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Baseline Concentrations of Fine and Coarse Particulate Matter in A Tropical City with Introduced Traffic Control Measures

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Abstract: Fine atmospheric particles ($PM_{2.5}$) and coarse particles (PM_{10}), have been reported as major contributors to the low life expectancy of 54 years in Nigeria, the most populous country in Africa. This study was designed to provide baseline data on $PM_{2.5}$ and PM_{10} levels in Benin City, wherein traffic control measures have recently been introduced. A light scattering approach (Cel – 712 Microdust Pro Real – time Dust Monitor) was employed for the PM quantification. The average $PM_{2.5}$ concentration obtained (31.48μgm^{-3}) was found to be higher than the WHO threshold limit (25 μgm^{-3}) by a factor of 1.25. At 60% of the sampling sites, the WHO 50 μgm^{-3}regulatory limit for PM_{10} was also violated, with a city range of 21.4 – 57.8 μgm^{-3}. Spatial variations in the PM fractions were statistically significant ($p<0.05$). The source identification and apportionment studies by Principal Component Analysis (PCA) and Multiple Linear Regression (MLR) suggested that motor vehicles were the major source of $PM_{2.5}$ (77.3%) and PM_{10} (70%) in the city with the remainder coming from refuse combustion. The average on–road respiratory deposition dose (RDD) rates analysis estimated that 6.96% of the measured PM were deposited in the tracheobronchial region, 12.36% in the alveolar and 78.86% in the head airway of the commuters and pedestrians in the city.

Keywords: Baseline, background, $PM_{2.5}$, PM_{10}, Respiratory deposition dose, light scattering, source apportionment.

INTRODUCTION

Premature death is the ultimate impact of air pollution on public health. [1] It is therefore essential to combat air pollution and to do this; the first pragmatic step is to create emission inventories that are accurate and consistent from fixed monitoring stations with reliable analytical instruments.[2] In the absence of continuous monitors as it is the situation in most African cities, validated data from periodic short – term studies from the use of discontinuous (active and passive) monitors in the environment of interest could suffice. Through this process, air quality standards and regulations are established and enforced and periodically monitored to ascertain compliance. In the developed nations of the world, both fixed and discontinuous monitors abound which have made air pollution abatement timely, seamless, effective and commendable.[3] Conversely, in the low income countries like Nigeria, fixed monitoring stations are non – existent due mainly to economic factors, technical knowhow, and the lack of stable electricity needed to power the sensitive monitors. Consequently, the literature is devoid of robust air quality data from Nigeria to engender effective air pollution management plan and epidemiological studies. Aliyu and Botai[4] reported recently that air quality studies across Nigerian cities revealed that pollution measurements were scantily distributed thus making it difficult to develop air quality management for its cities. Nevertheless, Edet [5] had since recognised the significance of air pollution to health as a major challenge in Benin City. Furthermore, Aliyu and Botai [4] have it on record that air pollution is a serious threat to public health in most Nigerian urban cities resulting from poorly managed private/commercial vehicles, unregulated recreational activities, trash burning, traffic congestions and biomass consumption. Etchie et al. [6] affirmed that exposure to ambient $PM_{2.5}$ pollution

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in Nigeria was responsible for the reduction in the life expectancy of her people by approximately 3.5 years on average.

Short – term studies on particulate matter fractions from different locations in Nigeria have been reported and include:average levels of $PM_{2.5}$ (62.7μgm^{-3}) and PM_{10} (390μgm^{-3}) measured at Ilorin metropolis,[7] PM_{10} concentration of 274.6 μgm^{-3} in Lagos (Olajire et al.,2011), mean PM_{10} values of 550, 35, 87, 340, 246, 130 μgm^{-3} and $PM_{2.5}$ values of 100, 14, 25, 67, 20, 30 μgm^{-3} respectively for Aba, Abuja, Lagos, Kano, Maiduguri and Port – Harcourt,[8] $PM_{2.5}$ concentrations range from 13 - 237 μgm^{-3} at industrial, high- and low – density residential sites in a Nigerian megacity.[9] Others include average $PM_{2.5}$ and PM_{10} concentrations of 219.73 μgm^{-3} and 451.96 μgm^{-3} respectively measured in Zaria,[4] and $PM_{2.5}$ range of 13.56 – 55.00 μgm^{-3} from selected urban centres of Niger Delta region.[10] For most of the above reported PM data, the WHO daily threshold limits of 25 μgm^{-3} and 50 μgm^{-3} for $PM_{2.5}$ and PM_{10} respectively were violated. PM pollution has been documented as the most health – relevant indicator of urban air quality[11] thus $PM_{2.5}$ and PM_{10} have attracted global attention in recent years. Globally, about 89% of the world's population is currently exposed to $PM_{2.5}$ concentrations above the WHO air quality guidelines.[12] Chronic exposure to fine PM has been linked with increased mortality and is associated with decreased lung function, decreased cystolic pressure and increased heart rate at high levels.[13] Furthermore, these PM fractions can cause adverse impacts to the environment. PM – related welfare effects include visibility impairment, climate impacts, effects on materials (e.g. building surfaces), and ecological effects. [14, 15]

