Research Article

Spatial Extent and Distribution of Ambient Airborne Particulate Matter (PM$_{2.5}$) in Selected Land Use Sites in Nairobi, Kenya

Caroline Kiai [iD],[1] **Christopher Kanali,**[2] **Joseph Sang** [iD],[1] **and Michael Gatari**[3]

[1]*Department of Soil, Water and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology,*
 P.O. Box 62000-00200, Nairobi, Kenya
[2]*Department of Agricultural and Biosystems Engineering, Jomo Kenyatta University of Agriculture and Technology,*
 P.O. Box 62000-00200, Nairobi, Kenya
[3]*Institute of Nuclear Science and Technology, College of Architecture and Engineering, University of Nairobi,*
 P.O. Box 30197-00100, Nairobi, Kenya

Correspondence should be addressed to Caroline Kiai; caroline.kiai@jkuat.ac.ke

Air pollution is one of the most important environmental and public health concerns worldwide. Urban air pollution has been increasing since the industrial revolution due to rapid industrialization, mushrooming of cities, and greater dependence on fossil fuels in urban centers. Particulate matter (PM) is considered to be one of the main aerosol pollutants that causes a significant adverse impact on human health. Low-cost air quality sensors have attracted attention recently to curb the lack of air quality data which is essential in assessing the health impacts of air pollutants and evaluating land use policies. This is mainly due to their lower cost in comparison to the conventional methods. The aim of this study was to assess the spatial extent and distribution of ambient airborne particulate matter with an aerodynamic diameter less than 2.5 μm (PM$_{2.5}$) in Nairobi City County. Seven sites were selected for monitoring based on the land use type: high- and low-density residential, industrial, agricultural, commercial, road transport, and forest reserve areas. Calibrated low-cost sensors and cyclone samplers were used to monitor PM$_{2.5}$ concentration levels and gravimetric measurements for elemental composition of PM$_{2.5}$, respectively. The sensor percentage accuracy for calibration ranged from 81.47% to 98.60%. The highest 24-hour average concentration of PM$_{2.5}$ was observed in Viwandani, an industrial area (111.87 μg/m³), and the lowest concentration at Karura (21.25 μg/m³), a forested area. The results showed a daily variation in PM$_{2.5}$ concentration levels with the peaks occurring in the morning and the evening due to variation in anthropogenic activities and the depth of the atmospheric boundary layer. Therefore, the study suggests that residents in different selected land use sites are exposed to varying levels of PM$_{2.5}$ pollution on a regular basis, hence increasing the potential of causing long-term health effects.

1. Introduction

Clean air is a basic requirement for human well-being and health [1]. Air pollution poses a significant threat to human health, and it is largely attributed to the occurrence of high morbidity and mortality rates worldwide [2, 3]. Urban air pollution is of great concern in both developing and developed countries. Biomass use in both rural and urban areas has remained to be the main source of air pollution [4]. According to the WHO [5], more than 6 million premature deaths in 2012 occurred as a result of exposure to air pollution. However, more than 3 million of these deaths were attributed to ambient air pollution [4]. The ever-increasing population and increased volume of traffic in urban areas also have resulted in severe air pollution [6, 7]. Although there has been a significant air quality improvement in most high-income countries, middle- and low-income countries are still experiencing poor to very poor air quality.

Airborne particulate matter pollution is a major environmental risk factor with well-documented short- and long-term effects on human mortality and morbidity [8]. Epidemiological studies have reported a strong association

between increased concentrations of inhalable particles and increased mortality. Falcon-Rodriguez et al. [9] and Turner et al. [10] illustrated that inhalation of particulate matter (PM) increases the prevalence of respiratory diseases, which include lung cancer and chronic obstructive pulmonary disease. PM exists in the atmosphere as either liquid or solid particles with varying sizes and compositions [11], Harrison 2 et al. [12]. The size and distribution of particles are characterized by ultrafine, fine, or coarse particles, each with an aerodynamic diameter equal to or less than 0.1, 2.5, and 10 μm, respectively. Particles with a diameter equal to or less than 10 and 2.5 μm, commonly referred to as PM_{10} and $PM_{2.5}$, respectively, are of special importance as they can reach the upper and lower portions of the respiratory tract of exposed individuals and can cause cardiovascular and respiratory illness [8, 13].

According to Shilenje et al. [14], Nairobi County has undergone a significant land use/cover change transformation principally occasioned by increasing numbers of residential estates, city expansion, industrialization, and a rising human population. According to a report by the JICA, Nairobi is ranked as the most industrialized urban center in East and Central Africa [15]. A total of 338 industries were registered in 2004 with the Directorate of Occupational Health and Safety (DOHS) [15]. Previous studies in Nairobi on air pollution have specifically determined the pollution levels on industries, major roads, and residential and commercial areas separately [16–20]. However, a comparison of the levels in the different land uses is important in an attempt to quantify the effect of urbanization on the environment.

As one of the developing countries, Kenya experiences serious environmental challenges concerning air quality deterioration, water pollution, noise pollution, and soil contamination. Most research has been done regarding water pollution and degradation of soil, but little attention has been given to air quality deterioration. This has led to limited information on air pollution within the urban centers. Therefore it is difficult to assess the impacts of urban development and increase in urban population. This study, therefore, aimed to assess the spatial extent and distribution of ambient airborne particulate matter ($PM_{2.5}$). This assessment is important to decision-makers, planners, and regulatory bodies in the sustainable management of air quality in urban centers.

2. Materials and Methods

2.1. Study Area. This study was conducted in selected land use sites within Nairobi City County, Kenya. Nairobi is Kenya's capital city, located at 1° 9′S, 1° 28′S and 36° 4′E, 37° 10′E (Figure 1). The city experiences four major seasons: warm dry season (December–February), the long rainy season (March–May), the cool and dry season (June–October), and the short rainy season (October–November) [21]. The altitude varies between 1600 m and 1850 m above the sea level and occupies an area of about 696 km^2. According to KNBS [22], the population of Nairobi is estimated to be about 4.4 million people. Rapid population

growth of about 4.6% per year has led to high congestion. The city has a population density of 3080 persons per square km compared to 50 persons per square km countrywide [23]. Temperatures generally vary from 12°C during the cold season to 29°C during the warm and dry season from December to March.

The monitoring points selected for this study were Viwandani (KCI), Mathare (KCM), Karura (KCF), CBD (KCC), Lucky Summer (KCL), Allsops (KCA), and Kahawa (KCK) (Table 1). The sites were selected using non-probability sampling technique, which involved selecting the sites based on the land use activity within the relevant areas that represented the entire study area.

2.2. Calibration of Low-Cost Sensors. This study was conducted using PMS7003 sensors by Plantower and cyclone samplers (BGI 400S) to monitor $PM_{2.5}$ mass concentration levels. PMS7003 sensors were chosen because of their low-cost ($30), previous versions of PMS sensors (PMS1003 and PMS5003) were evaluated, and their performances were propitious for monitoring $PM_{2.5}$ [24]. The sensors have a measurement chamber with a set of focusing lenses, light-emitting diode, and photodiode detector. They use the light scattering principle to measure the size distribution of fine particles using Mie theory [25]. Eight sensors were calibrated before deployment for four consecutive days (86 hours) from 4th to 7th December 2020 according to the procedure adopted by Pope et al. [26]. This involved colocating the sensors with a standard Andersen dichotomous impactor (Sierra Instruments Inc., USA) [21] which is located at the University of Nairobi (UON) 17 m above the ground away from traffic sources. The impactor has a sampler that segregates the stream of air that passes through it into coarse and fine portions that are filtered on preweighed Teflon filters of a diameter of 37 mm and a 2 μm pore size. Filters were replaced after every 24 hours and weighed in the laboratory. The 24-hour average mass concentration of $PM_{2.5}$ was then obtained by dividing sample mass after accounting for all the uncertainties over the total volume. The uncertainties were estimated to be 10% instrument error, 25% weighing, and 7% sampling error [26]. A comparison of the mass concentration obtained from the optical method and gravimetric method was made using the following equation to obtain the correction factor for each sensor that was applied to all the data collected from the different sites:

$$CF = \frac{GMC}{OMC}. \tag{1}$$

CF is the correction factor (scaling factor), GMC is the average gravimetric mass concentration, and OMC is the average optical mass concentration.

