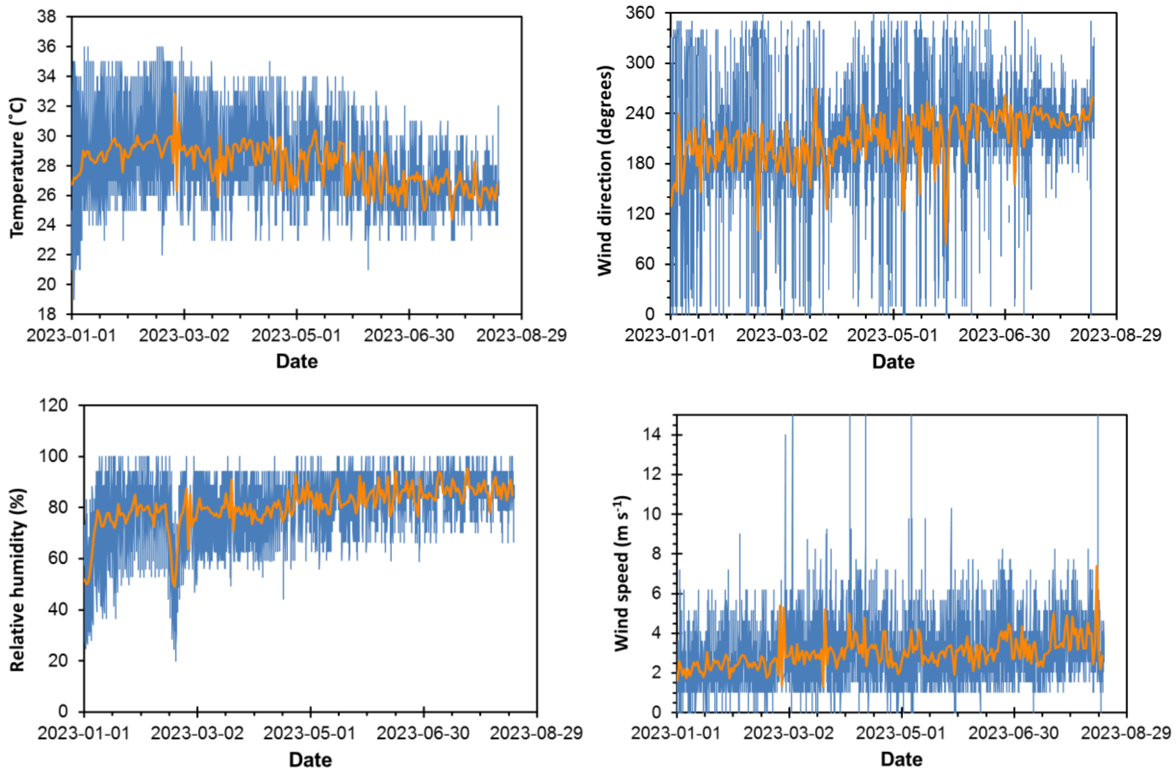


Figure 2. Meteorology of Lagos showing hourly data (blue line) and 24 h averages (orange line) of temperature, relative humidity, wind direction and wind speed from January 2023 to August 2023. All data was obtained from Lagos International Airport [ASOS network (https://mesonet.agron.iastate.edu/)].

The meteorology results as seen above show the relative humidity, wind direction, wind speed and temperature data from January to August 2023. From Figure 2, the temperature is uniformly decreasing from month to month with the exception of the start of March when there was an increase. The relative humidity is seen also to be increasing from month to month with little variability. The average temperatures recorded is approximately 28˚C with the highest temperatures seen in February and May while temperatures starts to drop off in

June due to the rains accustomed to June and July. The relative humidity ranges from 75% to 80% with its lows in February and its highs in June and July.
The wind direction shows that most of the wind into the city comes between 180˚ and 240˚ which is the southwest direction while the wind speed predominantly lies between 3-5 m/s. The wind direction is mostly coming in most from the south western direction. The Atlantic Ocean borders the southwestern side of the city which could be responsible for the sea to land breezes influx into the city. Pollutants tend to pile up in calm conditions when wind speeds are not more than about 2.78m/s. Speeds of 4m/s or more favour the dispersal of pollutants, which, clears the air. Winds of up to 9.72m/s brought Air quality index (AQI) down from 458 ('severe') on Nov 15 to 215 ('poor') in less than 48 hours in Delhi (https://economictimes.indiatimes.com/news/politics-and-nation/how-weather-determines-air-quality/wind-speed/slideshow/72159795.cms). The wind speed recorded favours more dispersal of pollutants thereby reduces the concentrations at any particular point close to the wind sources.
The different meteorology parameters as a function of time of day are presented in Figure 3.

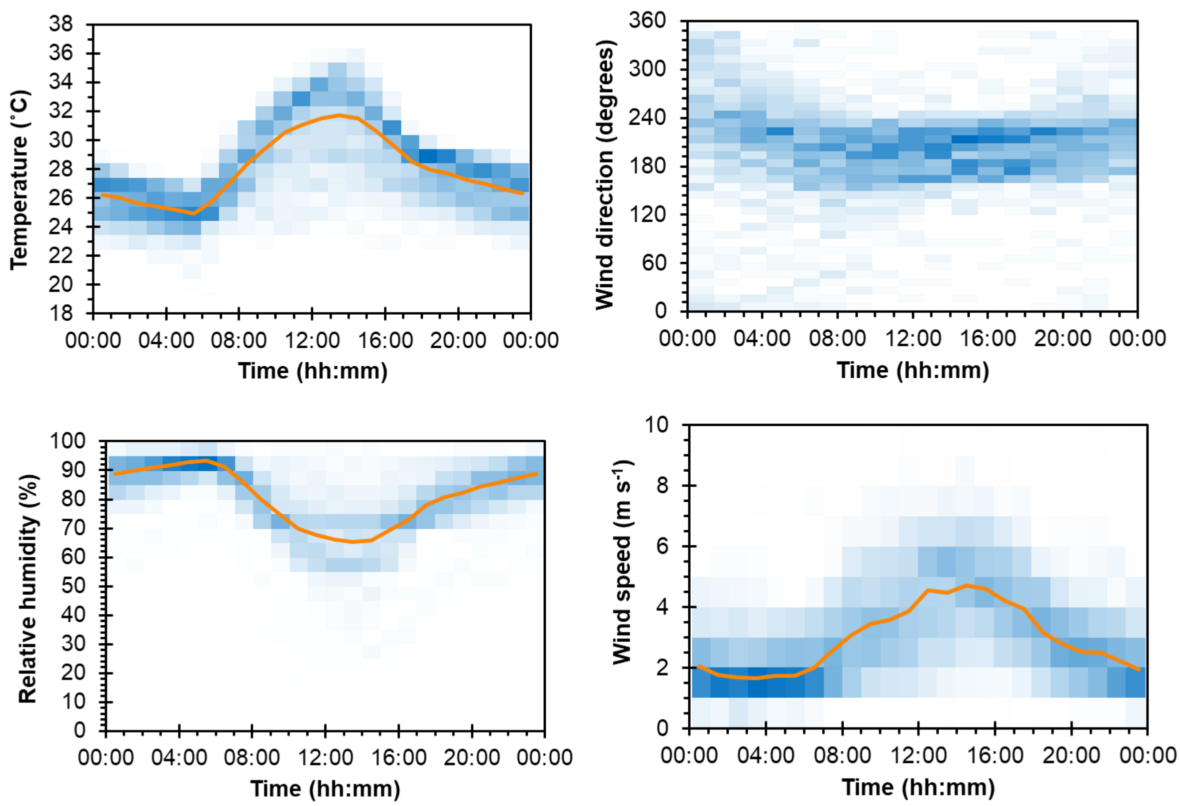


Figure 3. Meteorology of Lagos showing hourly averages of temperature, relative humidity, wind direction, and wind speed (orange lines), and relative probability of hourly values (blue fields) where a darker colour corresponds to a higher probability. Data cover the time period from 1 January 2023 to 17 August 2023. All data was obtained from Lagos International Airport [ASOS network (https://mesonet.agron.iastate.edu/)].

From figure 3 we can see that the temperature starts to rise at 6:00 as expected at sunrise, followed by a peak at 13:00. A decline in temperature levels is then noticed from 18:00 till midnight. The reverse is also the case with relative humidity where relative humidity levels are high and uniform from early in the morning till it a steady decline starts from 06:00 till 13:00 at which a steady increase is observed till midnight. Also note the variability of the data around the average values, as indicated by the different shades of blue where dark blue means a higher probability for a given value.
The wind speed starts increasing during the daytime from 5:00 with its peak at 13:00 while it starts reducing again from 17:00. For the wind direction, the wind tends to move more south westerly during the day. From both figures 2 and 3 the meteorology both as a function of month of the year and as a function of time of day is shown.

3.2. Online measurements results

Online measurement involved the placement of sensors at different locations in the case of the Purpleair sensors. These sensors were placed at Nigeria ports authority, Apapa, Lagos (harbour area); Mariere Hall at University of Lagos (Unilag), Akoka; Lagoon hotel at Bariga; Ojodu Berger, Ikorodu and a mobile station for the optical spectrometer at Unilag. These sensors were scattered in these parts including industrial areas, harbor areas and residential areas in a bid to see the differences in trends and concentration. We also made use of data obtained from an online sensor at the US embassy at Victoria Island, Lagos as they had the longest time series and gave us concentrations for a longer time period.

Meteorology affects air pollution in Lagos as we can see, the temperature changes, the relative humidity, the wind speed and direction all play a role in determining the concentration, spread, and trend of $PM_{2.5}$ pollution in the city. The first question that comes to mind is at what time of the day is the air most polluted? Is it in the morning, afternoon or evening and what could be the cause of the pollution levels at various times of the day? The first question is answered in figure 3 below which shows us concentration levels at various times of the day.

