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SPECIAL ISSUE: CELEBRATING 20 YEARS OF GEOGRAPHY IN KADUNA STATE UNIVERSITY - ADVANCES AND FRONTIERS IN GEOGRAPHY

Assessment of the Seasonal Variations in Elemental Composition of Fine Particulate Matter across Selected Industrial Locations in Lagos State, Nigeria

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ABSTRACT

Fine particulate matter ($PM_{2.5}$) poses a significant threat to environmental quality and human health, especially in rapidly urbanizing and industrializing regions like Lagos State, Nigeria. Understanding its elemental composition and seasonal variation is crucial for formulating effective air quality management strategies. This study monitored $PM_{2.5}$ concentrations and their elemental composition across eleven locations in five major industrial estates (Odogunyan, Ikeja/Ogba, Oshodi/Ilupeju, Apapa, and Surulere) and one control site (Alausa) in Lagos over a 12-month period. A total of 132 $PM_{2.5}$ samples were collected using air metric gravimetric samplers. Elemental analysis was performed using the Rigaku Energy Dispersive X-ray Fluorescence (ED-XRF) to quantify the presence of 51 elements. $PM_{2.5}$ concentrations varied significantly between the wet and dry seasons, with higher values recorded in the dry season (24.55–137.14 $\mu g/m^3$) exceeding WHO guidelines compared to the wet season (7.94–32.4 $\mu g/m^3$). Of the 51 elements screened, 41 were detected, with silicon (Si), barium (Ba), zinc (Zn), potassium (K), aluminum (Al), and calcium (Ca) being the most abundant. Spatial patterns revealed that Odogunyan and Surulere had the highest elemental burdens due to heavy industrial and vehicular activities. The study showed distinct spatial and seasonal variations in $PM_{2.5}$ concentrations and elemental composition, reflecting differences in industrial activity and environmental conditions. The presence of potentially toxic elements highlights serious public health concerns, especially in densely populated areas. There is an urgent need for the Lagos State Government to strengthen its air quality regulations and enforce cleaner industrial practices.

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1 Introduction

Air pollution is a global threat to public health, causing millions of premature deaths and chronic illnesses annually (Adjei & Afriyie, 2025). Air pollution is currently the fourth leading risk factor for global disease and death, only after hypertension, smoking, and dietary issues (Hoffmann et al., 2021). Combined exposure to outdoor and household air pollution results in approximately 7 million premature deaths annually, with the majority occurring in low- and middle-income countries (World Health Organisation [WHO], 2025). Particulate matter (PM) is formed in the atmosphere when there are chemical reactions between different pollutants. Particle penetration is closely dependent on particle size (Adjei & Afriyie, 2025).

Particulate matter (PM) refers to inhalable particles, composed of sulphate, nitrates, ammonia, sodium chloride, black carbon, mineral dust, or water. PM can vary in size and is generally defined by its aerodynamic diameter; PM2.5 and PM10 are the most common in the regulatory framework and are relevant to health (WHO, 2025). Coarse particles (particles with a diameter between 2.5 μm and 10 μm) mainly consist of pollen, sea spray, and wind-blown dust from erosion, agricultural spaces, roadways, and mining operations. Finer particles ($PM_{2.5}$) are derived from the combustion of fuels in power generation facilities, industries, or vehicles, and chemical reactions between gases. In ambient environments, major sources of fine particulate matter are location-specific and include traffic, transportation, industrial activities, power plants, construction sites, and waste burning (WHO, 2025). The burden of mortality is primarily driven by non-communicable diseases: fine particulate matter ($PM_{2.5}$) and gaseous pollutants (O_3, NO_2, SO_2) penetrate deep into the lungs and bloodstream, provoking cardiovascular events (heart attacks, strokes) and chronic respiratory disorders (COPD, asthma, lung cancer) (Adjei & Afriyie, 2025).

The industrial zones of Nigeria, one of the most industrialized nations in sub-Saharan Africa, are major contributors to air pollution. Heavy metals and transition metals are among the many elements that industrial areas frequently emit, depending on the type of industrial activity, making them major contributors to atmospheric $PM_{2.5}$. Comprehensive analyses of the elemental makeup of fine $PM_{2.5}$ at several sites, including petrochemical hubs, metal-working facilities, and steel smelting sites, are currently insufficient. Data are still fragmented, making cross-site comparisons challenging, even though existing studies have described $PM_{2.5}$ in particular industrial locations (the Ife–Ibadan highway and the Lagos metro) (Fawole et al., 2015; Okuo et al., 2017).

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Previous investigations have detected elevated concentrations of trace metals, such as lead (Pb), zinc (Zn), manganese (Mn), chromium (Cr), cadmium (Cd), nickel (Ni), copper (Cu), sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca), in $PM_{2.5}$ collected from industrial zones in Nigeria (Ezeh et al., 2017; Offor et al., 2016). Respiratory and cardiovascular disorders can result from PM2.5's ability to penetrate deeply into the lungs and bloodstream (WHO, 2021; Harrison & Yin, 2000). Because of their toxicity, endurance, and bioaccumulation, these metals present serious health hazards. However, these studies rarely compare elemental concentrations across multiple industrial sites or examine how patterns differ by season or industry type.

