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$PM_{2.5}$Monitoring and Associated Air Quality Indices (AQIs)using Pre-calibrated Low-Cost Air Monitors based on PMS5003 Laser Counters in Nairobi, Kenya

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Abstract
Manufacturing, construction, mining, transport, industrial processes and power generation release gaseous, solid and liquid wastes to the environment.Pollutants enter the human respiratory system leading to adverse health effectswhich are attributed to premature deaths worldwide. Particulate matter (PM) especially $PM_{2.5}$ are recognized as potent pollutants which penetrate deep into the human lungs. This study assessed the levels of $PM_{2.5}$ and associated air quality indices using pre-calibrated lowcostpurple air monitors employing PMS5003 Laser Counters. Ambient air pollution monitoring was done in residential, industrial and commercial areas in Nairobi City County for 6 months. Results reveal that four of the six sites studied had levels higher than the WHO 24 hourly averages (15µg/m^3 for $PM_{2.5}$). The sites show wide variations which can be attributed to land use as well as vehicular traffic volumes at the sites. The air quality index in all the study sites range from good to moderate save for IRS1 which recorded the highest value of 117.Wind speed and precipitation was found to have a significant impact on PM concentration at one study site (RS1). From the study it has been shown that low-cost monitors can provide a fast way of monitoring $PM_{2.5.}$

***Key words**: Air Pollution, $PM_{2.5}$, Emissions, Air monitors, air quality index*

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I. Introduction

Air pollution is the main cause of respiratory diseases which currently are among the major causes of premature deaths in the world today (WHO, 2018, Stanaway et al, 2018). The health risks that result from air pollution in developing countries which are rapidly industrializing are more adverse as compared to the developed countries (Mannucci et al, 2017). This is attributed to factors like poverty, use of aged motorized vehicles, improper urban planning, poor environmental laws and/or implementation of the laws in such nations (Zalakeviciute et al 2017, Gladsstein et al, 2014).

There are several industrial activities in the urban centers that have led to an influx of people into these areas more so in the developing countries. This influx has further deteriorated the quality of air by resulting in an increase in indoor pollution in addition to the outdoor pollution linked to the industries (Bruce et al, 2000). It has also resulted in increased vehicular emissions which further worsens the problem of air pollution (Angnunavuri et al, 2019). Some of the components of vehicular emissions are Particulate Matter (PM), CO, SO_2, NOx and Volatile Organic Compounds (VOCs).

Pollutants in the urban areas are also emitted by industries during their manufacturing processes or combustion of fossil fuels in the developing countries (Bruce et al, 2000). Indoor air pollution is also high because 56% of the population do not have access to clean sources of energy for domestic heating (UNDP-WHO, 2009).

Pollutants can be in solid, liquid and gaseous form. The solid and liquid components often referred to as particulate matter (PM) are grouped into different classes depending on their sizes. They range from PM $\leq$0.01µm (ultra-fine particles) to PM_{100} (very coarse particles). All these particles have different properties depending on their sources.

The deposition of PM is dependent on size with the smaller particles being not easily settle-able (Shastri L, 2020) while the coarse particles of PM> 10 go through deposition at a faster rate. The prevailing environmental conditions (e.g., humidity, temperature, wind, precipitation) also determine how these pollutants undergo complex chemical reactions in the atmosphere (Zhang et al 2015) and the rate at which they get deposited. Additionally, environmental factors affect the PM concentration in the ambient air (Zhang Y and Jiang W 2018). The concentration of the PM in the air depends on the rate of emission, dispersion, transport and the rate of removal from the atmosphere (Mariraj M. S., 2015).

PM as a class of pollutants has detrimental effects on human health and has been linked to increased rates of mortality (Hales et al. 2010).Pope et al. 2002,Krewski et al. 2009 and Lepeule et al. 2012 in their studies analyzed in detail the link between increased respiratory illnesses and mortality rates with increase in PM concentrations. The human respiratory system is directly affected by air pollution with the lungs being the main organ that is exposed if the pollutants get into the system during inhalation (Jenko P, Z. and Pražnikar, J. 2012). According to Hofmann 2011, the deposition of these PMs along the tract depends on the PM characteristics, deposition mechanisms, fluids dynamics and biological factors like breathing patterns, lung morphology etc.