Accuracy assessment of the sensors was obtained using equation (2) that was adopted by Liu et al. [27] to evaluate the degree of closeness between the values measured by the sensor and the reference:

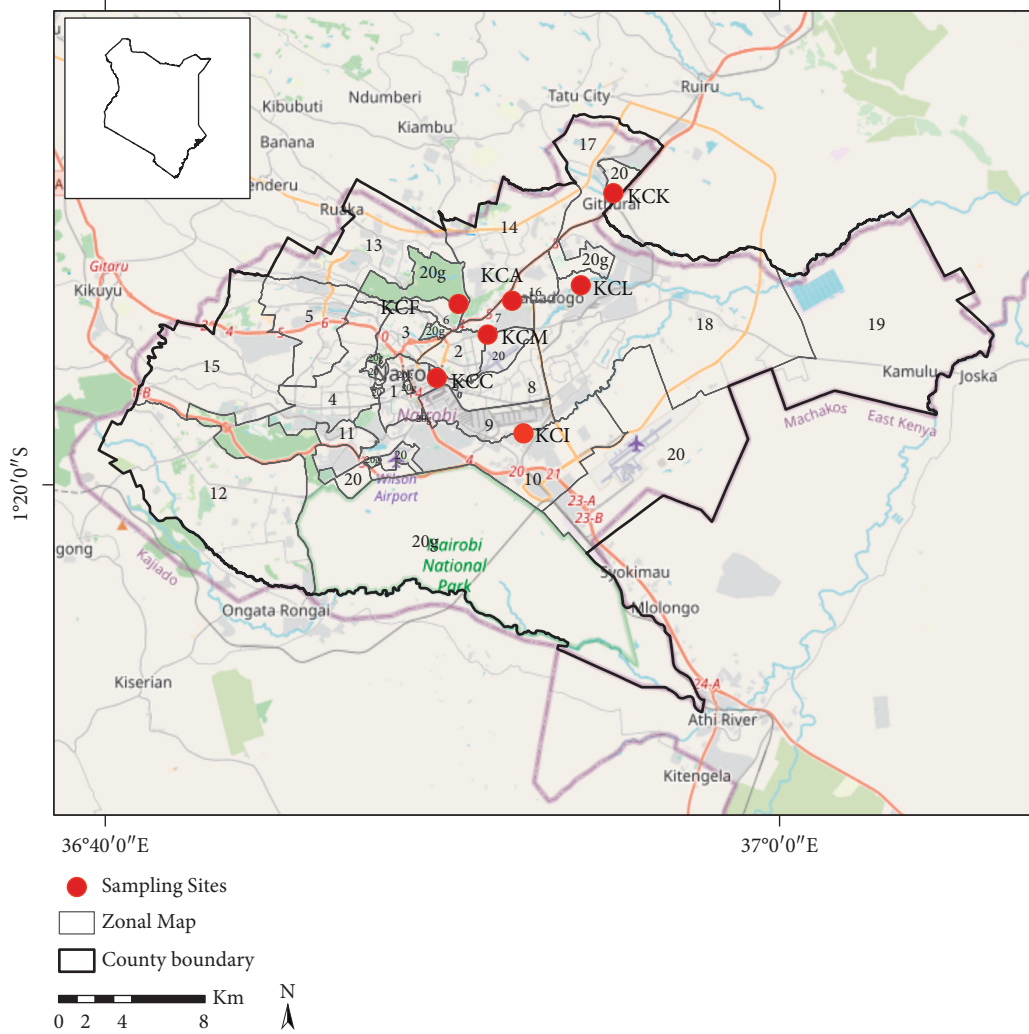$$A\% = 100 - \frac{|X - R|}{R} \times 100. \tag{2}$$

FIGURE 1: Location of selected sampling sites and their respective zone [9] for PM$_{2.5}$ mass concentration level monitoring in Nairobi City County, Kenya.

TABLE 1: Description of the location of the selected sites, sampling site codes, and prevailing land use according to the Nairobi zonal map.

Site name	Code	Latitude	Longitude	Description
Viwandani	KCI	−1.3086	36.8737	Main industrial area
Mathare	KCM	−1.2617	36.8561	High-density residential flats (informal settlement)
Nairobi CBD	KCC	−1.2823	36.8310	Commercial/residential/light industry
Karura	KCF	−1.2470	36.8417	Park/forest/recreation
Lucky Summer	KCL	−1.2383	36.9019	Residential mixed development/industrial
Allsops	KCA	−1.2455	36.8681	Low-density residential (site was 15 m away from Thika Superhighway)
Kahawa	KCK	−1.1943	36.9181	Agricultural, residential mixed development
University of Nairobi	KCU	−1.2794	36.8163	Location of the Andersen Dichotomous impactor, mounted 17 m above the ground level

Here, $A\%$ is the accuracy percentage, X is the average concentrations measured by the sensor for the entire calibration period, and R is the average concentration measured by the reference monitoring station.

2.3. Sensor-Based Monitoring.

The calibrated sensors were deployed one sensor per site to the seven sites with different land use types (Table 1). They were mounted to monitor ambient PM$_{2.5}$ at heights ranging from 1.5 m to 2.5 m above the ground level which is close to human breathing height. The sensors were programmed to log the concentration levels after every 1 minute continuously. Monitoring was done from 7th January to 29th March 2021. The data collected were analyzed using R statistical software version 4.1.0 to obtain hourly and daily average concentrations of PM$_{2.5}$. The

Kriging Geostatistical method was used to interpolate the hourly averages point data of $PM_{2.5}$ in ArcGIS software version 10.2 because it assumes that the direction or distance between sample points reveals a spatial correlation used while explaining the variation in the surface [28]. The general formula is formed as a weighted sum of the data and is given by

$$Z(\mathbf{so}) = \sum_{i=1}^{n} \lambda i Z(\mathrm{si}). \tag{3}$$

Here, n is the number of values measured, Z (si) is the value measured at the ith location, and λ_i is the weight for the measured value that is unknown at the ith location and so is the prediction location.

2.4. Gravimetric-Based Monitoring.
Gravimetric-based monitoring was done for a period of 1 month to collect air samples from the selected land use sites for elemental composition of $PM_{2.5}$. During this period, three samples were collected per site on weekdays for nonconsecutive days following the procedure that was used by Maina et al. [20]. Sampling was done using a BGI 400S personal sampling pumps with a cyclone. The personal sampler is a cyclone sampler with a geometry that allows only particles with an aerodynamic diameter of less than the required measurement to be deposited on the filter media. The principle of operation for the cyclone sampler is the theory of particle inertia to collect/select particles of a particular size range [29].