According to Pakbin et al.[16] fine and coarse PM fractions can have substantially different sources and sinks. For example, studies in Europe have shown that traffic contributes between 9 and 66% of $PM_{2.5}$ and 9 – 53% of PM_{10}.[17] Consequently, this study is intended to fill the existing gap in literature with respect to the baseline and background data of these PM fractions in Benin City with a population of over a million people. It would also identify and quantify the anthropogenic sources of the PM for ease of policy formulation on control. Finally, a comparison of human exposure to the different particulate types at the monitoring sites would be presented to understand the dynamics of exposure at these hotspots and also for future references and control purposes.

MATERIALS AND METHODS

Study area and schedule

The study was carried out in Benin metropolis, the capital of Edo state, located in the southern part of Nigeria. The city of Benin lies on Longitude 5.3ºE and Latitude 6.2ºN. The climate is equatorial with two distinct seasons (wet and dry), with an estimated land area of 500 km^2,[18] and a population of about 1,147,188.[19] Benin City is commercial in nature with operations of petroleum and other industries. Traffic volume is high in the city all year round, because the city is a link to the other parts of the country.

The measurements of the PM fractions in this study were carried out in the months of May, June and July, 2018. Five sampling sites were selected to obtain representative measurements of the study area; other considerations included the security of equipment and 24 hr accessibility by field operators. The sites were created at roadside verges, traffic intersections, and roundabouts. The sixth site was created in a remote re - growth forest in the outskirts of the city to provide background data for $PM_{2.5}$ and PM_{10}. Figure 1 and Table 1 represent the monitoring sites and their characteristics. The sites were Geo – referenced by using GARMIN GPS MAP765 chart plotting receiver.