The mode of deposition along the tract is through sedimentation for PMs between 1μm to 5μm, inertial impaction for PM>10 μm, diffusion PM< 0.5 μm, electrostatic interaction and interception (Tippayawong N. and Damrongsak D. 2003). Particles of PM_{10} are mainly deposited along the upper respiratory surface, those of $PM_{2.5}$-PM_{10} get deposited on the ciliated surfaces while the PM<2.5 get into the alveoli and may get into the blood capillaries through diffusion (Jenko P, Z. and Pražnikar, J. 2012). If they get into the blood capillaries, they translocate into the blood stream and may find their way into the various body tissues through blood circulation. Chronic bronchitis, increase in respiratory cancer and respiratory diseases has been linked to air pollution (WHO, 2006).

Health studies show a significant association between exposure to particle pollution and health risks, including premature death (Owino et al., 2022). Interpretation of air concentrations into air quality index (AQI) is an innovative way of understanding air quality and health impact nexus (US-EPA , 2021.). The air quality indices, corresponding PM $_{2.5}$ and the anticipated health impact and proscribed cautions based on the US-EPA are presented in Table 1

Table 1:US-EPA AQI indices for 24-hr average of PM2.5 in μg/m^3

24-hr PM2.5 Average	**AQI Value**	**Health Message**	**AQI Color**	**AQI Category**
0 – 15.4	0-50	None	Green	Good
15.5 – 40.4	51 - 100	Unusually sensitive people should reduce prolonged or heavy exertion	Yellow	Moderate
40.5 – 65.4	101 - 150	Sensitive groups should reduce prolonged or heavy exertions	Orange	USG
65.5 – 150.4	151 - 200	Sensitive groups should avoid prolonged or heavy exertions; general public should reduce prolonged or heavy exertion	Red	Unhealthy
150.5 – 250.4	201 - 300	Sensitive groups should avoid all physical activity outdoors; general public should reduce prolonged or heavy exertion	Purple	Very unhealthy
250.5 – 500.4	301 - 500	Everyone should avoid all physical activity outdoors	Maroon	Hazardous

II. Materials and Methods

2.1 Study area

Nairobi (01°17′11″S 36°49′02″E) is the capital city of Kenya and is the largest urban center in the country. It hosts a population of over 4.3 million people (KNBS, 2019). The city is classified as a subtropical highland climate and its average annual temperature ranges from as low as 16.5 ^{o}C to 20.5 ^{o}C with an average annual humidity is 72% and an annual precipitation of 745 millimeters.

The city is zoned into residential, industrial, commercial zones and a national park. PM pollutant sources are therefore related to human activities carried out in an area which could be restricted by zoning laws. PM sources are mainly vehicular traffic, open waste burning, road constructions, use of solid fuels, industrial, manufacturing processes and dust from local soils.

2.2 Data collection

The study area was categorized into three zones based on the activities taking place at the specific areas, namely; Residential areas, Industrial areas and Commercial areas. $PM_{2.5}$ was monitored over a cumulative period of six months. The air quality monitors were mounted at the sites at a mean height of 3 meters above ground to avoid bias from ground level sources. The levels of $PM_{2.5,}$ temperature and humidity were monitored and recorded at intervals of two minutes. The monitors were pre-calibrated through co-location with a BAM reference monitor and data corrected accordingly. The R^2 and RMSE were used to assess performance of the LCMS.