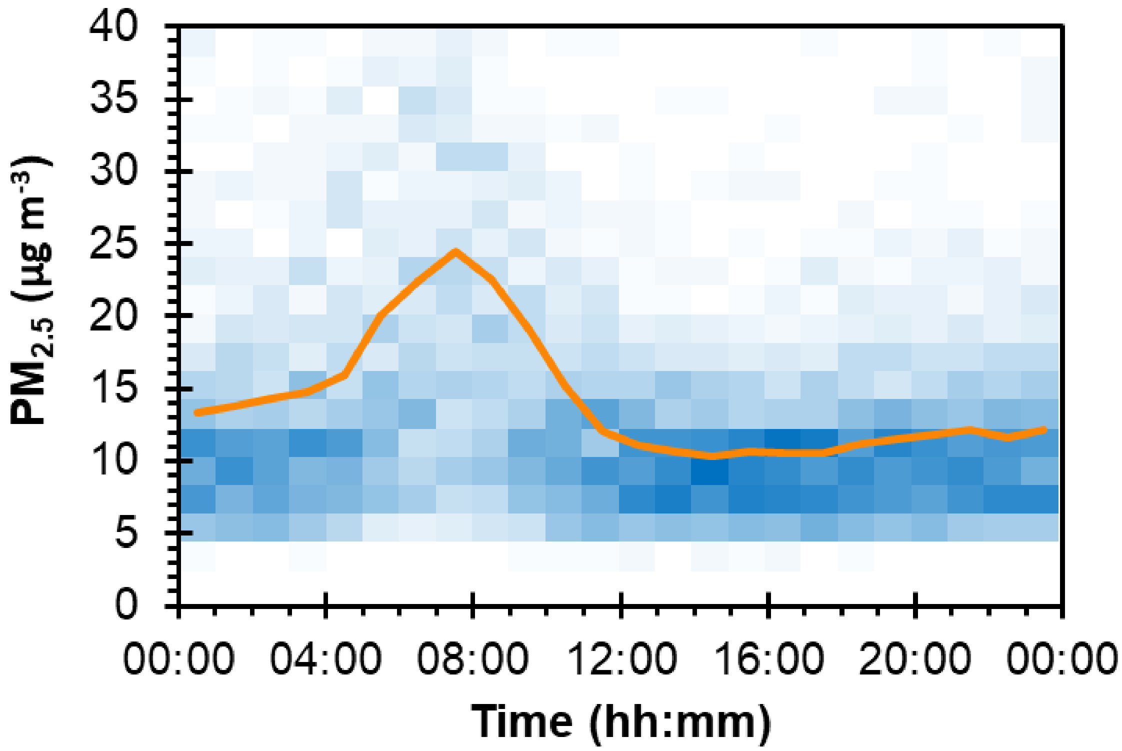
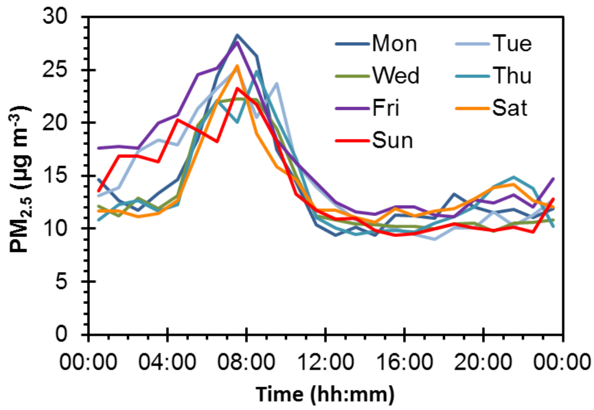


Figure 4. Diurnal $PM_{2.5}$ concentrations as a function of time of the day measured at the US Embassy, Lagos.

From figure 4, the $PM_{2.5}$ concentrations start increasing from as early as 5:00 with a peak period of between 7:00 and 8:00 then it starts declining from noon and is almost stable till midnight. This means the air pollution in Lagos starts from early in the morning when people move out for their daily activities and does not subside till around lunch hour. It is clear that human activities play a key role in air pollution in Lagos and how we go about or daily activities should be monitored in a bid to reduce air pollution in Lagos.

Since we already know that human activities play a key role in air pollution in Lagos, we can try to know what particular activities we do during the week may or may not increase air pollution in Lagos.

There are 7 days in a week and it is expected that $PM_{2.5}$ concentrations should be higher during the week and lower at weekends due to lesser traffic, fewer movements, operations in most companies being shut down etc. Figure 4 below shows the $PM_{2.5}$ concentration and trend obtained from the sensor at the US Embassy as a function of the day of the week.



Time	PM2.5	Mon	Tue	Wed	Thu	Fri	Sat	Sun
00:30	13,4	14,6	13,1	12,2	10,9	17,6	11,7	13,6
01:30	13,8	12,6	13,9	11,2	12,3	17,8	11,6	16,8
02:30	14,3	11,7	17,3	12,9	12,7	17,6	11,2	16,9
03:30	14,7	13,4	18,4	11,9	11,7	20,0	11,4	16,3
04:30	16,0	14,6	17,9	13,1	12,3	20,8	12,7	20,3
05:30	20,0	18,4	21,3	19,8	19,3	24,5	17,4	19,3
06:30	22,4	24,4	23,3	22,0	22,1	25,2	22,0	18,2
07:30	24,5	28,3	25,1	22,2	20,0	27,6	25,4	23,2
08:30	22,5	26,3	20,5	22,2	24,8	23,4	19,0	21,7
09:30	19,1	17,5	23,7	19,5	20,4	18,4	15,9	18,2
10:30	15,2	14,4	16,1	15,1	16,7	16,2	14,6	13,3
11:30	12,1	10,4	14,0	11,2	11,1	14,4	11,8	11,8
12:30	11,1	9,4	12,3	10,8	10,1	12,5	11,8	10,9
13:30	10,6	10,1	10,8	10,4	9,4	11,6	11,1	11,0
14:30	10,3	9,4	10,6	10,4	9,8	11,4	10,6	9,9
15:30	10,7	11,3	10,0	10,2	9,9	12,1	11,9	9,4
16:30	10,5	11,2	9,5	10,2	9,7	12,0	11,2	9,6
17:30	10,5	11,0	9,0	10,0	10,6	11,3	11,6	10,0
18:30	11,2	13,2	10,1	10,5	11,1	11,1	11,9	10,5
19:30	11,5	12,1	10,1	10,5	12,1	12,8	12,8	10,1
20:30	11,9	11,5	11,6	9,7	14,0	12,4	13,9	9,8
21:30	12,2	11,8	10,3	10,5	14,9	13,2	14,2	10,1
22:30	11,6	11,1	11,3	10,6	13,8	12,1	12,7	9,7
23:30	12,2	11,9	12,8	10,8	10,2	14,7	12,0	12,8

Figure 5. Diurnal $PM_{2.5}$ concentrations as a function of the day of the week were measured at the US Embassy, Lagos.

From Figure 5, a plot showing the diurnal concentrations as a function of day of the week on the right while the different variations are illustrated in the panel to the left. The PM concentration trends for all days of the week are almost the same with some difference in the highs and lows. Days with the highest peaks are Mondays and Fridays which isn't too surprising as those days mark the first and last days of weekly activities. Surprisingly however, low concentrations expected on weekends are nowhere to be seen with Saturday mornings having the third highest peak concentration. Are there other activities done on Saturday morning that may be responsible for these high concentrations? Most local markets and mini-marts have a peak period on Saturday mornings as most shoppers are home and try to stock up on needed items for the coming week, which may be one reason explaining the observed pattern.

Since we now know the weekdays and their recorded concentrations, we check to see if the monthly concentrations also have the same trend and which months have the highest pollution in a bid to determine why.

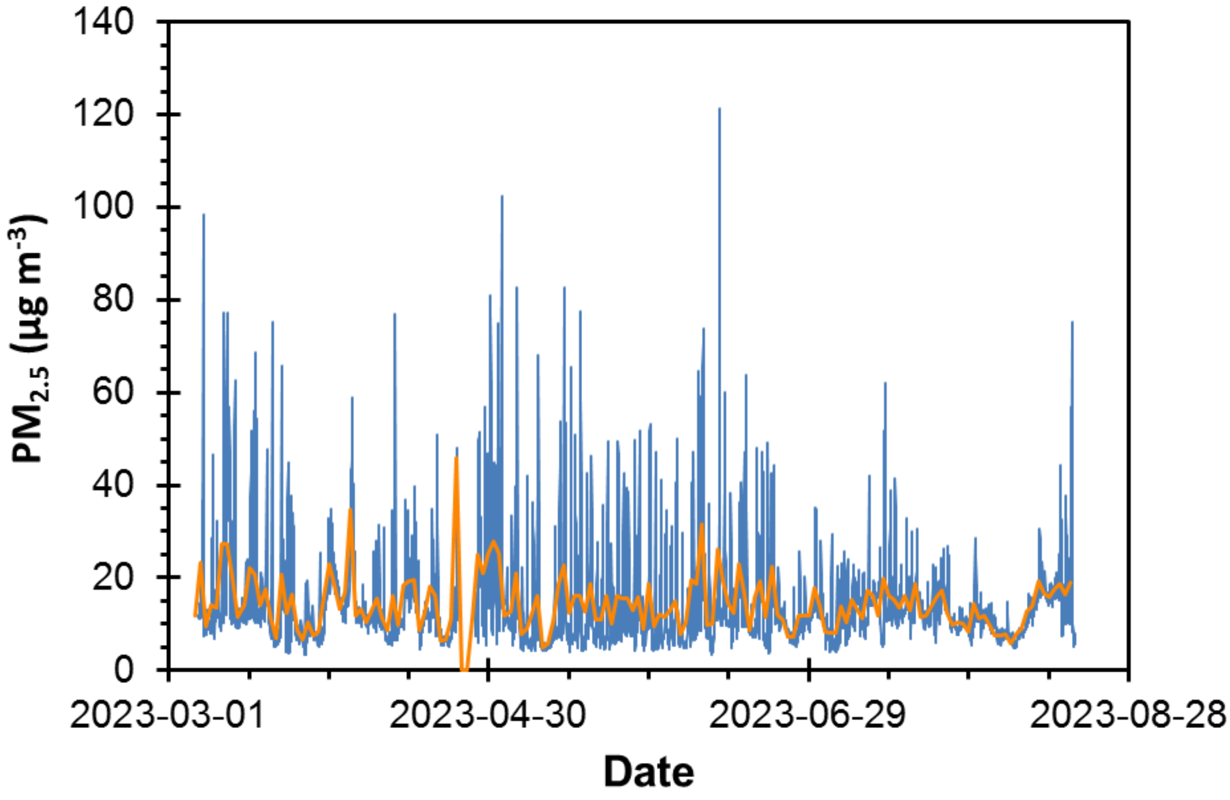


Figure 6. Hourly and daily (24hr averages) of $PM_{2.5}$ concentrations as a function of time and month at the US Embassy, Lagos.