Teflon filters of a diameter of 37 mm and a 2 μm pore size were used to collect $PM_{2.5}$. Clean Teflon filters were then loaded onto the filter holder. The sampler used has a rechargeable battery that ran for 8 hours. This made it possible for $PM_{2.5}$ sample collection even at remote sites. Preweighed filters were loaded into cassettes, which were then connected into the nozzle and placed in a sampling position. Samples were collected for 8 hours (8 a.m. to 4 p.m.) after which the filter cassettes were offloaded and sealed carefully in an air tight Petri dishes and stored in a clean environment to avoid the contamination of the collected samples. The flow rate was measured when the clean Teflon filters were loaded and after the sampling was done using a field rotameter. The rotameter was calibrated at different flow rates in the laboratory using a flow meter to facilitate a calibration graph for use in establishing correct average sample flow after the field sample collection [30]. $PM_{2.5}$ concentrations were calculated by the difference between the initial and the final weighting divided by the total volume of air that passed through the filter [31].

2.5. Elemental Composition of $PM_{2.5}$.
The elemental composition of $PM_{2.5}$ was determined by a nondestructive method using an energy dispersive X-ray fluorescence (EDXRF) spectroscopy at the Institute of Nuclear Science laboratory at the University of Nairobi. The air samples collected from the gravimetric-based monitoring were analyzed for K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Ca, As, Br, Zr, and

Pb. The spectrometer is made up of a Si (Li) detector that is used in detecting the spectral line characteristic, a sample chamber, and an emission energy analyzer. The filters were subjected to a current of 80 μA and a voltage of 30 kV for a period of 1500 seconds. The spectra were analyzed for quantitative analysis using the AXIL program following the procedure outlined by [21] to determine the concentrations in mass per unit area for thin film and later converted to mass per unit volume (concentrations in ng/m³).

3. Results and Discussion

3.1. Calibration of the Sensor Results.
The results of the calibration of the eight sensors are as shown in Table 2 and Figure 2. Table 2 shows the average concentrations of $PM_{2.5}$ from the standard measurements and sensor-based measurement and the scaling factors for each sensor. The scaling factors ranged from 1.09 ± 0.58 to 1.46 ± 0.93. Pope et al. [26] reported a scaling factor of 1.63 after performing a similar procedure at the same site with similar standard equipment. The variation in the scaling factors could be attributed to the variation in the sensor model used since they were using OPC-N2 sensors.

Figure 2 shows the accuracy percentage of the different PMS7003 sensors. The accuracies were determined using equation (2), and they ranged from 81.47% to 98.60%. Badura et al. [24] obtained similar accuracies (Figure 2) for the PMS7003 sensor model. The earlier versions of Plantower sensors (PMS5003 and PMS3001) were also reported to have good and higher repeatability [24, 32]. This showed that the sensors' level of accuracy is high and can be used to monitor $PM_{2.5}$.

3.2. Sensor-Based Monitoring Average Concentrations.
Figure 3 shows the distribution of $PM_{2.5}$ mass concentrations of the sites selected within Nairobi. The 24-hour mean for all the sites exceeded the WHO recommended guideline for $PM_{2.5}$ (25 μg/m³) except for one site, which is a background site that is forested (Table 1). The box plot distribution (Figure 3) in all the sites indicates that, in most cases, the residents are exposed to $PM_{2.5}$ pollution. The values for the average daily mass concentration levels ranged from 21.25 μg/m³ at the urban background to 111.87 μg/m³ at an industrial site. The Viwandani site (Figure 1) had the highest average concentration levels of $PM_{2.5}$ of 111.87 μg/m³ for the three-month period of monitoring. This average is higher than the ambient air quality tolerance limit recommended by NEMA for an industrial area in Kenya of 75 μg/m³ [33]. Many contributions were attributed to the surrounding industries, and part of them were from waste burning and indoor air.

The minimum and the maximum values recorded for the 24-hour mean at Viwandani were 38.75 μg/m³ and 513.84 μg/m³, respectively. Mutahi et al. [30] reported a mean value of $PM_{2.5}$ of 166 μg/m³ at Viwandani, which is slightly above the average value reported in this study. This difference might have been due to the differences in sampling seasons and the 12-hour sampling time per day by

TABLE 2: Average standard gravimetric measurement and sensor-based averages of different PMS7005 sensors and their scaling factors.

Average gravimetric concentrations ($\mu g/m^3$)	Sensors	Average sensor concentrations ($\mu g/m^3$)	Scaling factor
	PMS7003Z	16.23 ± 9.27	1.28 ± 0.74
	PMS7003N	18.92 ± 10.62	1.09 ± 0.58
	PMS7003M	15.78 ± 8.47	1.31 ± 0.78
20.70 ± 4.12	PMS7003A	18.37 ± 9.80	1.13 ± 0.60
	PMS7003C	14.16 ± 3.61	1.46 ± 0.93
	PMS7003D	17.60 ± 10.13	1.18 ± 0.65
	PMS7003L	18.87 ± 9.17	1.10 ± 0.58
	PMS7003I	17.33 ± 11.13	1.19 ± 0.66

Note: the letters Z, N, a, K, A, C, D, L, and I are used to differentiate the sensors since they are the same model (PMS7003).
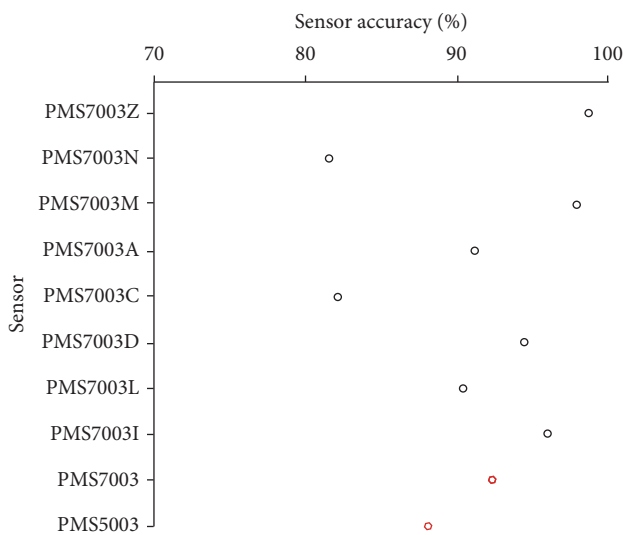

FIGURE 2: Sensor accuracies in percentage obtained in this study in comparison with accuracy percentages reported in a study that used a similar sensor model. Red dots represent accuracy values reported by Badura et al. [24].

Mutahi et al. [30]. However, a study by Shilenje et al. [14] showed low concentrations of $PM_{2.5}$ in the industrial area, which is largely attributed to the variations in meteorological parameters [34] during the monitoring period, precipitation of 0.52 mm/hr [14].

CBD site (Figure 1) had the second-highest 24-hour mean concentration of $82.56 \mu g/m^3$ with the values ranging from $34.42 \mu g/m^3$ to $155.58 \mu g/m^3$. These values are higher than the WHO recommended standard of $25 \mu g/m^3$. The site is characterized by high pedestrian and vehicular traffic, retail shops, street vendors, and other businesses. Kinney et al. [17] reported values ranging from 75.6 to $98.1 \mu g/m^3$ for 11-hour averages at different roundabouts within the CBD: Ronald Ngala, Tom Mboya, and River Road. Lucky Summer had a 24-hour average value of $60.00 \mu g/m^3$, which is more than twice the Air Quality Guidelines (AQI) recommended by WHO. This is to a large extent explained by the unpaved roads [35, 36], the large nearby dumpsite [37], and industrial sources from Babadogo [38]. Mathare site (Figure 1) had a 24-hour average of $50.07 \mu g/m^3$ with values ranging from 2.63 to $270.38 \mu g/m^3$. Ngo et al. [39] reported an 8-hour average of $62 \mu g/m^3$. The results from this study are slightly

lower than those reported by Ngo et al. [38]. This could be attributed to the differences in the sampling period since the study sampled $PM_{2.5}$ levels for 8 hours during daytime only, and there are fewer aerosol concentrations at night [40], which reduces the average 24-hour mean value. Kahawa site (Figure 1), on the other side, had a 24-hour mean of $28.37 \mu g/m^3$, which is slightly above the WHO recommended standard for $PM_{2.5}$. The low concentrations could be attributed to the surrounding vegetation cover around the site that could have reduced pollution levels [17].