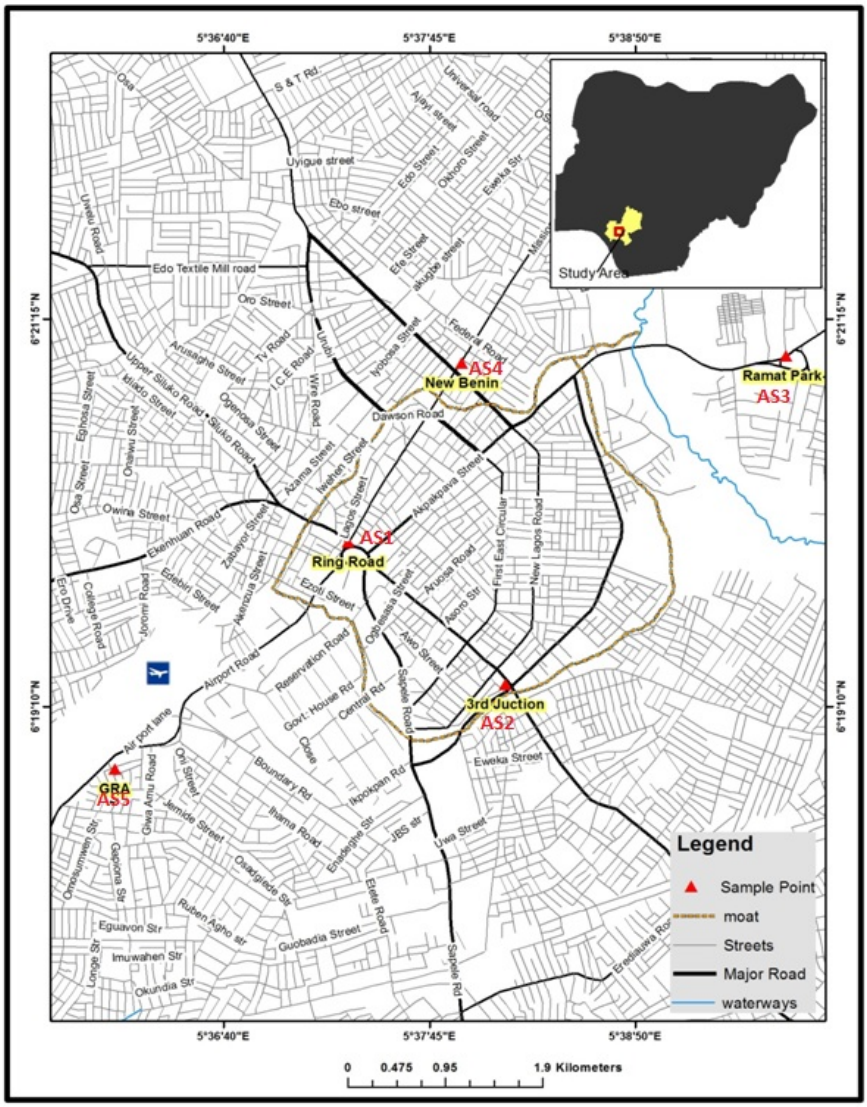

Figure 1. GIS base map of Benin City showing sampling locations and major routes.

Table 1. Sampling sites and characteristics

Site code	Coordinates	Elevation (m)	Traffic density (cars/hour)	Site description
AS1	N06° 20.020' E005°37.352'	92	3246	10m from the city centre Ring Road (roundabout) with seven link roads/streets. About 80 m from Oba market. High fast flowing traffic and human activities, with a building construction site about 20 m away from the point of measurement.
AS2	N06° 19.289' E005°38.181'	88	1594	15m from a traffic intersection at Upper Sakponba. Traffic volume is high and also human activities due to Ekiosa open market that is about 25m from the measuring spot.
AS3	N06° 21.008' E005°39.583'	83	3030	7m near a roundabout road at Ramat park. High, free flowing vehicular

				traffic and human activities. About 40m from Ikpoba Hill open market
AS4	N06º 20.980' E005º37.886'	92	1590	5m from a traffic intersection at New Benin. 25m from the popular New Benin Market with moderate traffic and commercial activities.
AS5	N06º 18.893' E005º36.087'	85	1534	4m from Airport Road, opposite the Benin Airport, low free flowing vehicular traffic, low commercial activities with few nearby residential and commercial buildings.
AS6	N06º 23.732' E005º37.905'	95	Nil	Control site in a remote re - growth forest location in the outskirt of the city

Eleven – hours sampling duration was observed at each sampling site and hourly mass concentrations of ambient $PM_{2.5}$ and PM_{10} were measured from 8.00 am to 7.00 pm on the sampling days. Traffic census was taken over the sampling duration for all the locations. This exercise revealed an average traffic volume of 2,199 vehicles/hour for the city. During this study, there were 266,232 registered private vehicles, 54,888 commercial vehicles and 1,690 motorcycles in Benin City (ESIRS, 2020).

Measurement methods

***Particulate Matter*:** The fine and coarse PM fractions concentration were measured using a Casella CEL – 712 Microdust Pro Real – time Dust Monitor (Model HB 4048 – 01) (Bedford, UK). The instrument uses a proven forward light scattering principle to make accurate and repeatable measurements of dust concentrations. This instrument has been validated by collocation following the instructions of the U.S. Environmental Protection Agency (U.S. EPA) to evaluate low – cost sensors.[20] The principle of the light – scattering method has been described in details elsewhere.[21] In brief, the instrument complies with EMC Directive 89/336/EEC of the European Union and uses a visible red semiconductor laser light (wavelength 635 nm, < 5 mW) as the sensing technique, with a measuring range of 0.001 mg/m^3 to 250 g/m^3. Prior to particulate measurements, the instrument was pre – calibrated by adjusting the zero and span settings using the correction factor obtained from the calibration exercise with the gravimetric sampler. Averaging time of 15 seconds was selected and the hourly mass concentrations of $PM_{2.5}$ and PM_{10} were measured (inclusive of the rush and non – rush hours) during the sampling days at each site. Polyurethane foam filter (PUF filter) in appropriate size selective adapter (37 mm diameter) was used for the $PM_{2.5}$ and PM_{10} fractions measurement.[22, 23] The appropriate PUF filters were inserted in the instrument's probe to ensure the accurate determination of the dust size.

The Microdust Pro is factory calibrated in accordance with a method traceable to isokinetic techniques as prescribed by ISO 12103 – 1A2 fine test dust (Arizona road dust equivalent). However, prior to taking measurements, in order to ensure optimal accuracy, the recommended four users–defined routine calibration dust type settings suitable for each particulate type was implemented.