Figure 6 shows the PM2.5 concentrations recorded from January 2023 to August 2023. There are relatively large variations also from day to day as can be seen. The highest peak is seen in April 2023 where $PM_{2.5}$ concentrations is as high as 45µg/m3 based on this sensor. What activities took place during this month that may have caused the increased volume of concentration? Was it caused mainly by human activities or a meteorological factor? This period is also around the hottest month in Nigeria. Does temperature levels also play a role in the increase in pollution?

It is now known what time and month the air is most polluted in this part of Lagos, we can then check to see how the different meteorological parameters affect $PM_{2.5}$ concentrations and perhaps answer some of our questions. Figure 5 below shows us the effect of meteorological factors on PM levels in Lagos.

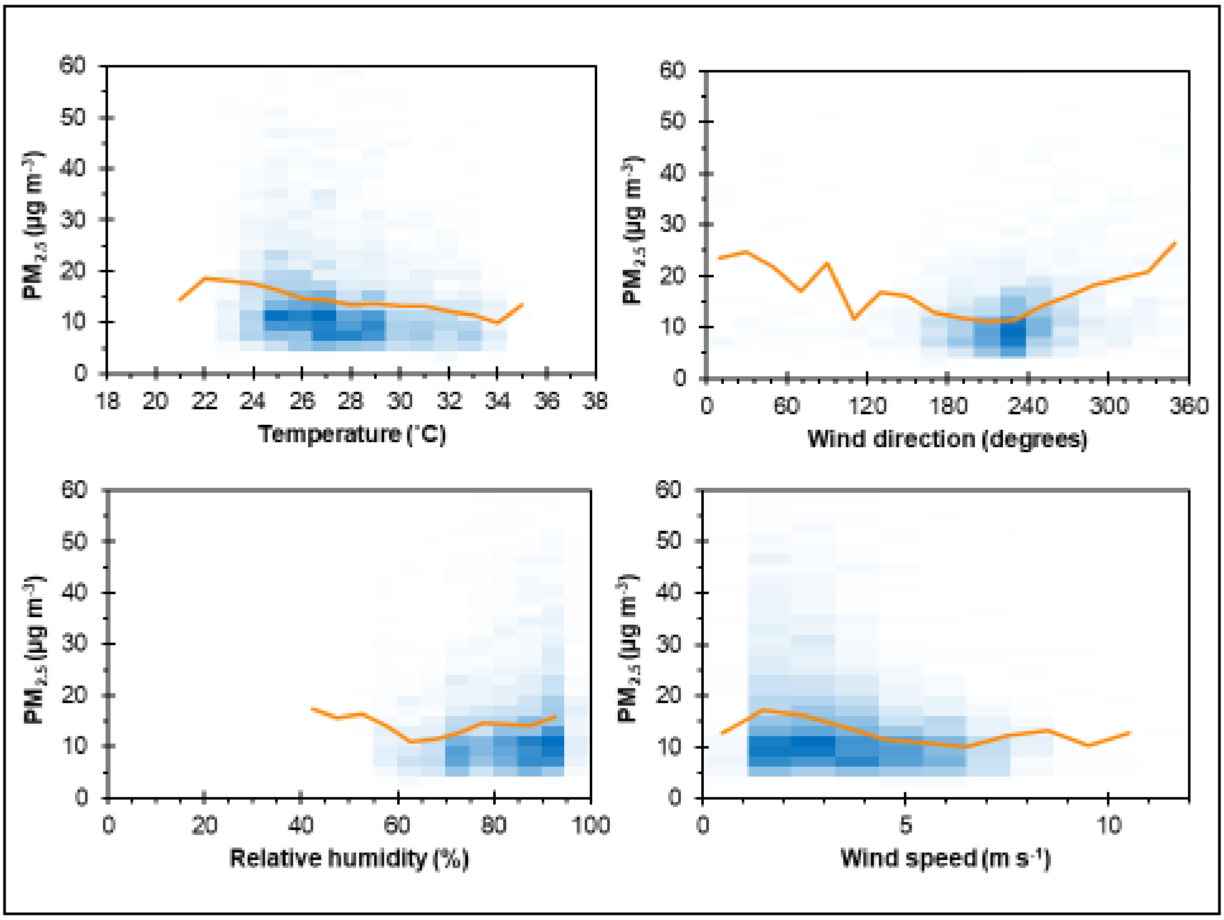


Figure 7. $PM_{2.5}$ concentrations from January 2023 to August 2023 as a function of the meteorological parameters (temperature, relative humidity, wind speed, and wind direction). All data was obtained from the US Embassy and Lagos International Airport [ASOS network (https://mesonet.agron.iastate.edu/)].

From Figure 7, there is no strong trend of $PM_{2.5}$ concentrations with respect to temperature. The highest concentrations are found when temperature is relatively low. Relative humidity increase also brings about a slight increase in concentration levels though from 50% to 60% there is some decrease in concentration levels. When the wind speed increases as $PM_{2.5}$ concentrations decrease, while when the wind direction is within 180° to 240° concentrations generally decrease. This is also expected as the wind majorly comes from the southwestern part of Lagos and therefore disperses some of the $PM_{2.5}$

concentrations from that area reducing its concentration. Figure 6 below shows the corresponding PM data as a function of wind direction in an angular plot.

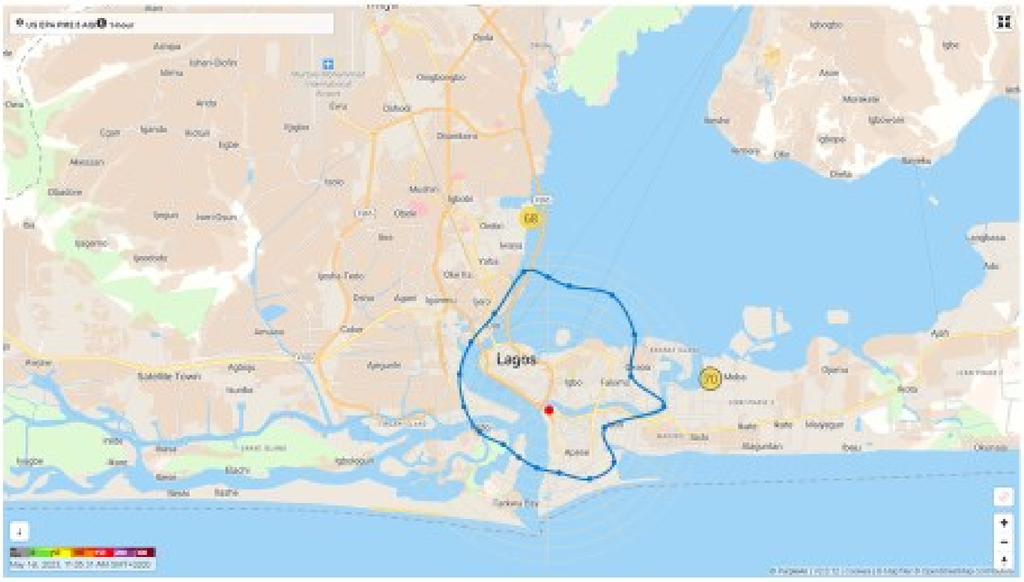


Figure 8. $PM_{2.5}$ concentrations as a function of wind direction at the US Embassy in Lagos from March 6 to 17 August, 2023. Picture gotten from purpleair device.

The red point in the map marks the position of the US Embassy, and the distance between the blue points to the red dot shows the intensity of $PM_{2.5}$ concentration. This consolidates what was stated previously as the concentration levels from the South West is the lowest while the concentration levels from the North, North East are the highest. Does the presence of water bodies play a role or not in the concentration? Do local sources increase the levels of pollution? Are the data from the US Embassy representative for other parts of Lagos?
Some of these questions posed are answered in the figure 8 where we take a look at the PM from other sensors in other parts of Lagos. We will be making use of data from the Purpleair sensors and the aerosol spectrometer (Grimm) to see how they present various concentrations.

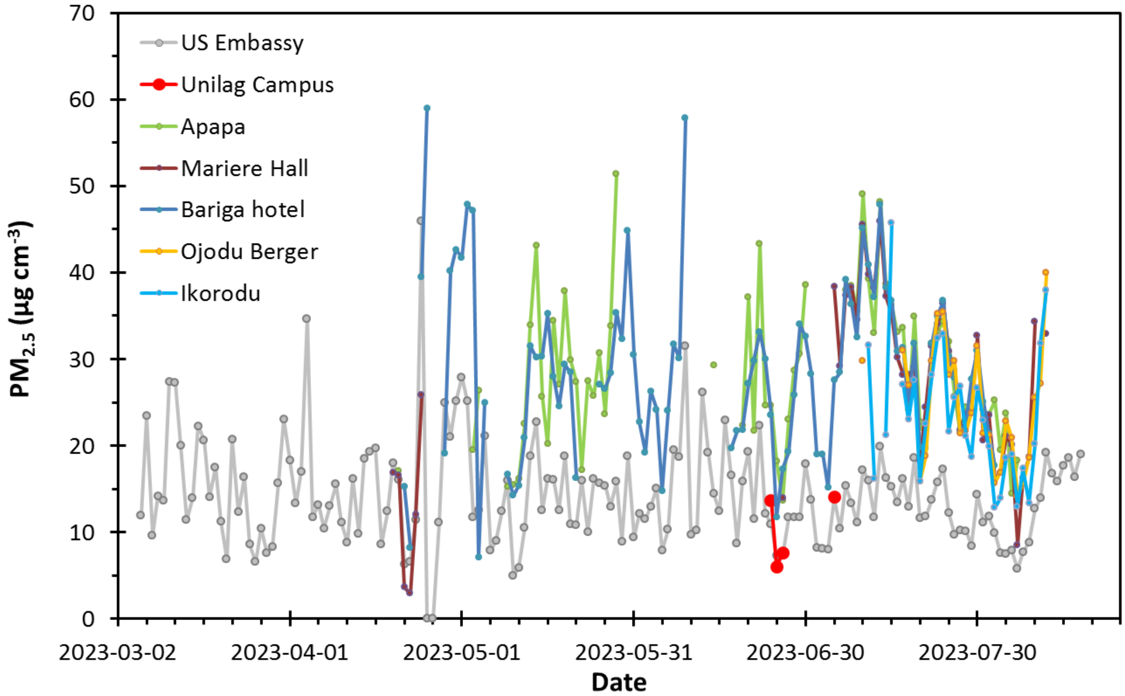


Figure 9. Daily (24h average) $PM_{2.5}$ concentrations at multiple urban sites in Lagos during the period from April 19 to August 11, 2023. All data were obtained with Purpleair PM Sensors, except ZephAir sensor at the US Embassy, Lagos and the "Campus Grimm" data that were collected with an optical spectrometer (Model 108, Grimm Inc.).