The lowest $PM_{2.5}$ concentrations were observed at the Karura site (Figure 1). The 24-hour mean for the study period was $21.25 \mu g/m^3$, which is lower than the $25 \mu g/m^3$ recommended by WHO. From the analysis, it was observed that 72% of the $PM_{2.5}$ measurements were above $25 \mu g/m^3$ and 28% were below $25 \mu g/m^3$. This shows that $PM_{2.5}$ mass concentrations are below the WHO recommended standard on most of the days in Karura, which is highly attributed to the fact that the tree cover in this site reduces $PM_{2.5}$ pollution. However, the hourly distribution of $PM_{2.5}$ as shown in Figure 4 for this site indicates that some hours have much higher concentrations with values ranging from 1.92 and $174.57 \mu g/m^3$, respectively. These values are higher than the values reported for the 24-hour mean for background sites [17, 20, 26]. Several studies have shown a significant reduction of air pollutants in areas with vegetation cover [2, 41, 42].

Figure 5 shows the spatial distribution of $PM_{2.5}$ in Nairobi City County. The color codes adopted for this are as stipulated by US EPA's breakpoint for $PM_{2.5}$ and Air Quality Index (AQI) [43]. The green color is good, yellow is moderate, orange is unhealthy for sensitive groups, red is unhealthy, purple is very unhealthy, and maroon is hazardous. The results show that there is a trend of peak during morning hours from 0500 to 0900 hours and evening peak that starts from 1600 to 2200 hours. From 1100 to 1500 hours, the larger part of Nairobi is under moderate AQI, and some parts around Kahawa, Westlands, and Dagoretti have $PM_{2.5}$ levels that are unhealthy for sensitive groups. The area around the industrial area (Viwandani) shows that the area is under $PM_{2.5}$ pollution that is unhealthy to the residents most times of the day except for a few times around midnight to 0300 hours. A study by Yadav et al. [40] observed similar peaks of $PM_{2.5}$, which occurred between 0700–1000 and 1900–2300 hours. In residential areas with informal settlements, much of the contribution to $PM_{2.5}$ in the
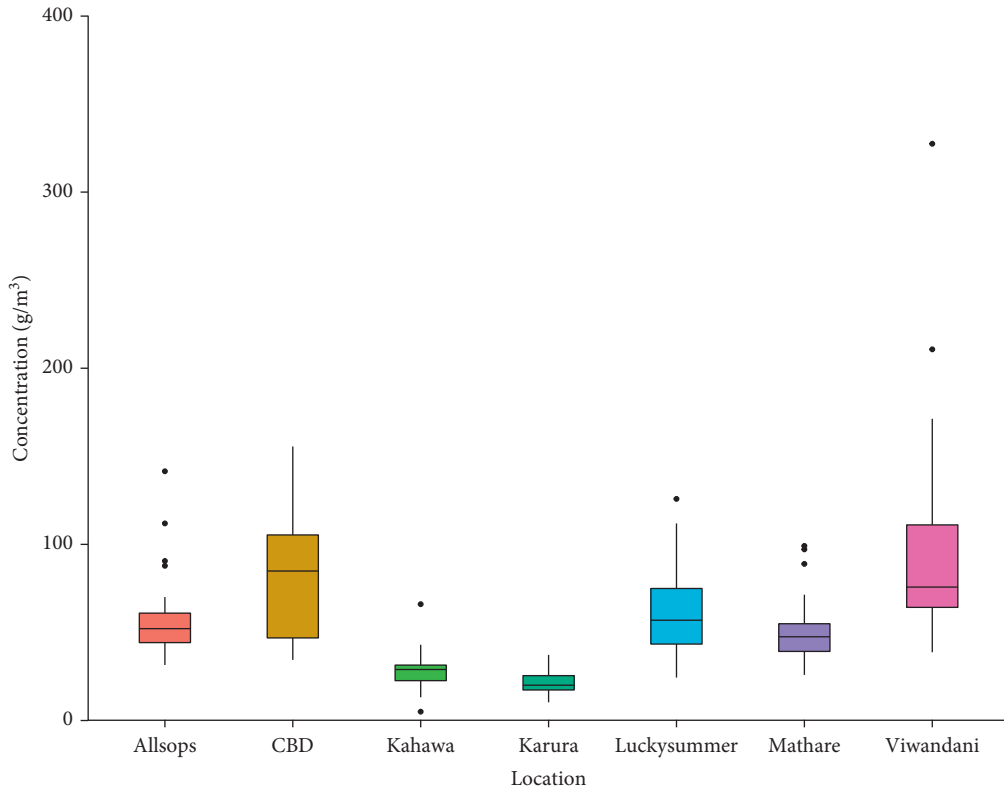
Figure 3: 24-hour mean distribution of $PM_{2.5}$ mass concentration ($\mu g/m^3$) in the selected land use sites in Nairobi City County.

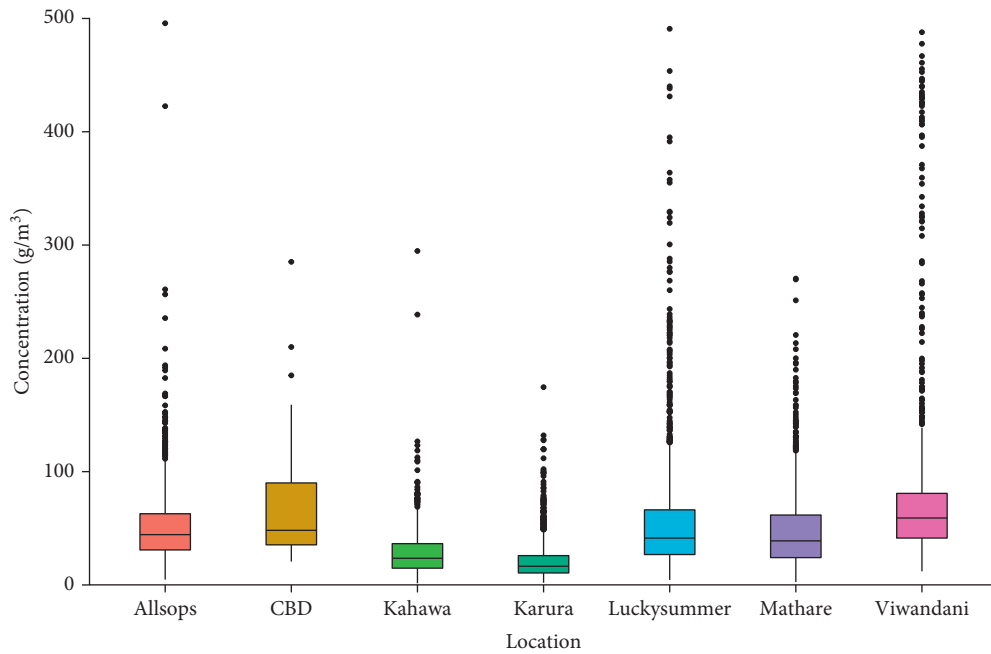Figure 4: Hourly distribution of $PM_{2.5}$ mass concentration ($\mu g/m^3$) in the selected land use sites in Nairobi City County.