Air Quality Indices

AQI were calculated using the formular developed by US-EPA using the equation 1.

$$\text{AQI} = \left[\frac{(PM_{obs} - PM_{min})(AQI_{max} - AQI_{min})}{PM_{max} - PM_{min}}\right] + AQI_{min} \text{ ………………………….1}$$

Where; PM_{obs} = observed 24-hour average concentrations in μg/m^3
,PM_{max} = maximum concentration of AQI color category that contains PM_{obs}
PM_{min} = minimum concentration of AQI color category that contains PM_{obs}
AQI_{max} = maximum AQI value for color category that corresponds to PM_{obs}
AQI_{min} = minimum AQI value for color category that corresponds to PM_{obs}
Ranges of AQI and average concentrations of PMs are presented in Table 3.1 based on US-EPA guidelines.

2.3 Data analysis

Raw data was first cleaned and corrected using regression equation developed using the reference and the LCMS. Data were analyzed using Excel as means, standard deviation, ANOVA and T-tests were used to determine variations.

2.3.1 Statistical Analysis

All the data collected was subjected through statistical analysis. The average values, minimums, maximums and standard deviations were estimated using excel. Influence of meteorological parameters on PM concentration was investigated by estimating the spearman's coefficient (r). The spatial variabilities of the pollutant concentrations at the different sites were also done so as to determine their distribution characteristics. Coefficients of Divergence (COD) between data sets of PM concentrations from different sites were calculated using Equation 3.

$$COD_{ab} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\frac{C_{ia} - C_{ib}}{C_{ia} + C_{ib}}\right]^2} \text{ ……………………………………..3}$$

Where;C_{ia} and C_{ib} are the PM concentarions simultaneously recorded at site a and b respectively while n is the number of observations recorded. COD which is ≤ 0.2 represent homogeneity between the sites while that which is greater than 0.2 represent heterogeneity between the sites (Krudyszet al, 2009, Pinto et al 2004).

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III. Results And Discussion

3.1 PM concentrations

The study sites from which air pollution data were collected from and their description are shown in Table 2. Daily mean concentrations of $PM_{2.5}$ pollutants in Nairobi from January to June, 2022 are summarized Table 3

Table2: Study sites and their descriptions

Site Code	Study location	Description	Co-ordinates
IS1	NCPB	Industrial area	-1.3052, 36.8824
IS2	Bins (industrial)	Industrial area	-1.3078, 36.8575
IRS1	Mukuru	Industrial/Residential	-1.3118, 36.8698
CS1	CBD	Commercial	-1.2843, 36.8211
CS2	Premier foods	Commercial	-1.2437, 36.8812
RS1	Embakasi	Residential	-1.3076, 36.903
RS2	Eagle Plains	Residential	-1.3259, 36.8552
NNP	Nairobi National Park	Park	-1.3729, 36.8530

Table 3: 24-Hourly averages of $PM_{2.5}$ (μg/m^3)

Site Code	Pollutant	Mean±SD (μg/m^3)	Min (μg/m^3)	Max (μg/m^3)	WHODaily limit (μg/m^3)	AQI
IS1	PM2.5	19.92±7.74	5.94	39.42	15	62
IRS1	PM2.5	42.18±13.44	27.62	99.1	15	117
RS1	PM2.5	21.70±4.09	13.67	32.72	15	71
CS1	PM2.5	15.66±9.22	5.23	36.22	15	58
IS2	PM2.5	22.24±5.80	12	30.4	15	72
CS2	PM2.5	20.0±4.04	13.3	26.8	15	68
RS2	PM2.5	10.04±2.56	5.5	14.3	15	42
NNP	PM2.5	9.53±2.76	5	13.3	15	40

3.1.2 Residential Zones

IRS1 recorded the highest average PM concentrations than any other site with $PM_{2.5}$ of 42.18±13.44μg/m^3(AQI 117) IRS1 is an informal settlement with unpaved roads and improper solid waste management systems so dust and open burning of waste is common. The area is surrounded by chemical, textile and other manufacturing industries which continuously release pollutants into the air. Use of charcoal and firewood as a source of fuel is another common practice by the residents in the area. All these activities might have contributed to the high pollutant concentrations in the area. The AQI score for this site indicates that the air quality is unhealthy for sensitive groups.