Figure 9 shows a scattered plot of the sensors placed in various parts of Lagos. They unexpectedly often follow similar trends even though they represent different parts of Lagos. There are different peaks in concentrations between various sensors and various areas. The highest peaks are found in Ikorodu and Apapa while the lowest peaks are found in Unilag and the US Embassy which is in Victoria Island. Ikorodu is a fast-growing residential area which is highly populated due to its closeness to Ogun state and Lagos City. Another reason for its large population is the low cost of living for people in that part, while Apapa is the central harbor area in Lagos where most shipping activities take place. Most shipping and haulage companies in Apapa operate round the clock and every day. Victoria Island is mostly a business and tourist area in Lagos, and it is home to many business offices, cinemas and parks. Unilag is an academic environment

and home to the University of Lagos. From the figure above even though the trends are the same for all areas, local sources also play a role in defining the detailed peaks in concentration. Residential and harbor areas where there are manufacturing industries are more polluted than leisure areas.
Lagos is generally classified by lagosians into the two sides, they are Lagos Island and Lagos Mainland. We took a drive from Lagos Island in particular the Lekki axis to Unilag which is in the Lagos mainland to check the pollution levels at various times of the day. The results can be seen in the next figure below. The aerosol spectrometer was mounted on a mobile vehicle for the collection of the data below.

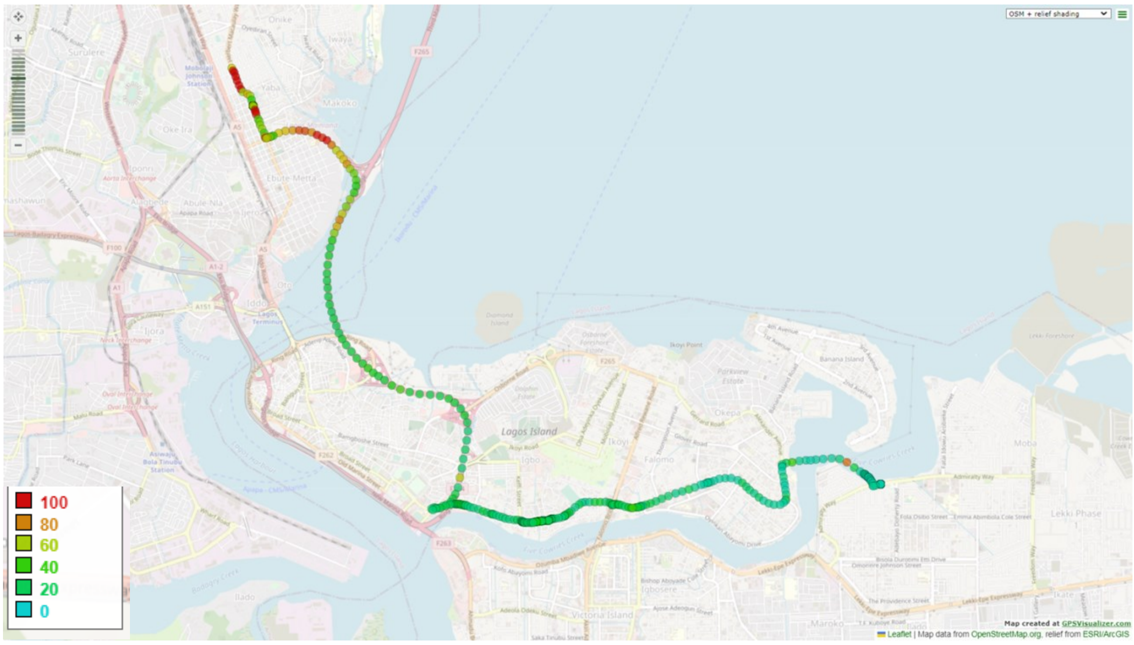


Figure 10a. Ambient $PM_{2.5}$ ($\mu g\ m^{-3}$) was measured with an aerosol spectrometer (Model 1.108, Grimm GmbH during travel by taxi between University of Lagos Campus and Hotel Lilygate in Lekki, Lagos at 16:15-16:50 on April 19, 2023. The time resolution of the $PM_{2.5}$ measurements was 6 s. Coordinates were stored using Runkeeper software.

This analysis was done to also check concentrations and how much they increase as a function of the time of day. From Figure 10a which was data collected in the afternoon, we can see that the pollution concentrations in the Unilag area (Lagos mainland are higher when compared to the ones found in Lekki area (Lagos Island). Many reasons may be responsible for this, including differences in population, local sources, meteorological factors, time of day etc.

Figure 10b helps us reduce the possible reasons as we took another trip through the same route but this time in the morning.

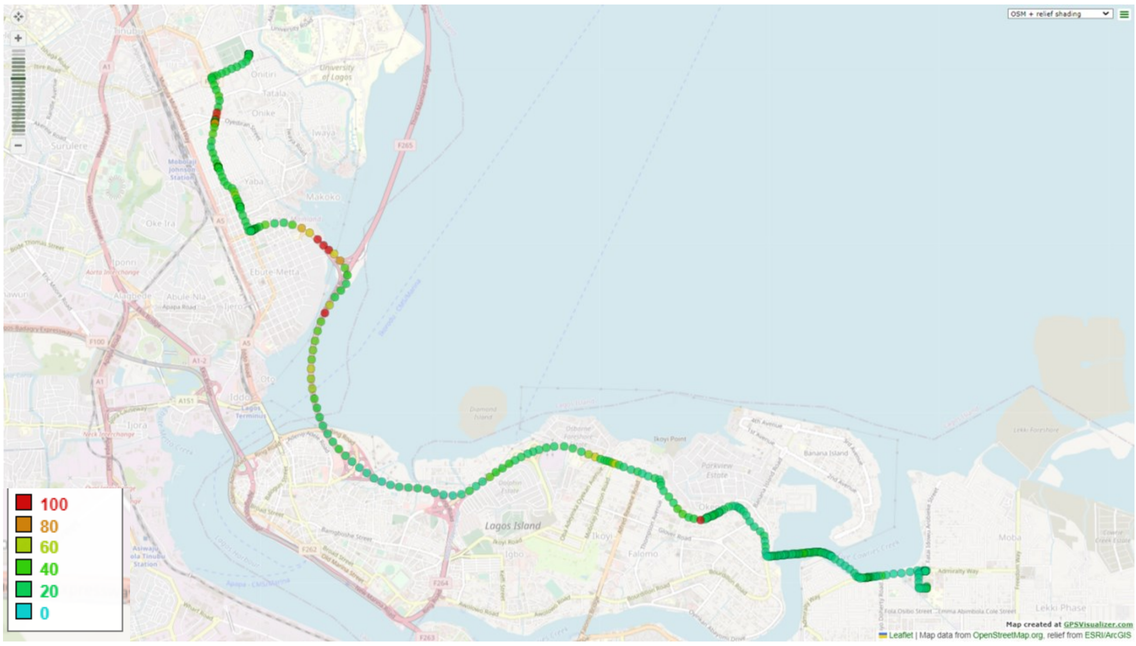


Figure 10b. Ambient $PM_{2.5}$ ($\mu g\ m^{-3}$) measured with an aerosol spectrometer (Model 108, Grimm Inc.) during travel by taxi between the University of Lagos Campus and Hotel Lilygate in Lagos at 07:57 – 08:38 on April 20. The time resolution of the $PM_{2.5}$ measurements was 6 seconds. Coordinates were stored using Runkeeper software.

Clearly, the data in both figures follow almost the same trend with figure 10a showing higher concentrations in the mainland while on the island the concentrations are more or less the same for both time periods. This shows us that time of day is not?? important in the concentration levels and this might be as a result of more combustion from daily activities, traffic or some other local sources.

Lagos like most other urban cities are a mix of formal and informal settlements. An analysis of $PM_{2.5}$ concentrations in an informal settlement was also gotten from the Makoko area which is in Lagos mainland and close to Unilag, Akoka. This informal settlement is dominated by a marine environment as most individuals living in the area fish as a means of livelihood. Houses are built on water and every family has a canoe which they use for transportation to and from land and also for fishing activities. Figure 11 below shows the Makoko area.

Figure 11. Pictures of the Makoko area. Taken by me with Samsung A32 on April 22, 2023.

On analysis of the PM concentrations in Makoko for different times of the day as can be seen in figure 6 below we can see that there is a distinct difference although not as much as was expected from an area where majority of the food processing and production is done by combustion. We can also notice that the increase is more in the afternoon than in the morning and this could be as a result of traffic and local power generation.