Furthermore, Nigeria has a significant health burden associated with ambient $PM_{2.5}$. According to WHO (2025), exposure to ambient pollutants causes thousands of early deaths each year, including deaths from cancer, heart disease, and respiratory conditions. Nevertheless, targeted actions and better control are limited by the lack of comprehensive exposure profiles connected to the elemental makeup of $PM_{2.5}$. Several studies have investigated variation in fine particulate matter globally (Akanni, 2010; Anake, 2016; Anake et al., 2018; Ezeh et al., 2017; Okue et al., 2017). Very few studies have quantified the elemental composition of fine particulate matter in recent times.

A systematic, comparative study becomes necessary to quantify and assess the seasonal and spatial variation in the elemental composition of $PM_{2.5}$ across industrial sites in Lagos State, Nigeria's most industrialised region. Policy making and industrial regulation are hindered by a lack of knowledge about how various industries contribute to particulate elemental pollution and how these contributions vary seasonally or geographically in the absence of such cross-site comparative assessment. The composition of fine particulate matter is replete with toxic and non-toxic elements, posing a significant health risk to workers in ambient environments across industrial locations in Nigeria. This study focuses on the elemental composition of fine particulate matter and its monthly and seasonal variation. It will assist policymakers in identifying suitable means of air pollution control and remediation to reduce the significant health burden posed by fine particulate matter to the public.

2 Materials and Methods

2.1 Study Area

Lagos State is situated in South Western Nigeria at latitudes 6° 2′ and 6° 52′ N and longitudes 2^0 42′ and 3^0 42′ E. It is bounded to the west by the Republic of Benin, on the southern boundary by a 180 km long Atlantic coastline, and on the northern and eastern boundaries by Ogun State. Lagos state has a landmass of 3,671 km^2, of which over 35% (787 km^2) is defined by lagoons, creeks, and islands (Soladoye & Ajibade, 2014; Price Waterhouse Coopers, 2015; National Bureau of Statistics, 2011). Lagos State has 20 local government areas, of which 16 are densely populated. The Climate of Nigeria is divided into three climate types: tropical rainforest, montane (highland), and tropical savanna (Ileoje, 2001; Eludoyin et al., 2013). The coastal landscape of Lagos State is bifurcated into five geomorphological sub-units: coastal creeks and lagoons, abandoned beach ridge complex, swamp flats, active barrier beach complex, and forested river floodplain (Adegoke et al., 1980). The topography is flat, slightly above mean sea level (Oluwole et al., 1994), and is defined by swamp forest of the coastal belt with fresh water, and by dry lowland rain forest with patches of vegetation in their natural state. This wetland vegetation is caused by the region's double-maximum rainfall pattern (Adelana et al., 2005; Odjugbo, 2010). The geology of Lagos state is made up of the tertiary and quaternary sediments, which comprise the Benin formation (Miocene to recent), recent littoral alluvium, and lagoon/coastal plain sands of the Dahomey basin (where the sea bed steeply slopes away from shore and stratigraphically consists of Abeokuta and Imo groups and Ilaro Formation) (Soladoye & Ajibade, 2014). The Dahomey basin extends across southeastern Ghana in the west, through southern Togo and southern Benin Republic, and into southwest Nigeria. The basin is bounded to the west by faults and marked by the Benin hinge line at its eastern limit (Yusuf & Abiye, 2019).

Lagos State accounts for over 60% of Nigeria's industrial and commercial activities and is financially solvent, with the capacity to generate over 75% of its revenues independently of federal allocation (LBS, 2015; Ajayi, 2007, 2011). According to the Lagos Bureau of Statistics (2015) report on revenue generation, Lagos state had a gross domestic product (GDP) of over 80 billion dollars in 2010, accounting for 36% of Nigeria's GDP and among the largest economies in Africa. Lagos State has a projected population of 21 million in 2021, according to the 2006 NPC projection, making it the seventh-fastest-growing city in the world and the third-largest city in Africa (Longe, 2011; Salau, 2016; NPC, 2006). It has a population growth rate of 3.2% and is projected to be over 30 million by 2025 (PWC, 2015). Over 80% of the population is domiciled on 37% of the metropolitan landmass, where all economic activities are concentrated and driven by a skilled workforce of over 45% with a literacy rate of 92% (Ojeh et al., 2016; PWC, 2015). The industrial estates in Lagos are Ikeja, Agidingbi, Amuwo Odofin, Apapa, Gbagada, Iganmu, Ijora, Ilupeju, Matori, Ogba, Oregun, Oshodi/Isolo/Ilasamaja, Surulere, Odogunya, and Yaba (Ajayi, 2007, 2011; Etim, 2012;

Ojiodu et al., 2013; Mashi et al., 2014). Some of these estates are both active and dormant in industrial activities. In terms of their sizes, activeness, and intensities of industrial activity, Ikeja/Ogba, Oshodi/Ilupeju, Apapa, Surulere, and Odogunyan industrial estates were selected for this study, as shown in Figure 1 and Table 1.