evening is due to increased cooking activities. Other studies have also observed similar trends [13, 44–47]. There is a decrease in $PM_{2.5}$ concentration levels at mid-morning (10 a.m.) to late afternoon/early evening (4 p.m.) due to the increase in the atmospheric boundary layer and low road traffic flows [45].
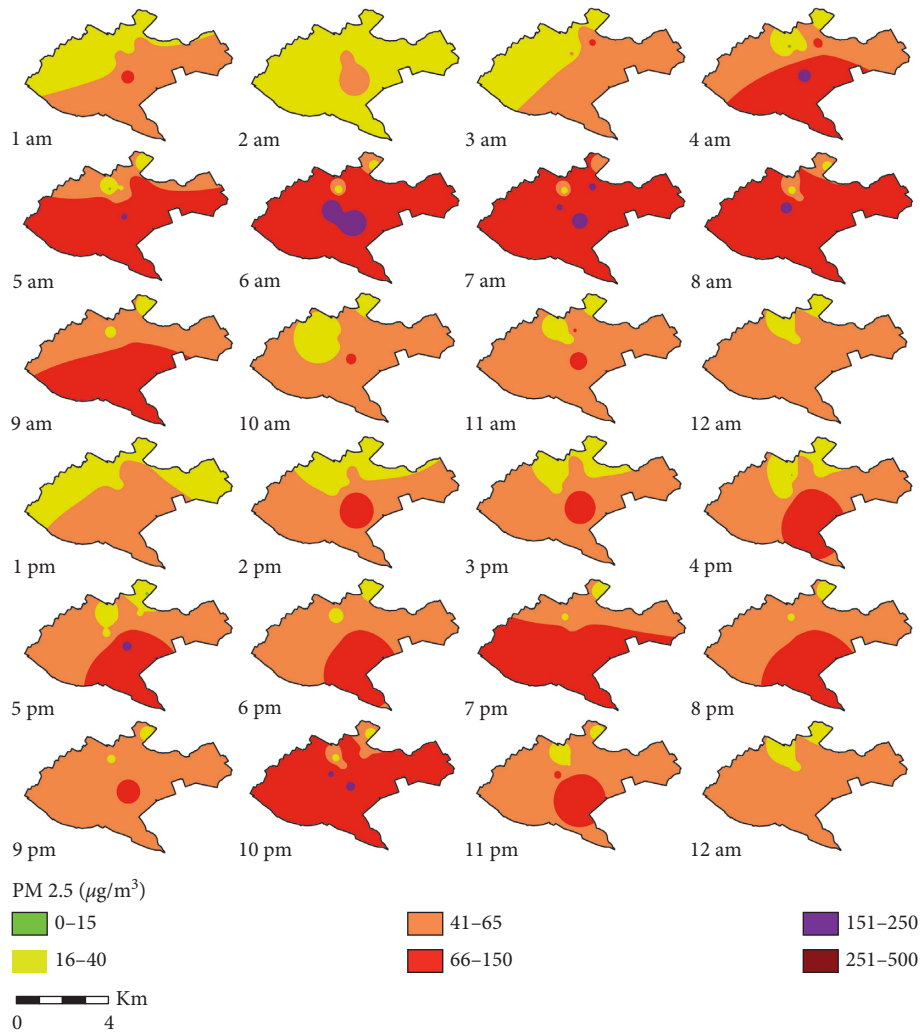
FIGURE 5: Spatial distribution of mean hourly PM$_{2.5}$ mass concentration in Nairobi City County.

3.3. Gravimetric-Based PM$_{2.5}$ Concentration Levels and Elemental Composition. The 8-hour average concentrations of PM$_{2.5}$ obtained from weighing the filters and applying equation (1) are shown in Figure 6. The three-day non-consecutive sampling using cyclone samplers showed that Viwandani had the highest average PM$_{2.5}$ concentrations (124.87 μg/m^3) and Karura had the lowest (28.82 μg/m^3). The results show a high and positive correlation between gravimetric-based and sensor-based measurements as the coefficient of determination (R^2) was 0.71. In addition, there is low significant variability between data measured using the cyclone samplers and Plantower PMS7003 sensors (Figure 7). The 29% variability could be due to filter handling [26] and the sampling period which tends to reduce the average concentrations when done for longer periods [30].

Figure 8 shows the relative percentage distribution of elemental composition in PM$_{2.5}$ samples for each site. The pie charts were constructed from the average concentration values for the selected elements in PM$_{2.5}$. The number of elements detected in PM$_{2.5}$ filter samples were 13: K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Ca, As, Br, Zr, and Pb. The most abundant elements are Fe, K, and Ca, largely attributed to

the natural resources that include Earth's soil, crust, and suspended dust from unpaved roads [48, 49].

The presence of Zn, Pb, As, K, Mn, and Cu suggests the presence of both anthropogenic and natural sources [11]. Natural sources mainly include Earth's crustal dust, and the anthropogenic include emissions from combustion of fossil fuels, car tires, and breaks [31]. KCF and KCU (Table 1) had lower concentrations of elements compared to all the other sites, and KCI had higher elemental concentrations, with Fe, Ca, and K having higher concentration levels because KCF is a forested area and the elements here are likely to have a natural source mainly soils. The forest of trees and scrubs around the area decreases the amount of dust that emanates from the ground [31]. The concentrations of all the elements ranged from a minimum of 6.79 to 44,668.42 ng/m^3. According to Gordon [11], the sources of K are highly linked to wood combustion, soils, incinerators, and lime kilns. Zn and Mn elements indicate that the source could be from metal industries [50, 51]. Elements such as Ca, Ti, Fe, and Mn are classified as crustal elements and are characterized by resuspended dust particles related to traffic and unpaved roads [38].
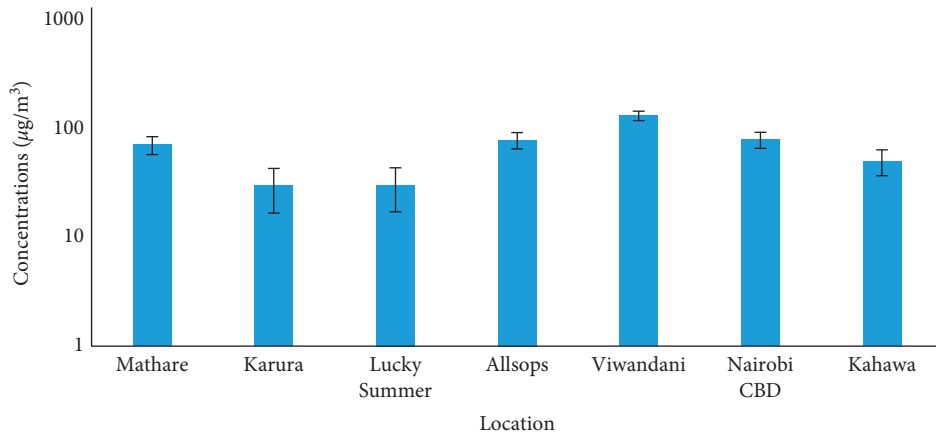
FIGURE 6: The average 8-hour average PM$_{2.5}$ concentration levels in the selected land use sites within Nairobi City County.
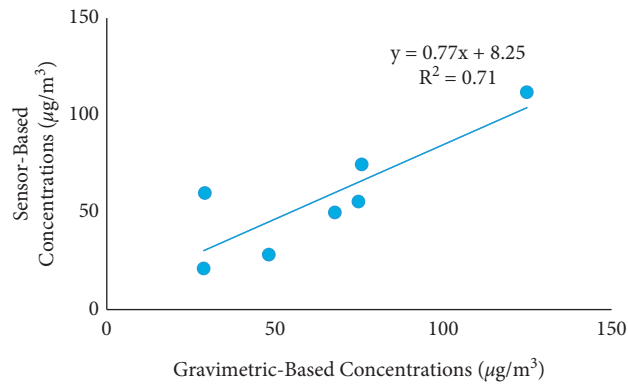