After performing a zero adjustment and span check, a calibration factor for the instrument at the sampling location was carried out (Figure 2).

Figure 2. Measurement and calibration exercise of PM Real-time Dust Monitor (Casella, Bedford, UK).

The calibration factor was computed via gravimetry using a low volume pump (Casella Cel Tuff I.S, Bedford, UK) and a 37 mm microfibre filter inserted into the dust sampler. Further details on the working principle, detection efficiencies and quality control of the gravimetric sampling approach can be found in Ukpebor *et al*.[21] Dust collection and measurements were carried out at the AS1 location over a 5 hour period (Fig. 2). Comparison of the dust sampler reading and the weight of the collected dust on the microfibre filter was carried out at the end of the sampling. The respective dust measurements were 0.643 and 0.616 mg/m^3 from the filter gravimetric study and the forward light scattering of the dust sampler. The user – defined correction factor for the PM was then calculated using the equation (1) below;

$$Correction\ factor\ (CF) = \frac{Gravimetric\ concentration(mg/m^3)}{Instruments\ measured\ average\ value\ reading(mg/m^3)} \quad (1)$$

$$CF = \frac{0.6431}{0.6160}$$

The correction factor of 1.044 obtained was subsequently applied automatically (via the instrument setup menu) for any measured value, to ensure optimal measurement accuracy. A unique characteristic of the CEL – 712 Microdust Pro is that it uses an on-site calibration filter to provide a spot check of the linearity of the instrument (Keison Products, USA).

Site Meteorology

Air temperatures, humidity and wind speed were simultaneously measured daily during the monitoring exercise by using a humidity/temperature meter, with resolutions of 0.1%RH and 0.1ºC (model RS 1364, RS components Ltd, UK). The wind speeds were measured using an LM – 8000 anemometer with a resolution of 0.1 ms^{-1} (Heat miser UK Ltd).

Estimation of Human Exposure.

The toxic impact of inhaled particles depends largely on the site at which they deposit within the respiratory system. Consequently, human exposure to airborne particles at the sampling sites was

estimated using respiratory deposition dose (RDD) estimates. The approach suggested by Kumar and Goel [24] as in Equation 2 was used to estimate the RDD rates for $PM_{2.5}$ and PM_{10}.

Deposited doses (in thoracic, tracheobronchial, alveolar regions) of PM fractions =
$$(V_T \times f) \times DF_i \times PM_i \quad (2)$$

Where V_T is the tidal volume, f is the frequency of breathing, DF_i and PM_i are the deposition fraction and mass concentration of particle size in µm. Value of V_T as 800 cm^2 per breath and f as 0.35 for men during light exercise conditions were used. [24, 25] The DF_i for the mass median diameter (d_p) of $PM_{2.5}$ and PM_{10} were calculated according to Equations 3-7 proposed by Hinds.[25]

$$\text{Alveolar region } (Df_{iAv}) = \left(\frac{0.0155}{dp}\right)\left[e^{(-0.416(\ln dp+2.84)^2)} + 19.11e^{(-0.482(\ln dp+1.362)^2)}\right] \quad (3)$$

$$\text{Tracheobronchial region } (Df_{iTb}) = \left(\frac{0.00352}{dp}\right)\left[e^{(-0.234(\ln dp+3.40)^2)} + 63.9e^{(-0.819(\ln dp+1.61)^2)}\right] \quad (4)$$

$$\text{Head airway region } (Df_{iHa}) = IF\left(\frac{1}{1+e^{(6.84+1.183\ln dp)}} + \frac{1}{1+e^{(0.924-1.835\ln dp)}}\right) \quad (5)$$

$$\text{Total } (Df_{iT}) = IF\left(0.0587 + \frac{0.911}{1+e^{(4.77+1.485\ln dp)}} + \frac{1}{1+e^{(0.508-2.58\ln dp)}}\right) \quad (6)$$

$$\text{The inhalable fraction } (IF) = 1 - 0.5\left(1 - \frac{1}{1+0.00076dp^{2.8}}\right) \quad (7)$$

Where dp is the particle aerodynamic sizes

Method of Data Analysis

The data was analysed using descriptive and inferential statistics. Descriptive statistics using mean, median, standard deviation, range (minimum and maximum) and percentage distribution using pie-chart. Inferential statistics involved the use of Analysis of Variance (ANOVA) to assess spatial variation, post hoc was conducted using Scheffe test. Principal Component Analysis (PCA) using Varimax rotation as well as Hierarchical Cluster Analysis were the multivariate analyses employed in this study. Though in literature there are quite a number of methods of performing Source Apportionment and Identification, this study employed the PCA and Multiple Linear Regression (MLR) vis-à-vis PCA-MLR method. The level of significance in the study is set at $p<0.05$. All data analysis was performed using the IBM Statistical Package for Social Sciences (SPSS) version 26.0 for windows.