On the other hand, RS1 though being a formal settlement area is still a developing estate with significant construction activities with diesel engine trucks ferrying construction material being common. Dust from unpaved roads and use of solid fuels like charcoal also contribute to air pollutants in this area which recorded an average of 21.70±4.09μg/m^3 (AQI 71) which is also above the WHO daily limits. However, RS2 being a completely developed residential place with well-developed social amenities, vehicular traffic is the main source of air pollution in the area. The recorded daily average PM concentration in this site was found to be 10.04±2.56μg/m^3(AQI 42) during the study period. RS2 has good air quality whereas that of RS1 is moderate as per the AQI.

3.1.2 Industrial zones

IS1 registered a mean of19.92±7.74μg/m^3(AQI 62) during the study period which exceeds WHO limits. This site is surrounded by plastic manufacturing companies, flour milling industries, textile industries and construction. Traffic from diesel trucks ferrying goods to and from nearby industries and fuel depots is heavy contributing further to the high pollutant concentrations.

IS2 on the other hand is on the edge of an informal settlement and is often faced with traffic from garbage trucks from the dump site within the area. There are some godowns, office space buildings and some industrial and commercial facilities. Pollutant concentration from this site had a mean of 22.24±5.80μg/m^3(AQI 72) which is above WHO limits. Both IS1 and IS2 are close to a common busy road to town. Both sites have similar air quality index which is moderate.

3.1.3 Commercial areas

The average PM concentrations for the sites under this category (CS1 and CS2) were 15.66±9.22μg/m^3(AQI 58) and 20.0±4.04μg/m^3(AQI 68) respectively. Generally, both areas are characterized by vehicular traffic and office buildings and pollutant concentrations are still above the WHO daily limit. Both commercial sites have moderate air quality and can be bothersome to unusually sensitive group of persons.

3.2 Hourly mean concentrations

Fig 3 shows the average hourly PM concentrations for a typical day at the IS1, RS1, IRS1 and the CS1. In RS1, the peak PM concentrations occur between 4am to 6 am in the morning and at around 5 pm in the evening. At the IS1, peak PM concentrations were recorded between 5am-7am in the morning and from 5pm to 8pm in the evening. The CS1 has a similar peak PM concentration to both RS1 and the IS1 however, the values recorded at the CS1 are much lower in comparison to the two sites. PM concentration trend inIRS1 is quite different with low PM concentrations recorded only at around 8am. It was also noted that PM concentrations were lower during the night than during the day in all the sites except for IRS1.