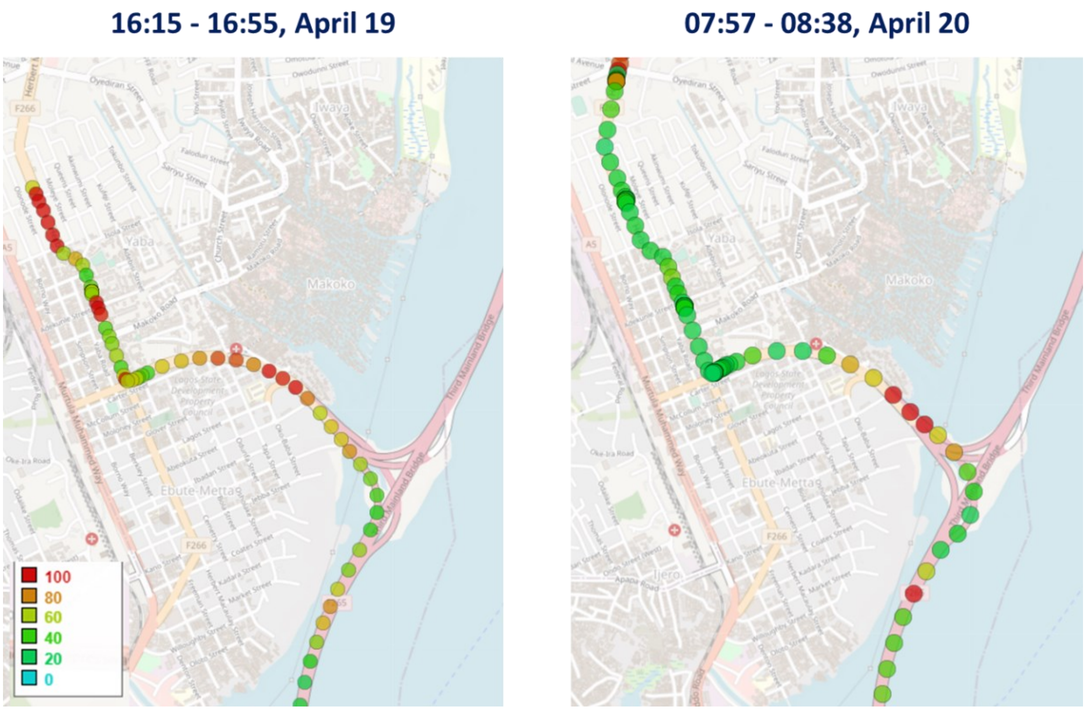


Figure 12. Ambient $PM_{2.5}$ ($\mu g\ m^{-3}$) measured with an aerosol spectrometer (Model 108, Grimm GmbH) during travel by taxi near the informal settlement Makoko in Lagos on April 19 (left panel) and April 20 (right panel), 2023. The time resolution of the $PM_{2.5}$ measurements was 6 s. Coordinates were stored using Runkeeper software.

There are different emission sources which produce particles of different sizes. Identification of these particles and their sizes can be useful in identifying the source. $PM_{1-2.5}/PM_{2.5-10}$ ratio gives useful information about the sources as natural or anthropogenic. Anthropogenic sources are known to produce more fine particles as a result of traffic emissions or burning activities resulting in a higher $PM_{1-2.5}/PM_{2.5-10}$ ratio, whereas natural sources such as windblown or road dust mostly have a higher contribution of coarse particles resulting in a lower value (Zakey et al. 2008; Querol et al. 2001; Kulshrestha et al. 2009; Spindler et al. 2013). Figure 7 shows the different particle sizes as measured with the aerosol spectrometer.

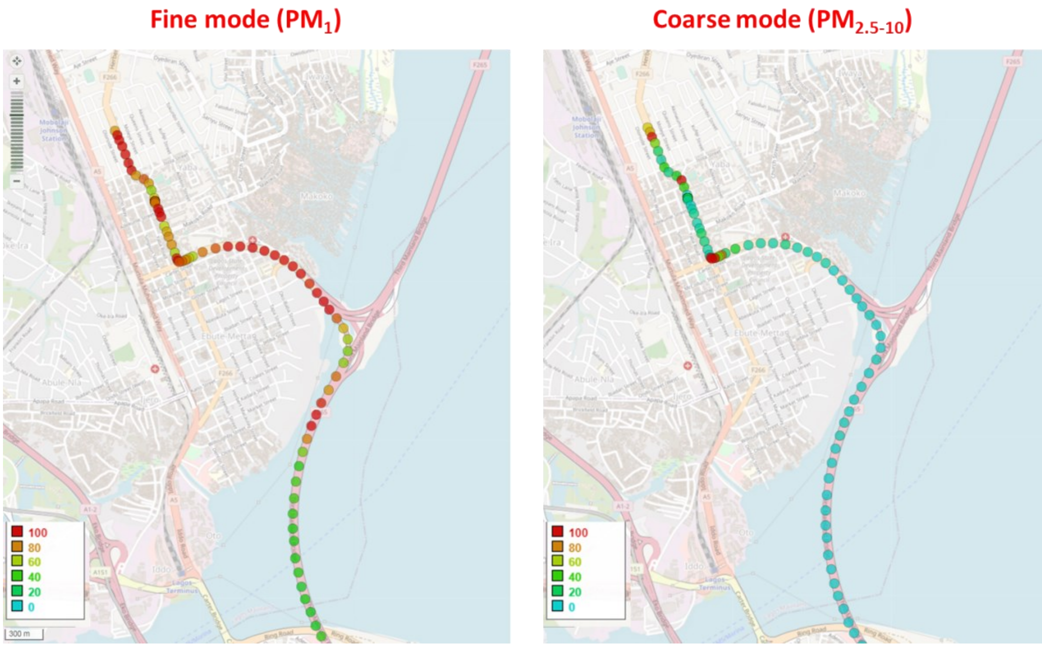


Figure 13. Ambient fine mode (PM_1; left panel) and coarse mode ($PM_{2.5-10}$; right panel) PM concentrations were measured during travel by taxi near the informal settlement Makoko in Lagos at 16:15-16:50 on April 19, 2023. The measurements were carried out

with an aerosol spectrometer (Model 108, Grimm GmbH) using a time resolution of 6 seconds. Coordinates were stored using Runkeeper software.

From the measurements, we can clearly see that there are more fine-mode particles than coarse particles. This is not surprising given the location and prevalent factors like burning and traffic that are probably responsible for it.

3.3. Offline measurement results

The results gotten from offline measurements are the cyclone samplers which were used to collected samples on filter papers both for the EDXRF analysis and the CIMS analysis. Over 60 filter paper samples were collected from Lekki, Akoka, Makoko, and Bariga areas of Lagos and were used for both analysis in the Laboratory.

3.3.1. EDXRF spectroscopy results

A total of thirty-five $PM_{2.5}$ samples were collected in different environments in Lagos from 18 April – 26 May 2023, and subsequently analyzed by EDXRF spectroscopy at University of Gothenburg on May 27- June 15 2023 of which 2 of the samples were blanks. The blank filter papers were also set aside for analysis as base. Each sample was taken during approximately 24hours at the rooftop at Lilygate Hotel, Lekki, the rooftop at the science department in University of Lagos, Akoka and the rooftop at D.K. Olukoya Central Research & Reference Laboratories also in University of Lagos, Akoka. The samples were stored at temperatures below 0° C directly after being collected and continuously until analyzed by EDXRF.
Out of the 35samples analyzed using EDXRF, 10 were removed due to various reasons like; very low XRF signal, negative or very low filter weight, no filter weight and broken capsule.
Figure 13. shows the elements seen during the EDXRF analysis and their average concentration in $PM_{2.5}$

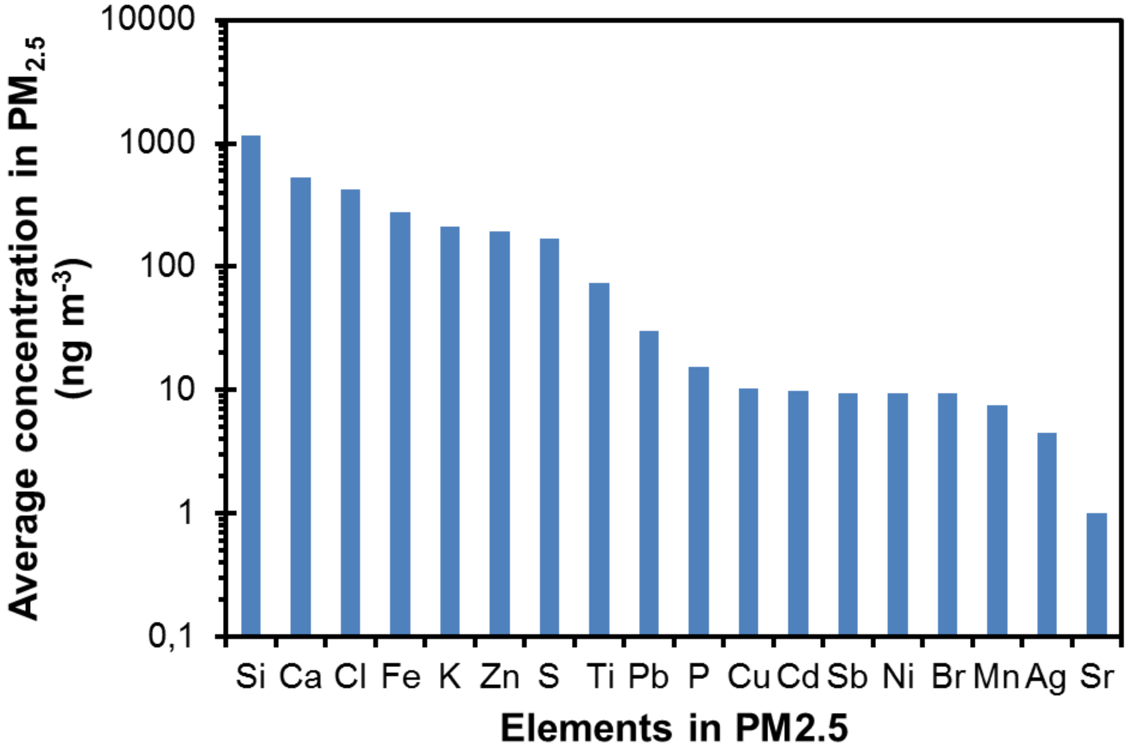


Figure 14. Average concentrations of elements in $PM_{2.5}$. Data is based on 25 samples collected in Lagos during the period from April 19 to May 26, 2023.

From Figure 14, silicon(S), chlorine (Cl), potassium (K) and calcium (Ca), Iron (Fe) are some of the major elements seen during this analysis. The concentration of just the major elements seen could give some information when analysed with respect to the time of collection. Figure 14 shows these concentrations.