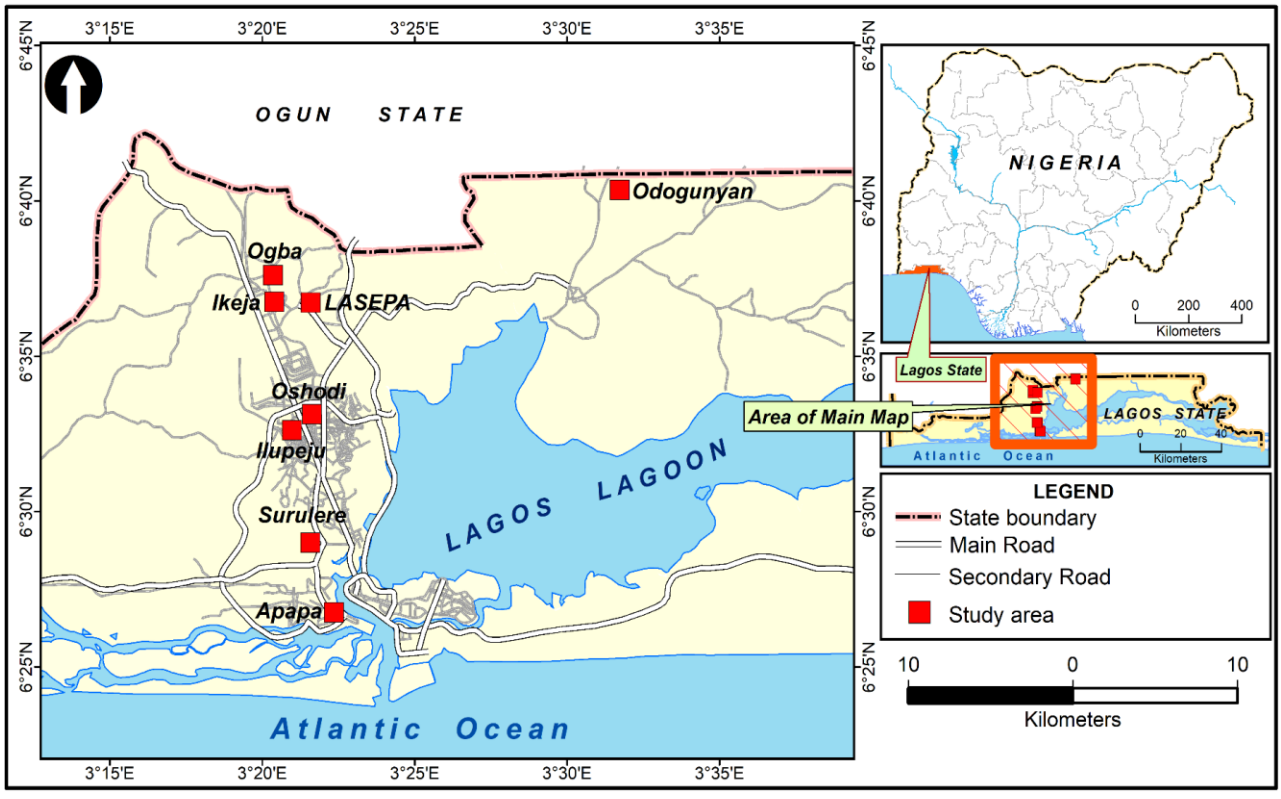

Figure 1: Study area showing the sampling points

Table 1: Sample sites

S/N	Industrial estate	Year of est.	Active industrial firm	Size (Ha)	Estate area	Estate type	Industrial nature
1	Ikeja/Ogba	1959	75	180	Mainland	IR	FBT, FM, C&P, DIP, PPP, TW, EE, WH, WWG, MVP, CCT, EE, and P.
2	Oshodi/Ilupeju	1962	57	330	Mainland	IR	FBT, DIP, PPP, C&P, CP& IT, TW, WWG, MVP, WH, and P.
3	Surulere	1957	39	25	Mainland	IR	FBT, WH, M&S, C, PPP, TW, DIP, E/P, EE, NMMP and MV
4	Apapa	1957	31	100	Coastal	IR	FBT, C&P, M&S, PPP, OMC, WH, CCT, and TW
5	Odogunya	1976	52	1582.27	Mainland	IR	FBT, C&P, DIP, M&S, PPP, TW, EE, WH, FM, FW, and E/P
6	Alausa (control)	1996	0	1	Mainland	GR	LASEPA premises, Government buildings, offices, and residential areas

Source: (Fagbohunka, 2014; MAN, 2014; LBS, 2016; Field Survey, 2021)

Note: IR: Industrial/Residential, GR: Government/Residential, Ha: Hectares, WH: Warehousing, M&S: Metals Iron and Steels Fabrication, C&P: Chemicals and Pharmaceuticals, CP&IT: Computer Parts and Information Technology Equipment DIP: Domestic/ Industrial Plastics and Nylons, FBT: Food, Beverages, Biscuits and Tobacco, PPP: Paper and Pulp Products, MVP: Motor Vehicle Assembly and Parts, NMMP: Non -Metallic Mineral Products, EE: Electrical and Electronics Products, TW: Textile and Wearing Apparels, WWG: Wood and Wood Goods, CCT: Cement, Clay, and Tiles, OMC: Oil Marketing Companies, E/P: Energy/Power, FM: Foam Manufacturing, P: Publishing, C: Carpets, FW: Footwear