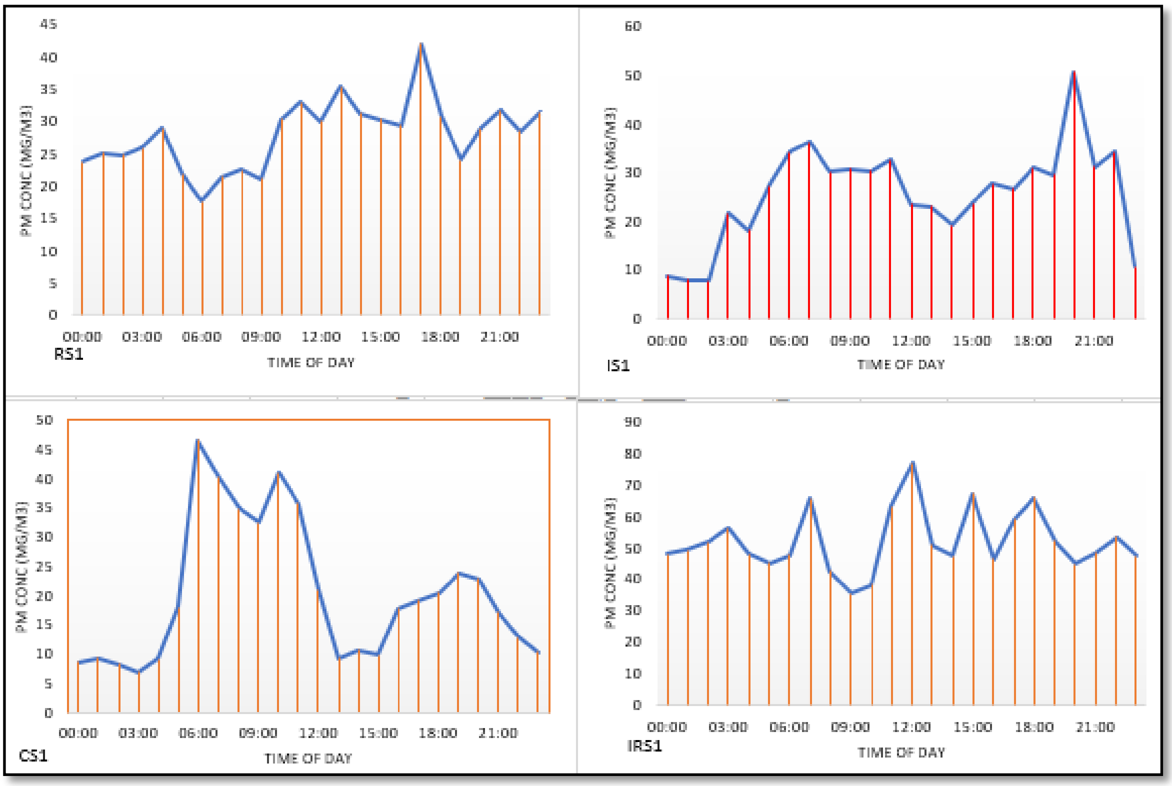


Fig 3: Hourly PM2.5 trends

3.3 Spatial Variations between different sites

The coefficients of divergence between the study sites were calculated using equation 1 and results are as shown in table 2.

Table 4: COD values of PM concentrations between the different monitoring sites.

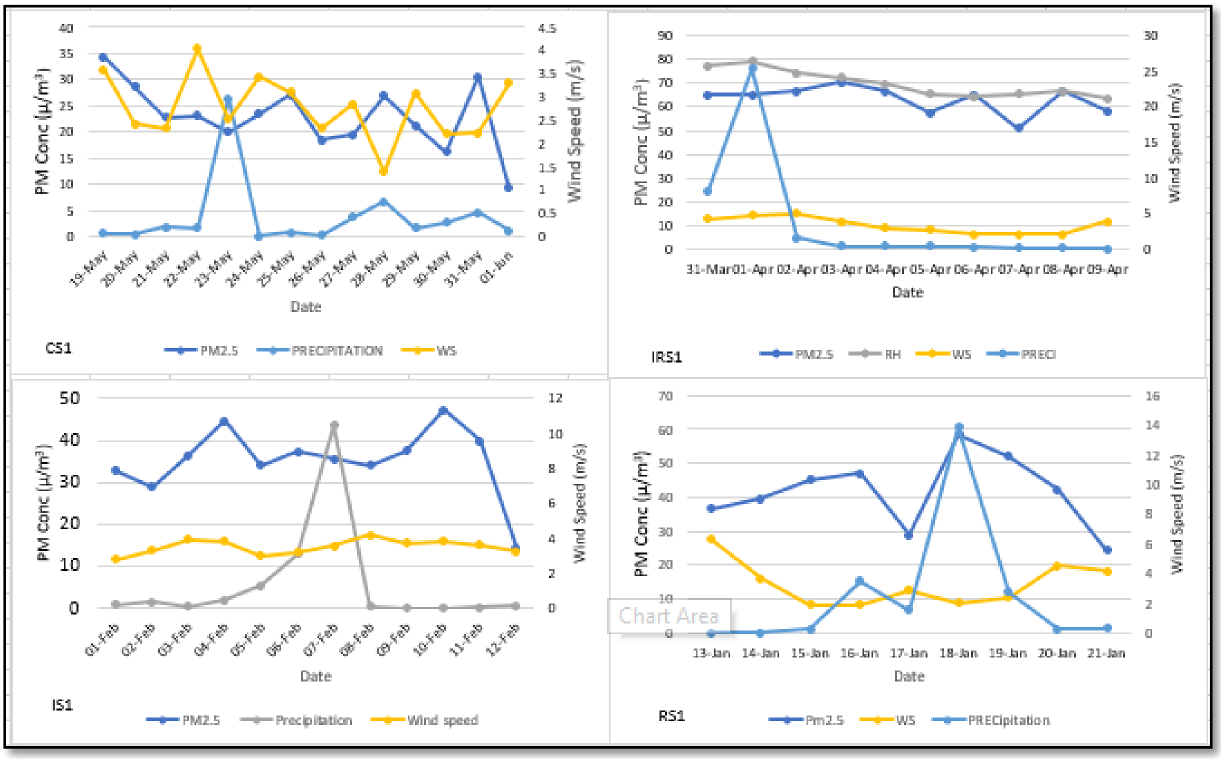
	IS1	IRS1	RS1	CS1	IS2	CS2	RS2	NNP
IS1		0.37	0.26	0.24	0.43	0.51	0.7	0.71
IRS1			0.25	0.51	0.43	0.5	0.7	0.72
RS1				0.37	0.2	0.27	0.54	0.56
CS1					0.23	0.12	0.34	0.38
IS2						0.18	0.4	0.43
CS2							0.33	0.37
RS2								0.07
NNP								