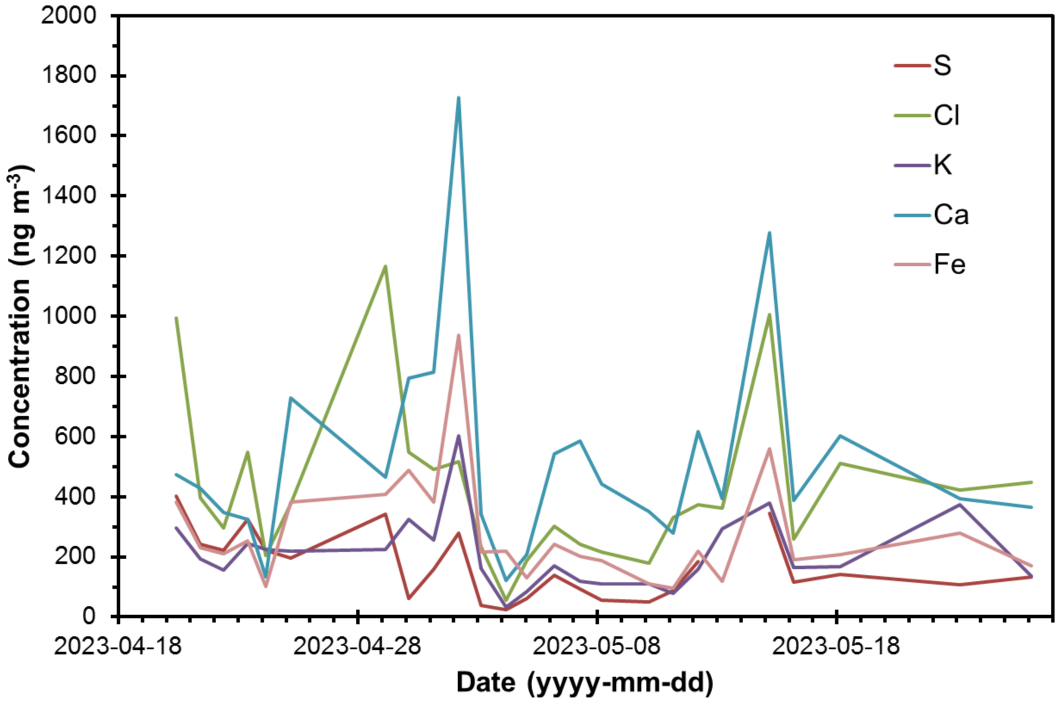


Figure 15. Concentrations of major elements in $PM_{2.5}$ in Lagos during the period from April 19 to May 26, 2023.

Looking at Figure 15, Calcium followed by Chlorine has the highest peaks of all the major elements seen during the sample collection days but silicon was the highest element seen in the average concentration of PM from Figure 14. Could these major elements be occurring as complementary elements? What happens with the trace elements seen in this analysis and could they be complementary even in trace amounts to the major elements?

Figure 16 below shows a correlation of all elements seen during the EDXRF analysis and clearly shows the pairings if any.

	Si	P	K	Ca	Ti	Fe	Sr	Mn	S	Br	Cl	Zn	Pb	Cu	Cd	Ag	Sb	Ni
Si	1,00	0,79	0,81	0,90	0,95	0,90	0,91	0,86	0,52	0,45	0,39	0,14	-0,22	0,13	-0,16	0,13	-0,17	-0,28
P	0,79	1,00	0,89	0,86	0,76	0,84	0,70	0,84	0,43	0,58	0,50	0,38	0,04	0,10	0,10	0,37	-0,24	-0,06
K	0,81	0,89	1,00	0,77	0,77	0,82	0,75	0,87	0,55	0,58	0,50	0,39	-0,04	0,30	0,05	0,19	-0,21	-0,11
Ca	0,90	0,86	0,77	1,00	0,91	0,87	0,82	0,80	0,38	0,50	0,40	0,15	-0,20	0,01	-0,05	0,24	-0,16	-0,22
Ti	0,95	0,76	0,77	0,91	1,00	0,91	0,88	0,85	0,51	0,51	0,45	0,19	-0,19	0,30	-0,10	0,15	-0,07	-0,24
Fe	0,90	0,84	0,82	0,87	0,91	1,00	0,90	0,89	0,46	0,62	0,54	0,41	0,05	0,24	0,05	0,21	0,03	-0,18
Sr	0,91	0,70	0,75	0,82	0,88	0,90	1,00	0,87	0,46	0,44	0,38	0,14	-0,22	0,18	-0,15	-0,03	0,04	-0,49
Mn	0,86	0,84	0,87	0,80	0,85	0,89	0,87	1,00	0,64	0,66	0,57	0,45	0,11	0,45	0,11	0,17	-0,04	-0,30
S	0,52	0,43	0,55	0,38	0,51	0,46	0,46	0,64	1,00	0,58	0,76	0,48	0,31	0,59	0,10	0,02	-0,01	-0,10
Br	0,45	0,58	0,58	0,50	0,51	0,62	0,44	0,66	0,58	1,00	0,82	0,84	0,71	0,55	0,55	0,49	0,36	0,04
Cl	0,39	0,50	0,50	0,40	0,45	0,54	0,38	0,57	0,76	0,82	1,00	0,80	0,76	0,57	0,50	0,22	0,21	-0,04
Zn	0,14	0,38	0,39	0,15	0,19	0,41	0,14	0,45	0,48	0,84	0,80	1,00	0,95	0,58	0,67	0,48	0,33	0,21
Pb	-0,22	0,04	-0,04	-0,20	-0,19	0,05	-0,22	0,11	0,31	0,71	0,76	0,95	1,00	0,76	0,72	0,54	0,39	-0,05
Cu	0,13	0,10	0,30	0,01	0,30	0,24	0,18	0,45	0,59	0,55	0,57	0,58	0,76	1,00	0,25	0,08	0,34	-0,04
Cd	-0,16	0,10	0,05	-0,05	-0,10	0,05	-0,15	0,11	0,10	0,55	0,50	0,67	0,72	0,25	1,00	0,47	0,57	0,21
Ag	0,13	0,37	0,19	0,24	0,15	0,21	-0,03	0,17	0,02	0,49	0,22	0,48	0,54	0,08	0,47	1,00	0,28	-0,10
Sb	-0,17	-0,24	-0,21	-0,16	-0,07	0,03	0,04	-0,04	-0,01	0,36	0,21	0,33	0,39	0,34	0,57	0,28	1,00	-0,13
Ni	-0,28	-0,06	-0,11	-0,22	-0,24	-0,18	-0,49	-0,30	-0,10	0,04	-0,04	0,21	-0,05	-0,04	0,21	-0,10	-0,13	1,00

Figure 16. Correlations between the concentrations of pairs of elements in $PM_{2.5}$.

Green indicates a high degree of correlation and red indicates anti-correlation. The displayed order of the elements has been chosen to highlight clusters of elements with high degrees of correlation. From Figure 16 we can see close correlations between silicon (Si) and phosphorus (P), we can also see a close correlation between zinc (Zn) and lead (Pb) amongst others. The correlations show us in great detail that some of the elements occur side by side with others which can help in determining why some elements have a larger volume when compared to others and also the source of PM concentration.

3.3.2. Sources of airborne PM in Lagos.

The twenty-five samples that were selected were used for the PMF analysis to get the source of airborne PM in Lagos. The data was arranged and inserted into the PMF model. A five-factor characterization was applied in order to clearly see the elemental markers which would aid in deciphering the various sources. This can be seen in Figure 17

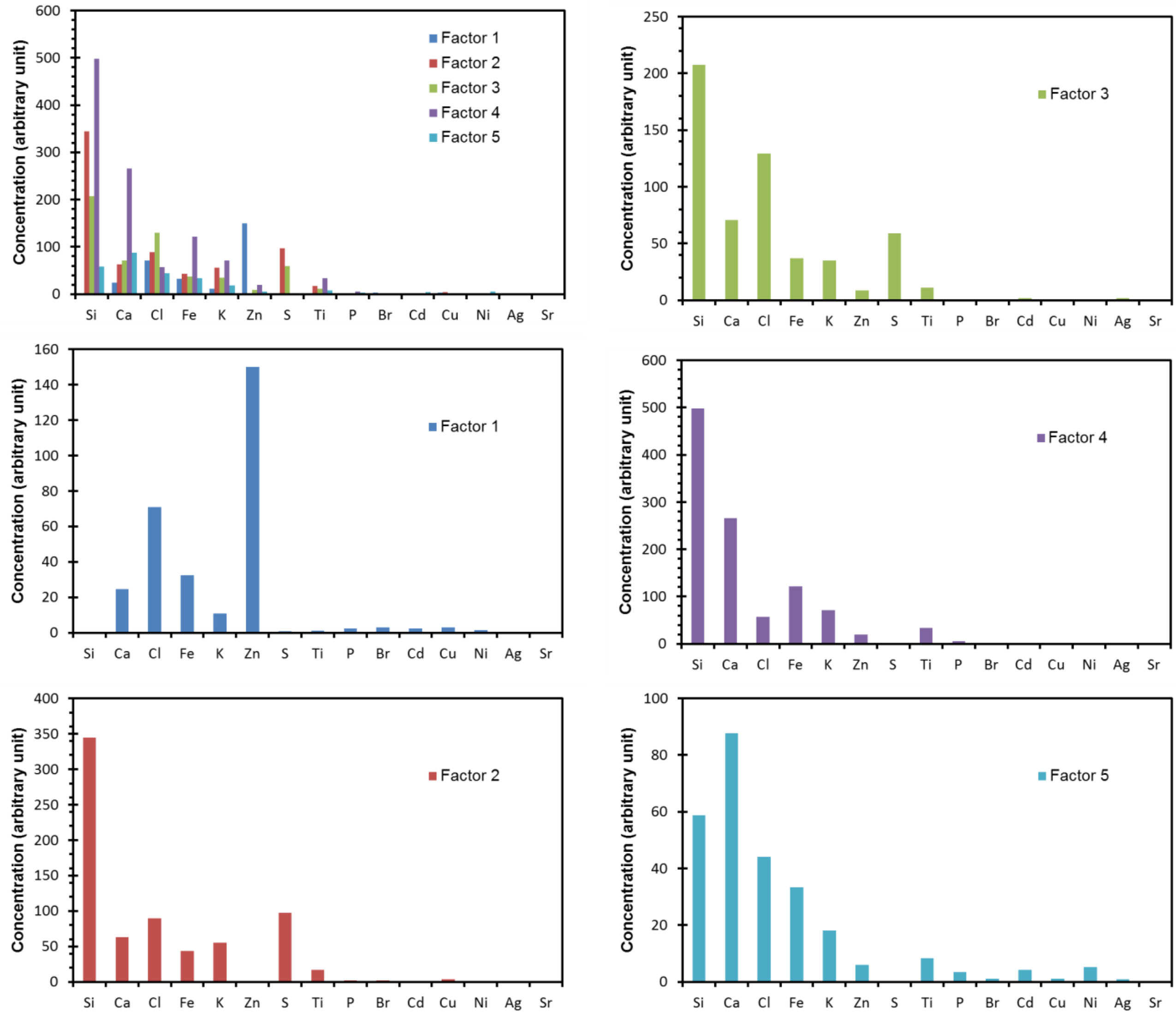


Figure 17. Factor profiles from a 5-factor PMF analysis of EDXRF results for PM2.5 samples collected in Lagos from 19 April to 6 May 2023.