2.2 Data Source

2.2.1 Fine Particulate Matter Ambient Pollutants

Random sampling techniques were used during the reconnaissance survey to select two sampling points for Ikeja/Ogba, Apapa, Oshodi/Ilupeju, Odogunya, Surulere industrial estates, and the control, making a total of 11 sampling points. Two air metric impactors embedded with a 47mm Teflon filter for fine particulate matter ($PM_{2.5}$), shown in Plate 1, were deployed and mounted at a height of 1.5-2.5m in two selected points in each industrial estate. Ambient levels of air pollutants were recorded on specific days at each industrial estate and at the control site over 12 months. A total of 132 filters were collected from the field over 12 months, spanning the wet and dry seasons, including the control site at Alausa. During field monitoring, the filters were first pre-weighted and recorded in mg using the weighing scale shown in Plate 3, then gently placed into the impactor, wrapped, and stored in a mobile box before deployment to the field. While in the field, the impactor is attached to the air meter, calibrated at the standard 5 liters per hour for monitoring, mounted on a stand 1.5 to 2.5m high, and switched on. Monitoring was carried out for 8 hours at all 11 sampling points per month, after which the impactor was removed, properly wrapped, stored in a movable box to prevent contamination, and transported back to the laboratory. At the laboratory, the filters are collected with the aid of a sterilized tweezer, post-weighted and recorded, sealed in a dispensing envelope, and stored in a desiccator as shown in Plate 4.

Plate 1: The Impactor for fine particulate matter

Plate 2: 47mm Teflon Filter

Plate: 3: Electronic Weighing Scale

Plate 4: Desiccator

2.3 Method of Data Analysis

2.3.1 Gravimetric analysis of the Teflon filter for PM2.5 mass concentration

The equation to calculate the mass of fine particulate matter collected on a Teflon filter and the results (Table 1) is:

$$M_{2.5} = \frac{M_{f-} M_i}{10^3} \quad (1)$$

Where $M_{2.5}$ = total mass of fine particulate collected during

sampling period (μg), M_f = final mass of the conditioned filter after sample collection (mg), M_I = initial mass of the conditioned filter before sample collection (mg), and 10^3 = unit conversion factor for milligrams (mg) to micrograms (μg)

Table 2: Mass ($M_{2.5}$) of fine particulate matter collected during sampling period (mg)

	Feb-20	Mar-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Apr-21	May-21
Apapa	Mass	Mass	Mass	Mass	Mass	Mass	Mass	Mass	Mass	Mass	Mass	Mass
Burma Road	0.4	0.6	0.7	0.4	1.2	0.5	0.6	0.7	1.1	0.9	0.4	0.3
Wharf Road	0.2	0.1	0.5	0.5	0.5	0.3	0.8	0.9	1.2	1.6	0.3	0.9
Ikeja/Ogba												
Ikeja	0.2	0.4	2.1	1.3	1.3	1	1.1	1.2	0.7	0.8	0.5	0.2
Ogba	0.5	0.7	1.6	1	0.9	0.7	1.2	1	1.1	1.6	0.4	0.7
Oshodi/Ilupeju												
Oshodi	0.4	0.8	0.6	0.3	0.6	0.3	0.3	0.4	0.3	2.3	0.4	0.2
Ilupeju	0.5	0.1	1	0.8	0.8	0.8	0.4	0.6	0.5	0.8	0.3	0.6
Odogunya												
Steel Junction Agbede	0.8	1	3.9	5.9	4.7	2.7	1	1.3	4.8	5	0.1	0.8
Odonla Street	0.4	0.8	5.3	6.3	5.1	4.1	1.7	1.6	3.2	3.5	0.4	0.1
Surulere												
Akanbi Ontiri Street	1	1.2	1.5	0.8	0.7	0.2	0.7	0.6	0.3	0.8	0.5	1
Abebi Road	5.2	5.5	1.4	1.7	1.6	1.3	0.9	1	0.4	1.4	0.3	0.2
Control	0.4	0.4	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1

$PM_{2.5}$ samplers were used to measure the total volume of ambient air passing through the sampler (V) in cubic meters at the actual temperatures and pressures recorded during sampling, as shown in Table 3.

Table 3. Volume (V) of sampled air in cubic meters (m^3)

Industrial Estates	Feb-20	Mar-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Apr-21	May-21
Apapa	0.031	0.032	0.031	0.031	0.032	0.034	0.03	0.03	0.032	0.032	0.031	0.032
Burma Road												
Apapa	0.031	0.031	0.031	0.031	0.033	0.033	0.031	0.031	0.033	0.033	0.031	0.031
Wharf Road												
Ikeja/Ogba												
Ikeja	0.037	0.037	0.036	0.036	0.036	0.036	0.036	0.037	0.035	0.036	0.037	0.032
Ogba	0.039	0.039	0.035	0.037	0.035	0.037	0.037	0.038	0.037	0.037	0.04	0.031
Oshodi/Ilupeju												
Oshodi	0.037	0.038	0.038	0.037	0.037	0.037	0.038	0.038	0.038	0.036	0.037	0.032
Ilupeju	0.038	0.037	0.04	0.04	0.037	0.04	0.039	0.039	0.037	0.038	0.038	0.034
Odogunya												
Steel Junction Agbede	0.037	0.037	0.039	0.037	0.038	0.039	0.037	0.036	0.037	0.037	0.039	0.037
Odonla Street	0.038	0.039	0.039	0.039	0.039	0.04	0.039	0.036	0.039	0.039	0.04	0.036
Surulere												
Akanbi Ontiri Street	0.039	0.038	0.039	0.039	0.039	0.039	0.039	0.037	0.039	0.036	0.035	0.039
Abebi Road	0.038	0.036	0.039	0.039	0.039	0.039	0.037	0.039	0.04	0.037	0.038	0.037
Control	0.04	0.035	0.04	0.035	0.04	0.03	0.04	0.034	0.033	0.04	0.04	0.04