FIGURE 7: Comparison between the average sensor-based monitoring and gravimetric-based using cyclone pump samplers (BGI 400S) concentration.
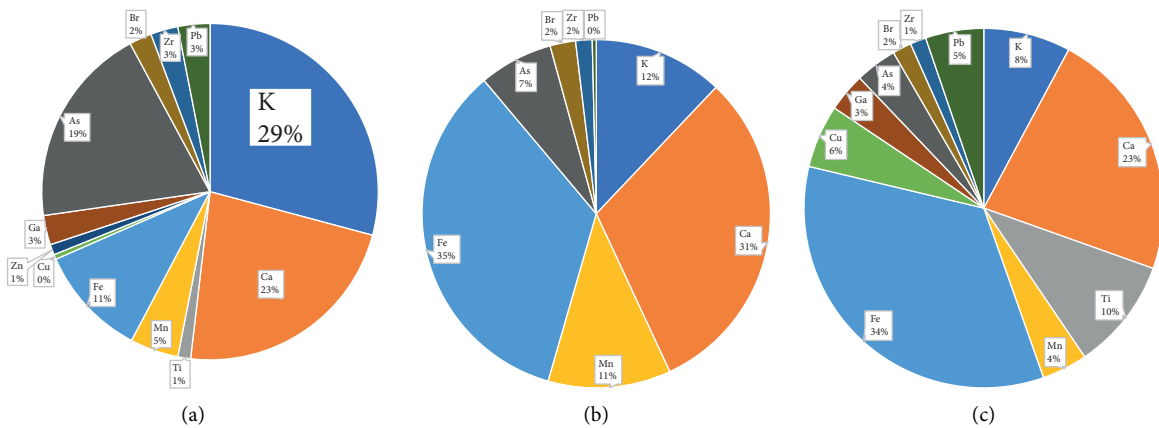

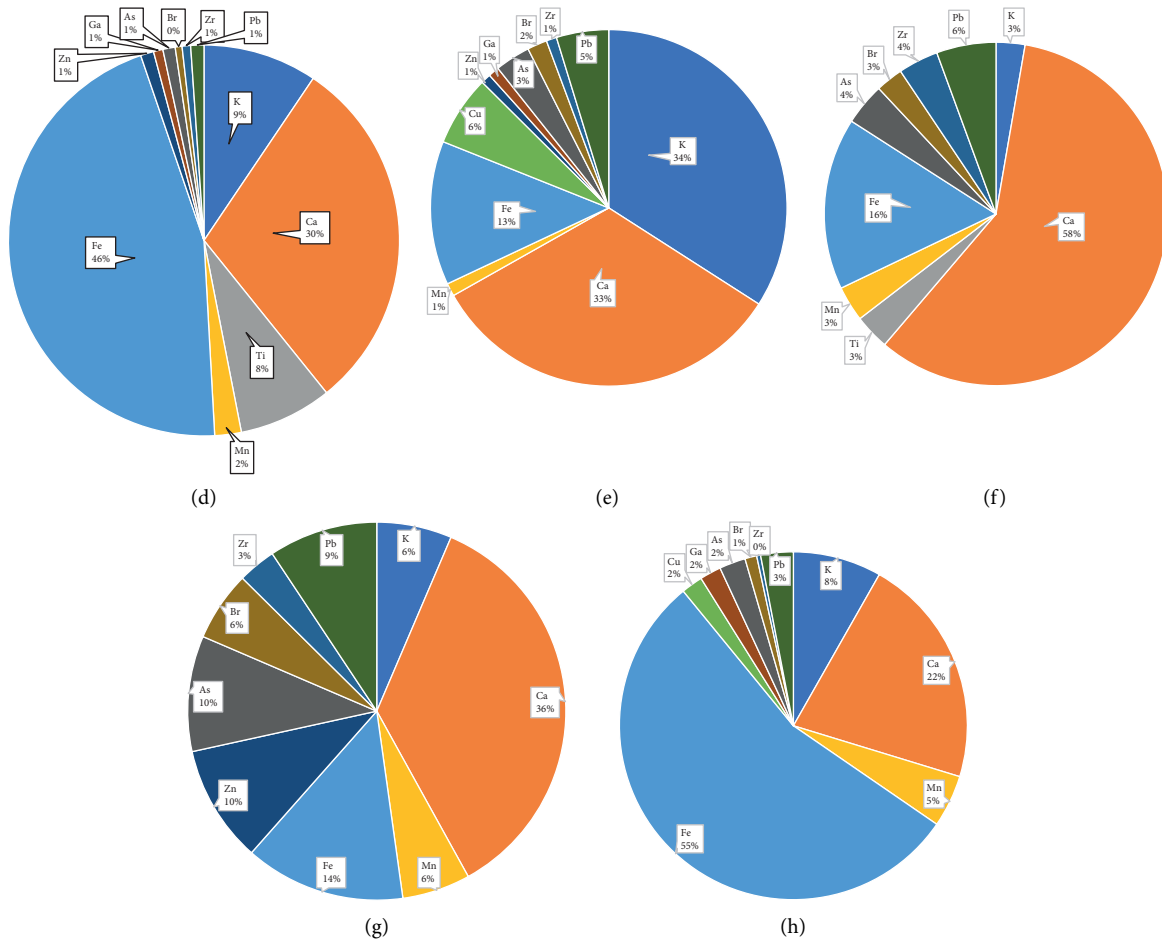|		
(a)	(b)	(c)

FIGURE 8: Continued.

Figure 8: The relative percentage concentrations of major elements in PM$_{2.5}$ collected in the filter samples using Cyclone pump samplers (BGI 400S) for selected land use sites in Nairobi City County for an 8-hour period: (a) KCM, (b) KCL, (c) KCA, (d) KCI, (e) KCC, (f) KCK, (g) KCF, and (h) KCU.

Table 3: The correlation coefficient r between average concentrations of the elemental composition of PM$_{2.5}$ in selected land use sites in Nairobi City County.