The first factor had high loadings of Zinc (Zn) with Chlorine (Cl). From the correlation in Figure 16, we now know that Zinc also occurs alongside Lead (Pb) and Bromine (Br). Zn is well associated with industrial emissions from smelting industries (Querol et al. 2007). It is believed that the first factor also comprises traffic emissions since Zn is an additive to oil and is also emitted from brake ablation (Thorpe and Harrison 2008). Zn is also a major emission from worn-out tires (Panko et al. 2018). This factor makes up 10% of the elements included in the PMF analysis.

The second factor has a high percentage of Sulphur (S) alongside Si, Cl and Potassium (K). This factor is believed to be from solid fuel combustion. S originates from petroleum products sold in Nigeria which are high in S used for both vehicles and power generation in Lagos. With the dry weather conditions and poor road surfaces, non-exhaust traffic emissions such as re-suspension of road dust (Si, Ca, Ti) were also present in this factor (Salma and Maenhaut 2006, Pant and Harrison 2013). Cl and K were reported from vehicle emissions (Cui et al. 2017).

The third factor is mainly characterized by Si, Cl, and Ca. This factor is believed to be marine aerosol. Si, Cl and Ca bear the markers of marine aerosol deposition likely from the Atlantic Ocean as the sea breezes blow toward land (Tian et al 2010).

The fourth factor is dominated by Si, Ca, and Fe which from correlation are associated with other crustal elements identified from samples (Towett et al. 2013) and accounted for. It is distinguished from road dust due to the absence of Pb, Zn, and S. This factor is believed to be mineral dust. This factor accounts for 37% of the total samples analysed. Mineral dust is considered to be one of the highest components of particles found in $PM_{2.5}$ collected in Lagos.

The fifth factor is characterised by Ca with Si, Fe and the presence of Zn which occurs alongside Pb. This factor is soil/road dust due to the high presence of Ca, Zn and Pb. This accounts for the lowest factor noted during the PMF analysis.

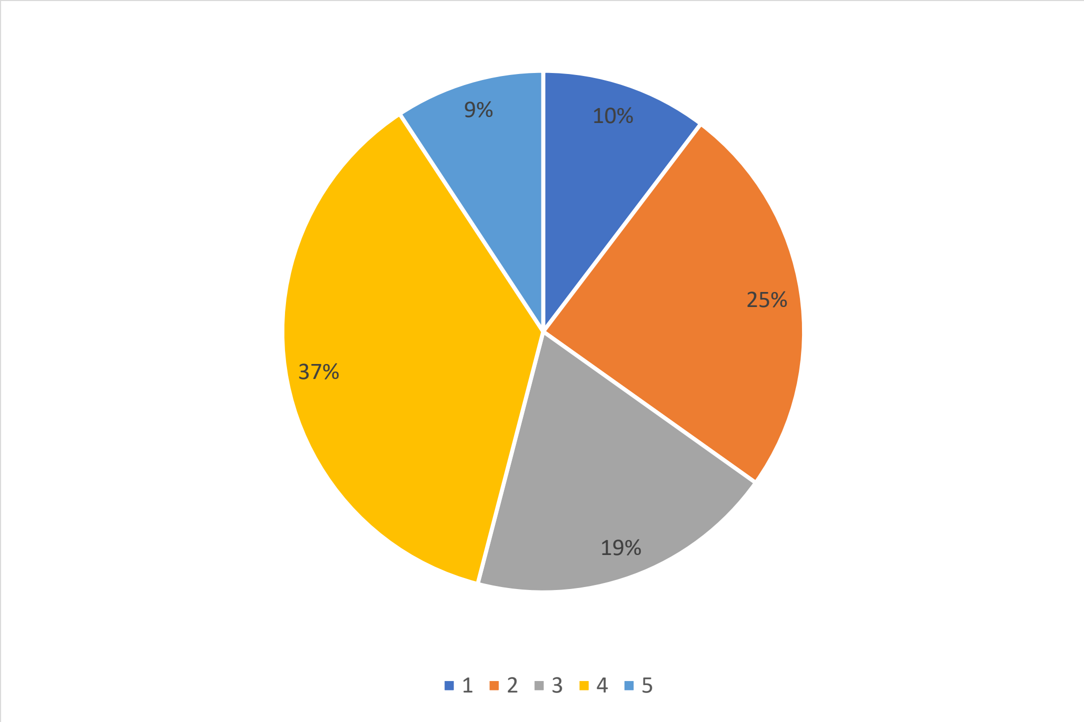


Figure 18. Percentage contribution of source factors from PMF analysis to $PM_{2.5}$ collected in Lagos.

From Figure 18, the fourth factor is the highest component of the PMF analysis done and most of the factors seen in this analysis consist of dust particles which agrees with UNEP (https://www.unep.org/interactives/air-pollution-note/) that windblown dust is the highest component of air pollution found in Africa.
It is however important to note that these percentages are for the elements included in the PMF analysis. They are thus not the % of each source. For instance, mineral dust has a high concentration of aluminum, which is not measured here. Sea spray has a high content of sodium (Na) that is not measured, and so on. It should also be noted that these is representative of 26 samples which is a low number to make a complete interpretation from during PMF analysis.

3.2.2. CIMS results

A total of eighteen $PM_{2.5}$ samples were collected in different environments in Lagos on 22 - 24 April 2023, and subsequently analyzed by CIMS at the University of Gothenburg on May 9-10 2023. Each sample was taken for approximately 30 min under the following conditions: *i*) during walking through the two informal settlements Makoko and Bariga in Lagos, *ii*) during travel by car within the city, or *iii*) during walking or stationary on the campus of the University of Lagos. Duplicate samples were taken in each case by two individuals following the same procedures, but using different sampling equipment. The samples were stored at temperatures below 0° C directly after being collected and continuously until analyzed by CIMS.

The samples taken in Makoko and Bariga are likely to be affected by sampling in close proximity to local sources including wood and charcoal burning. Samples taken in traffic are affected by local vehicle emissions, while the campus may be considered an urban background environment with limited effects of local sources.

During CIMS analysis, each filter was heated for 20 minutes while the temperature was linearly ramped from room temperature to 200° C, followed by heating for 20 min at 200° . The evaporated material from each sample was analyzed by CIMS, which produced high-resolution mass spectra in the m/z = 3 – 891 mass range with a 1s time resolution. A first preliminary analysis of the complex CIMS results is reported here since a detailed analysis cannot be included within the time limits of the present thesis project.

The mass spectra in general show relatively low signals for many masses and a longer sampling time than 30 minutes would have improved signal-to-noise ratios. A background produced by material deposited in the CIMS inlet during the earlier analysis of other samples also obscured the present results for several masses. The duplicate samples taken at the same time usually show good agreement but with notable differences in the case of sampling in Makoko and Bariga where walking paths are often narrow and the two researchers sampled local sources differently.

The most pronounced signals in the data are observed for m/z = 97 and 225. These masses correspond to the ions HSO_4^- (m/z = 97) and $IH_2SO_4^-$ (m/z = 225), which both originate from particle-bound sulfuric acid (H_2SO_4) in the aerosol samples.

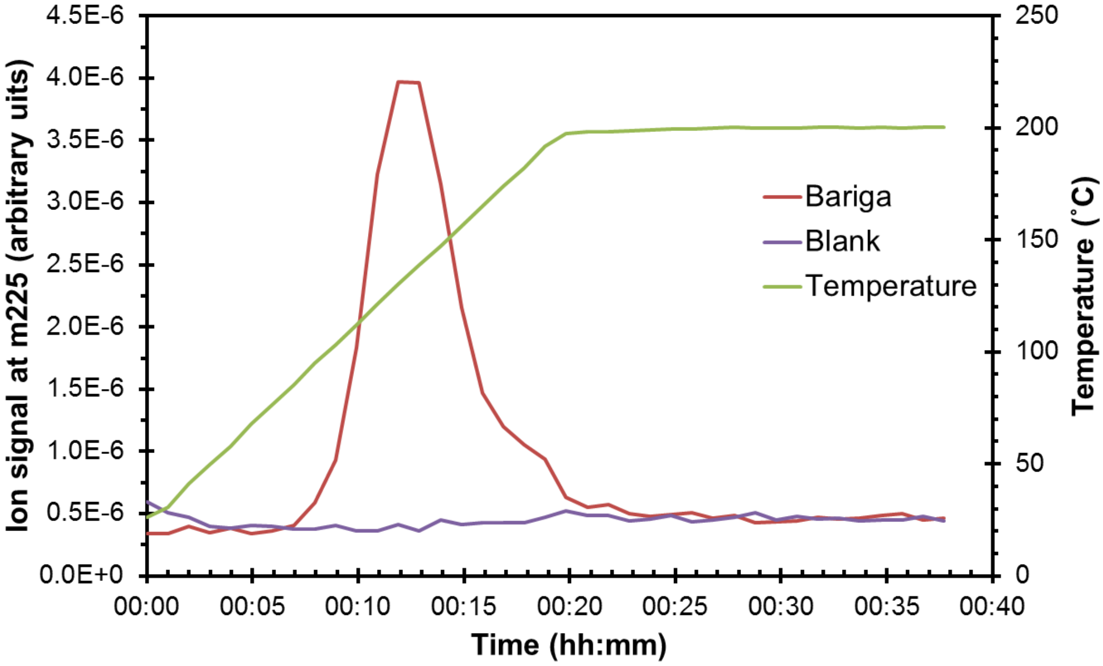


Figure 19. Relative ion signal at m225 ($IH_2SO_4^-$) as a function of time (left y-axis) and the temperature of the filter (right axis) during CIMS analysis of a filter sampled in Lagos. The sample was collected during a 30 min walk through the Bariga informal settlement (N06 31.723'; E003 23.879') on April 23, 2023. The analysis of a blank filter is shown for comparison. Experimental data were normalized to the sum of the m127 (I^-) and m145 (IH_2O^-) signals to correct for differences in ionization efficiency during the course of the analysis.