The formula V is:

$$V = Q_{avg} \times t \times 10^{-3}$$

Where Q_{avg} = average flow rate over the entire duration of the sampling period (5L/min), t = duration of sampling period (min) as shown in Table 3, and 10^{-3} =unit conversion factor for liters (L) into cubic meters (m^3)

$$PM_{2.5} = \frac{M_{2.5}}{V}$$

Where $PM_{2.5}$ = mass concentration of $PM_{2.5}$ particulates ($\mu g/m^3$), $M_{2.5}$ = total mass of fine particulate collected during sampling period (μg), and V = total volume of air sampled taken directly from sampler (m^3)

Table 4: Duration (t) of sampling in hours

Industrial Estates	Feb-20	Mar-20	Jul-20	Aug-20	Sep-20	Oct-20	Nov-20	Dec-20	Jan-21	Feb-21	Apr-21	May-21
Apapa												
Burma Road	6.1	6.3	6.1	6.2	6.4	6.8	6	6	6.4	6.3	6.2	6.3
Wharf Road	6.2	6.1	6.2	6.1	6.6	6.6	6.1	6.1	6.6	6.6	6.1	6.1
Ikeja/Ogba												
Ikeja	7.4	7.4	7.2	7.1	7.1	7.1	7.2	7.4	7	7.2	7.4	6.4
Ogba	7.7	7.7	7	7.3	7	7.3	7.4	7.6	7.3	7.4	7.9	6.1
Oshodi/Ilupeju												
Oshodi	7.4	7.6	7.5	7.4	7.4	7.4	7.5	7.5	7.5	7.1	7.3	6.3
Ilupeju	7.6	7.4	7.9	7.9	7.3	7.9	7.8	7.8	7.4	7.6	7.5	6.8
Odogunya												
Steel Junction Agbede	7.4	7.4	7.8	7.3	7.5	7.8	7.4	7.1	7.3	7.4	7.7	7.4
Odonla Street	7.5	7.7	7.7	7.7	7.7	7.9	7.8	7.2	7.7	7.8	7.9	7.2
Surulere												
Akanbi Ontiri Street	7.7	7.5	7.7	7.7	7.7	7.7	7.7	7.3	7.8	7.2	7	7.7
Abebi Road	7.5	7.2	7.8	7.8	7.8	7.8	7.3	7.7	8	7.3	7.5	7.4
Control	8	7	8	7	8	6	8	6.8	6.5	8	8	8

Source:

2.3.2 *Protocol for analysis of fine particulate matter bound elemental composition using ED-XRF*

(i) Scope and applicability

The standard operating procedure (SOP) outlines the process for identifying the elemental composition of particulate matter (PM) deposited on filter media using Energy-Dispersive X-ray Fluorescence (ED-XRF). It is intended for use with a Rigaku NEX CG ED-XRF spectrometer (Plate 5). According to USEPA method IO-3.3, it can analyze elements from sodium (Na-11) to uranium (U-92) without causing damage. The protocols address data collection, filter preparation, handling, analysis, calibration, and monitoring, as well as operational safety.

(ii) Summary of method

Under vacuum, a Rigaku NEX CG ED-XRF spectrometer is used to analyze a PM filter sample. The interaction between atoms of the elements present in the filter deposit and X-ray photons from the excitation source forms the basis of the principle. The Rigaku NEX CG ED-XRF spectrometer uses a 50 kV end-window X-ray tube with a palladium (Pd) anode as its X-ray source. One of the five secondary targets is the focus of the generated X-rays, with polarized X-ray photons used to ignite the sample. The atoms in the sample lose their inner-shell electrons due to these photons. Every element found in the sample has vacancies filled with outer shell electrons, and the transitions that cause X-ray emission are typical of each element. In a solid-state silicon drift detector, these distinctive X-rays are picked up. Each incoming photon generates electrical charges, which are sorted into energy channels, tallied, and shown as a sample spectrum of X-ray counts versus energy during analysis. The background created by X-ray scattering from the tube into the detector is superimposed on the spectrum's distinctive peaks. The spectrum's individual peak energies correspond to specific elements, and peak areas are proportional to elemental mass loadings (though at high

concentrations, the correlations may become non-linear). Every spectrum is collected over the allotted time and stored for later use with the Rigaku Quantez program. A completely integrated device that excels in high-throughput, high-sensitivity analysis for several elements is the Rigaku NEX CG ED-XRF spectrometer (Plate 5). For many elements, the polarizing optical route and high-power excitation source offer low detection limits, enabling the investigation of small sample sizes. Because the system's gain-correction technique ensures high analyzer stability, fewer calibrations are required. The samples are reanalyzed several times because ED-XRF is a non-destructive method. However, some volatile species (such as ammonium, nitrate, chlorine, and bromine) may be lost during vacuum exposure.