The COD values between the sites IS1/RS1, IRS1/RS1, RS1/IS2, CS1/CS2, NNP/RS2 are in the region of 0.2 while the COD values for IS1/NNP, IRS1/RS2 and IRS1/CS2 are higher than 0.5. The pairs of sites with low COD values have homogenous PM distributions which suggests that sources of pollutants to such sites could be similar. On the other hand, high COD values between pairs of sites have heterogeneous PM distributions and concentrations hence their sources are different.

It is noted from the results in table 2 that to a large extend, the PM concentrations and distributions are similar between sites of similar category while there is a clear difference with those of different land usage.

3.4 PM concentration Variation in relation to Precipitation and Windspeed

The correlation coefficients (r) for wind speed and Precipitation with $PM_{2.5}$were calculated. The (r)s obtained for both meteorological parameters against PM2.5 were low for sites IS1, CS1 and IRS1 indicating that the impact that these factors had on the pollutant concentration was insignificant. However, for the site RS1 r for PM vs wind was -0.53 while PM vs precipitation was 0.67. At RS1, PM concentration is inversely related to wind speed while it is directly related to precipitation. Figure 4 illustrates the relationships between PM2.5 with wind speed and precipitation.



IV. Conclusion

From the study, it was established that the concentrations of PM $_{2.5}$ were above the WHO limits in most of the study sites except NNP, Eagle plain. The Nairobi National Park which is a natural habitat with little human developments had concentrations below the WHO limits. Based on the AQI, IRS1 had unhealthy air quality.

Industrial area and its environs have high levels of PM concentrations leading to adverse exposure and therefore is high level risk of respiratory illnesses among people who spent most of their time in the area. As found out from the study, zones with little or no industrial activities have relatively safer air with less PM pollution. This does not then imply that residents in such areas are not exposed to the polluted air in industrial and commercial areas. Majority of residents in the city spent their days working in the industrial areas and commercial areas and only spent a fraction of the day in the less polluted residential areas.

Concentration trends for the PM shows that the peak periods are similar for all the areas that were studied. Time of day corresponding to high vehicular traffic was found to be the peak points for PM concentrations. It was however observed that meteorological conditions did not have a significant influence of the PM concentrations.

Statistical analysis showed that some of the sites had homogeneous PM concentrations while others had heterogeneous PM concentrations when compared. This implies that some sites could have similar sources of pollutants hence the same mitigation measures may be implemented for them. On the other hand, the heterogeneity of PM concentrations between some sites means that specific measures must be devised for such sites which could have pollutants originating from different types of sources.

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Conflict of interest

Authors declare no conflict of interest

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