Figure 19 shows the observed m225 peak during an applied temperature ramp in the CIMS. The sample was taken during a 30 min walk through the Bariga informal settlement in Lagos on April 23. The data are compared with the results from analysis of a blank filter, and the comparison indicates that background was a limited problem for this particular mass. A pronounced desorption peak is observed with a peak value at x ˚C, which is consistent with desorption of sulfuric acid.

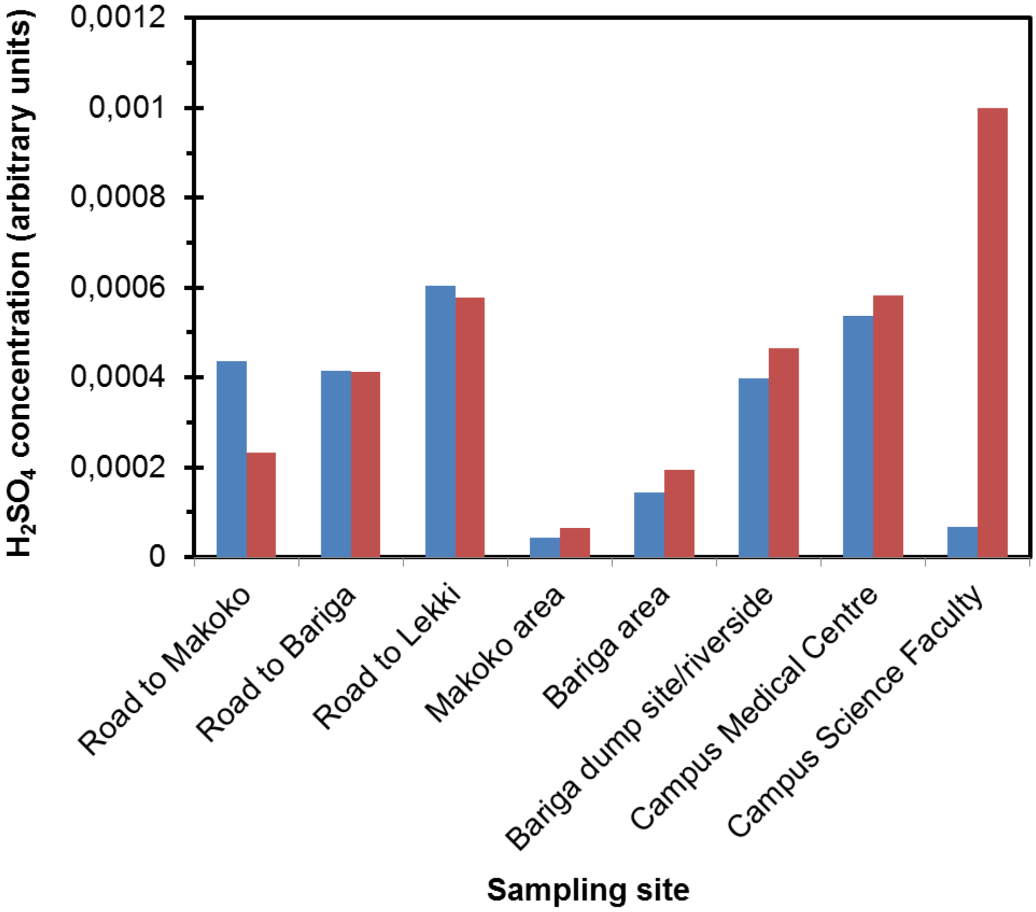


Figure 20. Relative sulfuric acid concentration measured by CIMS at m225 ($IH_2SO_4^-$) in different environments in Lagos during April 22-24, 2023. Duplicate samples were taken in each case using two sampling units. An average background measured on two blank samples has been removed from the displayed results.

Figure 20 shows the observed integrated sulfuric acid results for samples taken in multiple environments in Lagos on 22-24 April 2023. Similar particle-bound sulfuric acid concentrations are observed in traffic ("Road to…" samples) between the different sites. The observed concentrations are lower in the Makoko and Bariga housing areas, and the campus results are on average and comparable to the traffic results. The relatively low concentrations in the informal settlements are surprising considering their proximity to both the Unilag campus and major roads. The reason for the large difference between the samples taken on the roof of the Science Faculty building at the Unilag campus has not been resolved. A malfunction of one of the sampling units is one possible explanation.

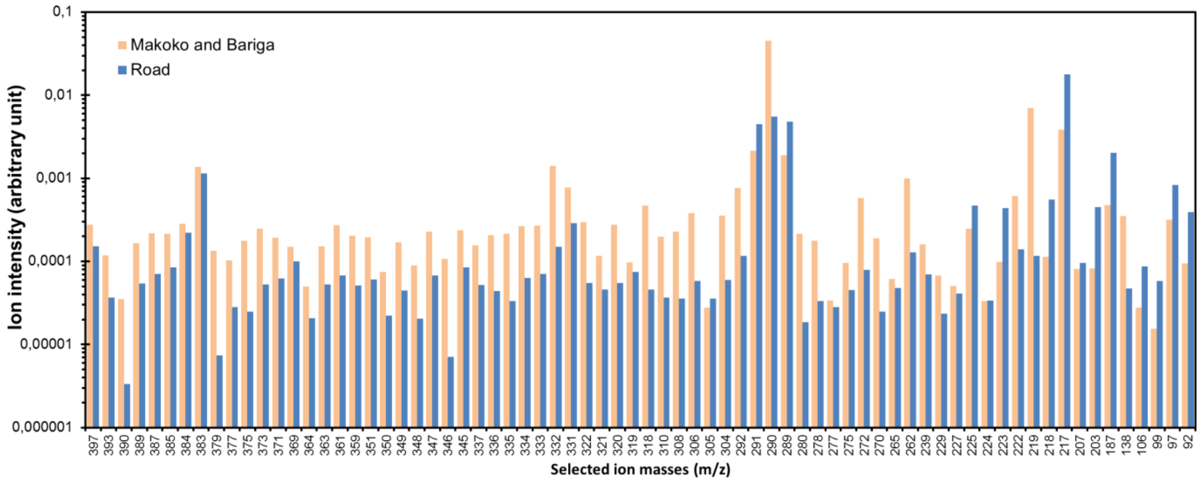


Figure 21. Average ion concentrations in samples from the settlements Makoko and Bariga (orange) and in road environments (blue) for selected masses in the m/z = 92 -397 range. Displayed masses were selected by visual inspection based on them having intensities above the background for one or several samples. Background levels observed for blank filters were removed from the data.

Figure 21 shows a comparison between average mass spectra obtained in the informal settlements and in traffic. The displayed masses were selected by visual inspection based on their intensities being above background levels for one or several samples. The observed ion intensities are often higher in traffic than in Makoko/Bariga for m/z < 225, while the opposite is true for higher m/z values. Characterization of the responsible compounds and the associated sources will require further detailed analysis.

3.4. Potential Mitigation Methods

Lagos as a state needs a standard working metrological station that is collected regularly. The absence of data makes it almost impossible to accurately tell its current PM concentration and how it varies with seasonal and wind changes. From the PMF analysis done, we can see that traffic and biomass contributions are not as high as expected although this could be a result of the holidays that were unaccounted for during the periods of measurement. Possible mitigation methods due to the PMF analysis include;

1. Ensuring proper road maintenance and improving the wear resistance of roads in a bit to reduce road dust and circulation.

2. Encourage alternate sources of power generation like solar and if fuels must be used it should be at a centralized location where various measures are put in place to reduce or eliminate air pollution.
3. Banning the use of substandard and worn-out tires on vehicles. This can also be done by limiting the importation of used/worn-out tires.
4. Encourage and support alternative means of transportation like the waterways which are abundant and the introduction of electric train systems as this will reduce fuel combustion and pollution.
5. Improve information dissemination as a majority of the population does not know the long-term implications of polluting the environment, especially in semi-rural and rural areas. It will also be worthwhile to present them with innovative ideas on how to do their business as the majority of people living in the rural areas are fishermen or farmers and biomass combustion is the only way they know.
6. Introducing stringent regulation, especially to emerging industries like the refinery on sustainability and reduction of air pollution to the minimum.

4. Conclusions

Meteorology, location, source, particle size and time of day all play a role in defining air pollution in Lagos. More populated areas are more polluted than less populated areas.

The PM concentrations in Lagos all follow the same trend irrespective of location. They are however higher in the Lagos mainland than in the Lagos Island. The analysis was not long and concise enough to definitely state the PM concentrations of Lagos however we can say that local sources play a role in local pollution levels and should be monitored and checked.

This study identified the sources of air-borne PM pollutants in Lagos to include mineral dust, soil dust, traffic, solid fuel combustion, industrial activities, and marine aerosols. Mineral dust accounted for the highest single source percentage which emphasizes the role of meteorology and dust movement in the pollution of Lagos. From the chemical analysis, the presence of sulphates in the PM is very glaring.

The pathway to achieving sustainable development in Lagos would be faster attained if the potential possible mitigation methods are enforced and adhered to and it would see the pollution of Lagos cut down to more than half of its current pollution which would translate to a healthier environment and a safer sustainable city.

Outlook

Firstly, this study can be improved upon by constantly getting more data for a longer period of time. This study did not cover the whole of Lagos as planned so it cannot give a true picture of the city's pollution problems.

Secondly, this study was done only with mostly the inorganic components of particulate matter, and this was due to time and data constraints. It is assumed that 70% of the filter papers are filled with organic elements which were not conclusively analysed.

Finally, to get an accurate reading of air-borne pollution, indoor and outdoor pollution is usually considered but for this study, we only studied outdoor pollution. It was noticed that dust movement plays a large role in polluting Lagos so indoor pollution should be properly analysed.

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