	K	Ca	Ti	Mn	Fe	Cu	Zn	As	Ga	Br	Zr	Pb	PM$_{2.5}$
K	1												
Ca	0.699	1											
Ti	0.5935	0.9343	1										
Mn	0.5861	0.8092	0.8195	1									
Fe	0.6431	0.9481	0.9897	0.8468	1								
Cu	0.3319	−0.1172	−0.1784	−0.3386	−0.1831	1							
Zn	0.686	0.842	0.8678	0.6963	0.8907	−0.1798	1						
As	0.4538	0.052	−0.0165	0.3042	−0.01	−0.1177	0.0964	1					
Ga	0.7395	0.617	0.7064	0.6573	0.6698	0.123	0.6114	0.5384	1				
Br	0.7406	0.738	0.54	0.6403	0.5527	0.0695	0.5699	0.5073	0.5876	1			
Zr	0.5212	0.7385	0.5783	0.6522	0.5615	−0.256	0.4902	0.5051	0.5555	0.8911	1		
Pb	0.6436	0.6457	0.4841	0.2798	0.45	0.4552	0.4347	0.1783	0.5416	0.8079	0.6904	1	
PM$_{2.5}$	0.8349	0.8407	0.8288	0.6827	0.8099	0.2824	0.7236	0.2565	0.8793	0.7522	0.6452	0.7964	1

Table 3 shows the statistical correlation coefficient r of the elements in PM$_{2.5}$ samples. The results indicate that there are significant correlations between PM$_{2.5}$ concentration levels and K, Ca, and Ti.

Mn, Fe, Zn, Ga, Br, Zr, and Pb coefficients range from 0.65 to 0.88. This shows that there are positive correlations

between most of the elements in PM$_{2.5}$ which suggests that they originate from more common/similar sources. The elements with (r) that is more than 0.5 shows that there is a strong relationship between the elements [20]. High correlations were observed between K, Ca, Ti, Br, Ga, and Zn. The high correlation between K, Ca, Ti, and Ca is

predominantly thought to originate from soils that are generated from soil emissions through transportation [31].

4. Conclusion

This study showed that the sensor accuracies ranged from 81.47% to 98.60%, which indicates that low-cost sensors can be used to monitor air quality provided they are calibrated before deployment. They can provide useful information that can be used by urban planners, decision-makers, private sector, government, and the public in general.

The results of the distribution of $PM_{2.5}$ in the selected land use sites ranged from a daily mean of $21.25 \, \mu g/m^3$ to $111.87 \, \mu g/m^3$. The observed 24-hour mean for all the sites was above the WHO recommended standard of $25 \, \mu g/m^3$ except for the Karura site (Figure 1), which is a forest reserve ($21.25 \, \mu g/m^3$). This implies that many residents in Nairobi are on regular occasions exposed to $PM_{2.5}$ pollution, which has the potential of causing a long-term impact on health. However, vegetation cover has a great potential of reducing $PM_{2.5}$ pollution and toxic elements hence the need to sensitize the public on greening the city in an effort to improve urban air quality.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

References

[1] World Health Organization, "Air quality guidelines global update 2005," *Atmospheric Environment*, vol. 22, no. 9, pp. 2070-2071, 2005.

[2] D. J. Nowak, D. E. Crane, and J. C. Stevens, "Air pollution removal by urban trees and shrubs in the United States," *Urban Forestry & Urban Greening*, vol. 4, no. 3-4, pp. 115–123, 2006.

[3] World Health Organization, *Evolution of WHO Air Quality Guidelines: Past, Present and Future*, WHO, Geneva, Switzerland, 2017.

[4] World Health Organization, *Economic Cost of the Health Impact of Air Pollution in Europe: Clean Air, Health and Wealth*, WHO, Geneva, Switzerland, 2015.

[5] World Health Organization, *WHO Expert Meeting: Methods and Tools for Assessing the Health Risks of Air Pollution at Local, National and International Level*, WHO, Geneva, Switzerland, 2014, http://www.euro.who.int/__data/assets/pdf_file/0010/263629/WHO-Expert-Meeting-Methods-and-tools-for-assessing-the-health-risks-of-air-pollution-at-local,-national-and-international-level.pdf.

[6] S. Gulia, S. M. Shiva Nagendra, M. Khare, and I. Khanna, "Urban air quality management-a review," *Atmospheric Pollution Research*, vol. 6, no. 2, pp. 286–304, 2015.

[7] N. Bruce, D. Pope, E. Rehfuess, K. Balakrishnan, H. Adair-Rohani, and C. Dora, "WHO indoor air quality guidelines on household fuel combustion: strategy implications of new evidence on interventions and exposure-risk functions," *Atmospheric Environment*, vol. 106, pp. 451–457, 2015.

[8] G. D. Thurston, R. T. Burnett, M. C. Turner et al., "Ischemic heart disease mortality and long-term exposure to source-related components of U.S. Fine particle air pollution," *Environmental Health Perspectives*, vol. 124, no. 6, pp. 785–794, 2016.

[9] C. I. Falcon-Rodriguez, A. R. Osornio-Vargas, I. Sada-Ovalle, and P. Segura-Medina, "Aeroparticles, composition, and lung diseases," *Frontiers in Immunology*, vol. 7, no. JAN, pp. 1–9, 2016.

[10] M. C. Turner, Z. J. Andersen, A. Baccarelli et al., "Outdoor air pollution and cancer: an overview of the current evidence and public health recommendations," *CA: A Cancer Journal for Clinicians*, vol. 70, no. 6, pp. 460–479, 2020.

[11] G. E. Gordon, "Receptor models," *Environmental Science & Technology*, vol. 22, no. 10, 1988.

[12] R. M. Harrison, D. Bousiotis, A. M. Mohorjy et al., "Health risk associated with airborne particulate matter and its components in Jeddah, Saudi Arabia," *Science of The Total Environment*, vol. 590-591, pp. 531–3539, 2017.

[13] M. Kampa and E. Castanas, "Human health effects of air pollution," *Environmental Pollution*, vol. 151, no. 2, pp. 362–367, 2008.

[14] Z. Shilenje, K. Thiong, V. Ongoma, S. O. Philip, P. Nguru, and K. Ondimu, "Roadside air pollutants along elected roads in Nairobi city, Kenya," *Journal of Geology & Geophysics*, vol. 5, no. 5, 2016.

[15] Japanese International Cooperation Agency, *The Study on for Final Report Executive Summary*, Japanese International Cooperation Agency, 2004, https://openjicareport.jica.go.jp/pdf/11823093_01.pdf, Tokyo, Japan.

[16] M. J. Gatari, J. B. C. Pettersson, W. Kimani, and J. Boman, "Inorganic and black carbon aerosol concentrations at a high altitude on Mt Kenya," *X-Ray Spectrometry*, vol. 38, no. 1, pp. 26–36, 2009.

[17] P. L. Kinney, M. G. Gichuru, N. Volavka-close et al., "Traffic impacts on PM2.5 air quality in Nairobi, Kenya," *Environmental Science & Policy*, vol. 14, no. 4, pp. 369–378, 2011.

[18] G. O. Odhiambo, A. M. Kinyua, C. K. Gatebe, and J. Awange, "Motor vehicles air pollution in Nairobi, Kenya," *Research Journal of Environmental and Earth Sciences*, vol. 2, no. 4, pp. 178–187, 2010.

[19] T. Egondi, K. Muindi, C. Kyobutungi, M. Gatari, and J. Rocklöv, "Measuring exposure levels of inhalable airborne particles ($PM_{2.5}$) in two socially deprived areas of Nairobi, Kenya," *Environmental Research*, vol. 148, pp. 500–506, 2016.

[20] E. G. Maina, A. N. Gachanja, M. J. Gatari, and H. Price, "Demonstrating $PM_{2.5}$ and road-side dust pollution by heavy metals along Thika superhighway in Kenya, sub-Saharan Africa," *Environmental Monitoring and Assessment*, vol. 190, 2018.

[21] M. Gatari, J. Boman, and D. Maina, "Trace element categorization of pollution sources in the equator town of Nanyuki, Kenya," *X-Ray Spectrometry*, vol. 34, no. 2, pp. 118–123, 2005.