(iii) Normative reference

The Rigaku NEX CG EDXRF User Manual, USEPA method IO-3.3

(iv) Interferences

The Rigaku NEX CG ED-XRF software processes all spectra from samples and field blanks, and the analyzer determines and reports the raw intensities for each element. After that, raw intensities are blank-corrected to account for spectral noise and background contamination from the filter substrate. By deducting blank raw intensities from sample raw intensities, the intensities of the reference or sample materials are adjusted for any fluorescence originating from the sample media. The filter lot could be the source of certain potential problems.

(v) Sample filter handling

For PM sampling, ARA n-FRM samplers are used. In the gravimetric laboratory, Teflon filters are received and weighed to determine their mass (loading). After comparing the post-sampling filter masses of three successive sample sets, the set with the highest mass is forwarded for elemental composition analysis. A visual inspection must confirm that all filters to be examined are in good condition. Until they are timed for room temperature and vacuum analysis, the filters are kept cold at 4 °C.

(vi) Procedure

The Rigaku NEX CG user's guide provides full instructions for installing and operating the XRF instrument.

(vii) Application setup

A specific application must be created and configured before the analysis of a sample can begin. Selecting the items to be reported, the circumstances of the acquisition and reporting schemes, a calibration standards file, and standard measurement are all necessary for setting up the application.

(viii) Calibration

The Rigaku NEX CG EDXRF spectrometer has demonstrated itself to be a stable analyzer that requires no regular calibrations. The first installation, roughly once a year, when the analyzer fails verification tests, and whenever an analysis-critical part of the analyzer (such as the detector or X-ray source) is serviced or replaced, are all times when calibrations are carried out. Before sample analysis, the Multi-Channel Analyzer (MCA) is calibrated, and the library is calibrated monthly. To calibrate the Rigaku NEX CG EDXRF spectrometer, standard reference materials are utilized. These include UCDAVIS Standard Reference Material (UCD-47-MTL-ME-177) air particulate on polycarbonate filter membranes, $PM_{2.5}$ deposits on PTFE membranes, and 47mm Micro matter thin film foil on the Nucleopore membrane. Every standard sample media type includes a matching blank membrane that must be used as a blank and examined.

(ix) Sample preparation and measurement

After removing the filters from cold storage for analysis and letting them come to room temperature in a desiccator for 2 hours in their petri slides, the filters are placed in sample holders, and the powder is gloved-cleaned. To remove the sample tray, release the center knob (Plate 5) and open the sample chamber. The filters are revealed by removing the aluminum sample cup holder from its lining and inverting it. We remove the current filters and place them back in the proper petri dishes. Before the filters are inserted into the sample cups, the cups are Kim wiped to remove any residue from prior filters. Using flat paddle tweezers, the cells are removed from their petri plates by grasping the outer ring, then placed face up. After swapping out the liners, the sample cup holder is placed back onto the sample tray, inverted. The spectrometer's sample chamber cover is opened, and the sample tray is reinserted into the chamber, ensuring the alignment pin is correctly seated before fastening the tray. The spectrometer's sample-chamber cover is closed. The spectrometer is started by selecting the "Startup Option" Startup/Shutdown icon, checking the "Initialize Spectrometer" box, making sure no other boxes are checked, and choosing "Start." The spectrometer arranges all filters and blanks with valid status flags into trays for analysis.

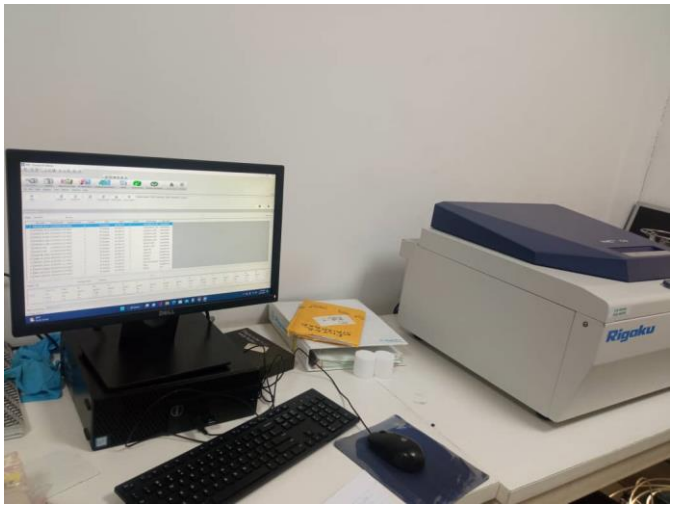

Plate 5. Rigaku NEX CG ED-XRF spectrometer and analysis application

3 Results

Particulate pollutant concentrations were higher during the dry season than during the wet season, due to reduced precipitation-driven washout. The average fine particulate matter level was between 7.94µg/m^3 and 32.4 µg/m^3 during the wet season, as shown in Fig. 2 and 24.55µg/m^3 to 137.14µg/m^3 during the dry season, as shown in Fig. 3.

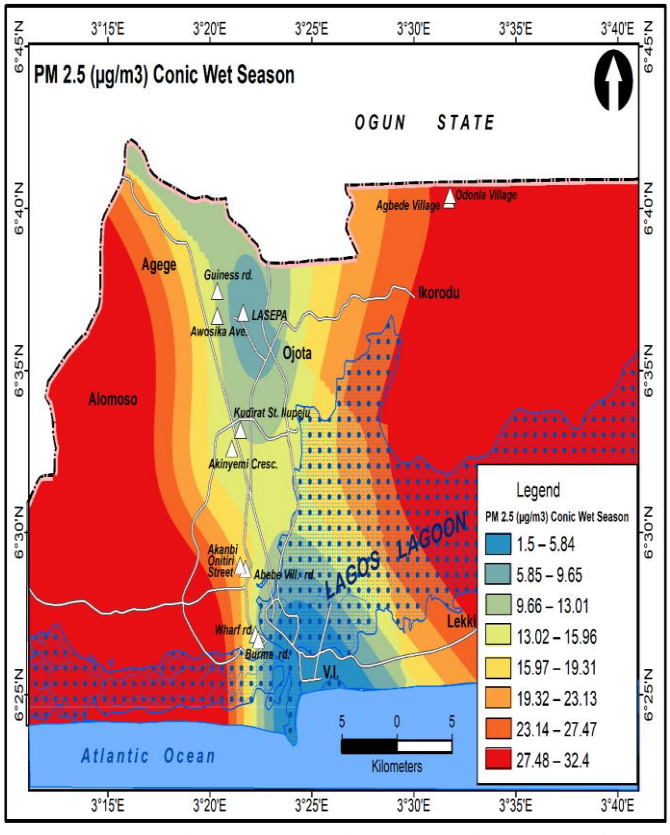

Figure 2: Spatial variation in fine particulate matter ($PM_{2.5}$) levels in the wet season across selected industrial locations in Lagos state

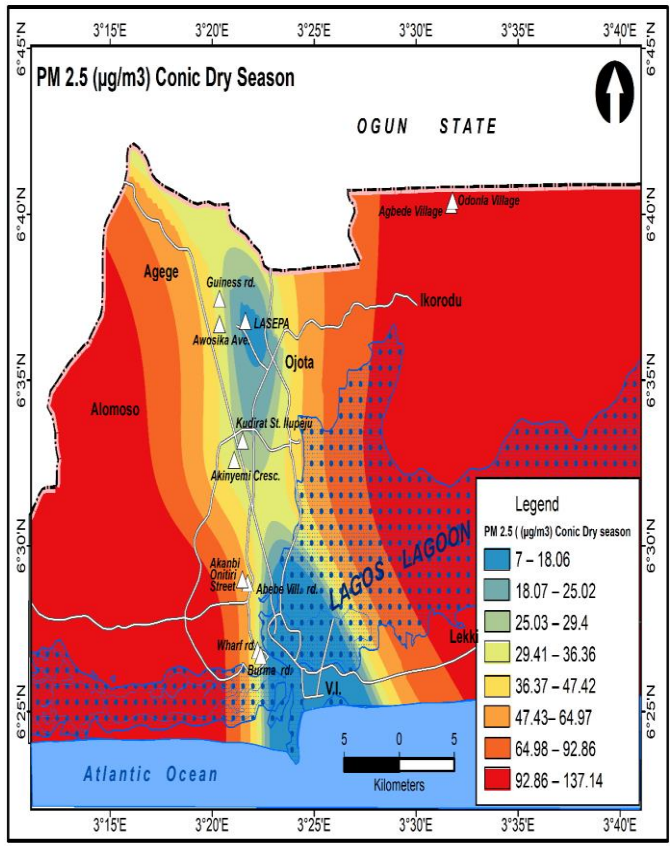

Figure 3: Spatial variation in fine particulate matter (PM2.5) levels in the dry season across selected industrial locations in Lagos state

Fine particulate matter elemental composition (Table 4 and Table 5) revealed 41 elements across the sampling points and the control site. The abundant elements in descending order of concentration across the sampling points are 11: Si > Ba > Zn > K > Al > Ca > Fe > Mg > Ti > V > Sr. The less abundant elements are 20: Sn > Cl > Mn > Sm > Ce > Ta > S > Ni > As > Se > Br > Rb > Y> Sn > Pb > Th > U > Yb > Sb > Co >Sc while elements not detected are 10: W > Cu > I > Na > P > Cr > Zr > Nb > Mo > Cd. Amongst the abundant elements, silicon (Si) ranged between 119 - 180µg/m^3 across the sampling point. Barium (Ba) ranged between 75 - 88 µg/m^3, zinc (Zn) ranged between 51 - 64µg/m^3, potassium (k) ranged between 32- 38µg/m^3, calcium (ca) ranged between 19 - 24µg/m^3 aluminum (Al) ranged between 15 - 27µg/m^3, titanium (Ti), vanadium (V) and strontium (Sr) ranged between 0.97- 3.2µg/m^3, magnesium (Mg) ranged between 0.0 - 4.53µg/m^3. Amongst the trace elements; lead (Pb), thorium (Th), ytterbium (Yb), uranium (U), tantalum (Ta), samarium (Sm), cerium (Ce), antimony (Sb), tin (Sn), rubidium (Rb), bromine (Br), selenium (Se), arsenic (As), nickel (Ni), cobalt (Co), manganese (Mn), scandium (Sc), chlorine (cl), yttrium (y) and sulfur (S) were minimal (0.01-0.98µg/m^3) across the sampling point and the control site. At the same time, sodium (Na), potassium (K), chromium (Cr), copper (Cu), zirconium (Zr), niobium (Nb), molybdenum (Mo),