[22] Kenya National Bureau of Statistics, *2019 Kenya Population and Housing Census*, Kenya National Bureau of Statistics, Nairobi, Kenya, 2019, https://www.knbs.or.ke/.

[23] M. Omwenga, "Integrated transport system for liveable city environment: a case study of Nairobi Kenya," in *Proceedings of the 47th ISOCARP Congress 2011*, pp. 1–9, 2011, http://www.isocarp.net/data/case_studies/2022.pdf.

[24] M. Badura, P. Batog, A. Drzeniecka-osiadacz, and P. Modzel, "Evaluation of low-cost sensors for ambient $PM_{2.5}$ monitoring," *Journal of Sensors*, vol. 16, 2018.

[25] B. Alfano, L. Barretta, A. Giudice et al., "A review of low-cost particulate matter sensors from the developers' perspectives," *Sensors*, vol. 20, no. 6819, 2020.

[26] F. D. Pope, M. Gatari, A. Poynter, R. Blake, and U. Kingdom, "Airborne particulate matter monitoring in Kenya using calibrated low cost sensors," *Atmospheric Chemistry and Physics*, vol. 18, pp. 1–31, 2018.

[27] H. Liu, P. Schneider, R. Haugen, and M. Vogt, "Performance assessment of a low-cost $PM_{2.5}$ sensor for a near four-month period in oslo, Norway," *Atmosphere*, vol. 10, no. 41, pp. 1–19, 2019.

[28] B. S. Babu, "Comparative study on the spatial interpolation techniques in GIS," *International Journal of Scientific & Engineering Research*, vol. 7, no. 2, pp. 550–554, 2016.

[29] P. Molnár, *Elemental Composition of Fine Particles: Exposure in the General Population and Influence from Different Sources*, Intellecta DocuSys AB, Gothenburg, Sweden, 2007.

[30] A. W. Mutahi, L. Borgese, C. Marchesi, M. J. Gatari, and L. E. Depero, "Indoor and outdoor air quality for sustainable life: a case study of rural and urban settlements in poor neighbourhoods in Kenya," 2021.

[31] A. M. Tepe and G. Dogan, "Chemical characterization of $PM_{2.5}$ and PM2.5–10 samples collected in urban site in Mediterranean coast of Turkey," *Atmospheric Pollution Research*, vol. 12, pp. 46–59, 2021.

[32] South Coast Air Quality Management District (SCAQMD), *Field Evaluation of SainSmart Background*, SCAQMD, Diamond Bar, CA, USA, 2018, http://www.aqmd.gov/docs/default-source/aq-spec/field-evaluations/sainsmart---field-evaluation.pdf.

[33] National Environment Management Authority (NEMA), *The Environmental Management and Coordination (Air Quality) Regulations*, NEMA, Nairobi, Kenya, 2014.

[34] Z. Liu, L. Shen, C. Yan, J. Du, Y. Li, and H. Zhao, "Analysis of the influence of precipitation and wind on $PM_{2.5}$ and PM10 in the atmosphere," *Advances in Meteorology*, vol. 2020, Article ID 5039613, 13 pages, 2020.

[35] M. H. Askariyeh, M. Venugopal, H. Khreis, and A. Birt, "Near-road traffic-related air pollution: resuspended $PM_{2.5}$ from highways and arterials," *International Journal of Environmental Research and Public Health*, vol. 17, no. 2851, 2020.

[36] S. Kundu and E. Stone, "Environmental science," *Environmental Science Processes and Impacts*, vol. 16, no. 6, 2014.

[37] A. E. Peter and S. M. S. Nagendra, "Dynamics of $PM_{2.5}$ pollution in the vicinity of the old municipal solid waste dumpsite," *Environmental Monitoring and Assessment*, vol. 193, no. 5, pp. 1–16, 2021.

[38] N. Ngo, S. Kokoyo, R. Tested, Y. Programme, and J. M. Klopp, "why participation matters for air quality studies: risk perceptions, understandings of air pollution and mobilization in a poor neighborhood in why participation matters for air quality studies: risk perceptions, understandings of air pollution and Mo," 2015, https://doi.org/10.1016/j.puhe.2015.07.014.

[39] N. S. Ngo, M. Gatari, B. Yan et al., "Occupational exposure to roadway emissions and inside informal settlements in sub-Saharan Africa: a pilot study in Nairobi, Kenya," *Atmospheric Environment*, vol. 1, pp. 179–184, 2015.

[40] R. Yadav, L. K. Sahu, S. Nisar, A. Jaaffrey, and G. Beig, "Temporal variation of particulate matter (PM) and potential sources at an urban site of Udaipur in Western India," *Aerosol and Air Quality Research*, vol. 14, no. 6, pp. 1613–1629, 2014.

[41] J. Chen, X. Yu, F. Sun et al., "The concentrations and reduction of airborne particulate matter (PM10, PM2.5, PM1) at shelterbelt site in Beijing," *Atmosphere*, vol. 6, no. 5, pp. 650–676, 2015.

[42] H. Nygren, "Influence of vegetation and urban densification on exposure to particle pollution in Gothenburg," 2015, http://bioenv.gu.se/digitalAssets/1538/1538456_helen-nygren.pdf.

[43] J. E. White and R. A. Wayland, "Airnow air quality notification and forecasting system," 2016.

[44] S. Bathmanabhan, S. Nagendra, and S. Madanayak, "Analysis and interpretation of particulate matter–PM10, PM2.5 and PM1 emissions from the heterogeneous traffic near an urban roadway," *Atmospheric Pollution Research*, vol. 1, no. 3, pp. 184–194, 2010.

[45] Y. Zhang and F. Cao, "Fine particulate matter ($PM_{2.5}$) in China at a city level," *Scientific Reports*, vol. 5, no. 14884, pp. 1–12, 2015.

[46] F. N. Mutua, C. Kanali, and P. M. Njogu, "Determination of PM 10 and PM2.5 concentration in ambient air samples in Nairobi City, Kenya," *International Journal of Science and Research*, vol. 5, no. 11, pp. 502–510, 2016.

[47] C. Mcfarlane, P. K. Isevulambire, R. S. Lumbuenamo et al., "First measurements of ambient $PM_{2.5}$ in kinshasa, democratic republic of Congo and Brazzaville, republic of Congo using field-calibrated low-cost sensors," *Aerosol and Air Quality Research*, vol. 21, no. 7, pp. 1–16, 2020.

[48] L. Han, W. Zhou, W. Li, and L. Li, "Impact of urbanization level on urban air quality: a case of fine particles ($PM_{2.5}$) in Chinese cities," *Environmental Pollution*, vol. 194, pp. 163–170, 2014.

[49] P. I. Beamer, "Migration of contaminated soil and airborne particulates to indoor dust," *Environmental Science & Technology*, vol. 43, no. 21, pp. 8199–8205, 2009.

[50] M. Skorbiłowicz, E. Skorbiłowicz, and W. Łapiński, "Assessment of metallic content, pollution, and sources of road dust in the city of bia ł ystok (Poland)," *Aerosol and Air Quality Research*, vol. 20, pp. 2507–2518, 2020.

[51] M. Santoso, D. D. Lestiani, I. Kusmartini et al., "Nuclear analytical techniques for identification of elemental composition of fine and coarse airborne particulate matter collected in bandung, Indonesia nuclear analytical techniques for identification of elemental composition of fine and coarse airborne," in *Proceedings of the 6th International Symposium on Applied Chemistry (ISAC)*, Tangerang, Indonesia, November 2020.