cadmium (Cd), iodine (i) and tungsten (w) were not detected (0.000µg/m^3) across the sampling points and the control site. Seasonally, higher concentrations of abundant and trace elements were observed during the dry season (Table S1) than during the wet season (Table S2) at the sampling points and the control site.

4 Discussion

The elemental composition of fine particulate matter across the sampling points and the control revealed the presence of 34.75% (41) of 118 known elements in the periodic table. Amongst the 41 elements, 8.47% (10) were not detected, while 26.27% (31) were detected across the sampling points and the control site. Amongst the detected elements, 9.32% (11) are abundant while 16.95% (20) are trace elements across the sampling points and the control. The variation in abundant and trace elements across the sampling points and the control is primarily due to the combination of the nature and intensity of ambient industrial and traffic emissions. For example, the concentration of elemental iron is higher in Odogunya than in other sampling points due to the dominant presence of iron and steel plants, which burn iron ore for the production of billet, ribbed bars, and wire rods in the area. Silicon, aluminum, barium, and zinc varied across the sampling points due to the presence of diverse manufacturing companies across the industrial estates. Some of the elements are toxic to the environment, while others are not.

The toxicity of an element to humans and their environment depends on its concentration, exposure, and vulnerability (Brauer et al., 2021). Heavy metals rarely degrade or disappear in nature and are fundamental in determining the level of risk posed by air pollution (Turkyilmaz et al., 2020). An average human inhales between 12,000 and 16,000 liters of oxygen daily and cannot survive without it for 3 minutes, which is fundamental for man's survival and well-being (Saxena & Sonwani, 2019; Türk & Kavraz, 2011; Surya, 2021). Examples of non-toxic, abundant elements found across the sampling site are silicon, iron, zinc, calcium, magnesium, and strontium, while toxic elements are aluminum, titanium, vanadium, and barium.

Trace elements are both toxic and non-toxic to man and his environment; examples of non-toxic trace elements essential to support life across the sampling points are: chlorine, sulfur, potassium, manganese, nickel, selenium, and cobalt, while the toxic trace elements are lead, arsenic, and uranium. A significant number of abundant and trace elements were higher at the sampling points than at the control site and the WHO safety limit for humans. For example, Vanadium ranged between 1.5 -2µg/m^{3,} which is higher than the WHO standard of 1. Manganese, nickel, lead, and arsenic all exceeded the WHO standard and the control site levels, especially during the dry season. Analysis of PM2.5-bound elements found significant levels of arsenic, lead, and chromium in both the air and the soil, suggesting that pollutants released into the ambient environment are removed through precipitation scavenging, dry deposition, and gravitational settling (Oke, 1987).

Similar studies have also found a clear seasonal distinction in fine particulate matter-bound elements. For example, Oweisana et al. (2021) studied variations in toxic elements in Port Harcourt and found higher levels during the dry season than during the wet season. Anake, (2016) and Anake et al. (2020) study on the spatio-temporal variability of 22 trace metals (As, Cr, Pb, Ni, Cd, Mn, Ti, V, Ba, Fe, Al, Mo, Ca, Zn, Cu, Mg, Sr, Se, Ag, K, Na, and Sb) in atmospheric fine particulate matter in Agbara, Ota, Ewekoro industrial areas and Covenant University found all 22 trace metals to be higher during the dry season than the wet season.

5 Conclusion

The findings of this study highlight pronounced spatial and seasonal disparities in $PM_{2.5}$ concentrations and elemental composition across industrial areas in Lagos State. Elevated $PM_{2.5}$ levels during the dry season underscore the influence of climatic factors, particularly the absence of precipitation, which limits atmospheric cleansing. The highest concentrations and elemental burdens were recorded in Odogunyan and Surulere, likely due to the nature and intensity of industrial operations in these areas. Silicon, barium, and zinc emerged as dominant elements, pointing to industrial and construction-related emissions. The detection of 41 elements and the absence of 10 others suggest localized industrial signatures that vary by estate. These insights call for stringent air quality management strategies, including continuous monitoring, regulatory enforcement, and the adoption of cleaner industrial technologies. Such measures are essential for reducing public exposure to harmful air pollutants and for guiding sustainable urban-industrial development in Lagos State. Fine particulate pollution is a perennial problem that will continue to attract significant world attention due to its negative impact on environmental and human health. There is a need for studies to focus on emerging toxic and non-toxic elements in fine particulate matter across cities worldwide to develop a sustainable plan for cities. The study was limited by inadequate funding and the number of fine particulate matter sensors, which, if sufficient, could have improved sensor coverage across industrial locations in Lagos State.

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