RESULTS AND DISCUSSION

This study was designed to provide information on the baseline ambient levels of fine and coarse particulate matter (PM) fractions in Benin City, after the recently introduced traffic control measures. The results obtained are provided below:

Microclimatic Parameters during the study

The climatic parameters measured during this study and the data obtained are shown in Figure 3.

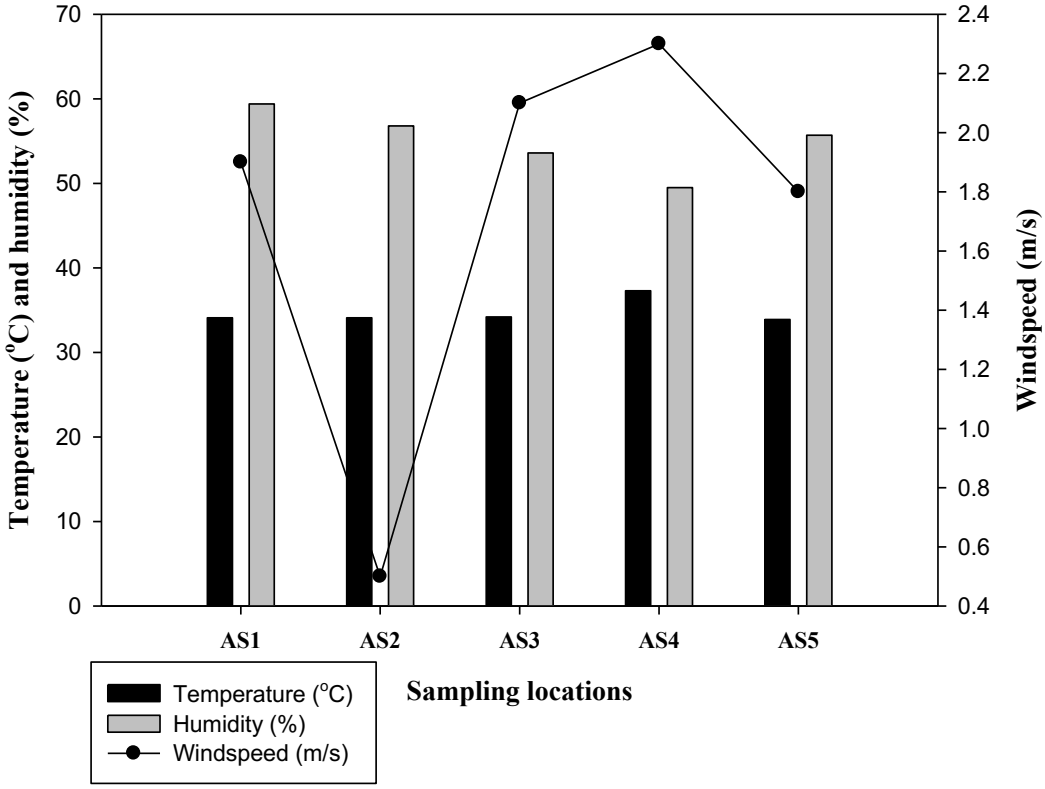

Figure 3. Measured micro-climate parameters during sampling

As expected for a tropical climate, high atmospheric temperatures were recorded with a maximum of 37.3°C and a minimum of 33.9°C**.** A relatively humid atmosphere was observed during sampling with a mean of 55.0%. The mean wind speeds were between 0.5 and 2.3 m/s. The obtained climatic data are consistent with the historical microclimatic parameters of the study area.[26] Low wind speeds were observed, which are also typical of the area under study. Andreae,[27]; Dovile,[28] and Al-Azmi *et al*.[29] reported that meteorological conditions play a vital role in defining air quality within an area, either by facilitating the dispersion and dissipation of pollutants or worsening air quality exceedances. According to Hosler,[30] pollutants accumulate in an area for wind speeds less than 3.1 m/s.

Effects of Relative Humidity on PM

The most noted source of bias on the collection efficiency of the Cel -712 Microdust Pro sampler and hence it's measuring capability, is the influence of high ambient relative humidity (RH).[31, 32] This limitation was taken into consideration during sampling to be certain of the accuracy and reliability of the PM data being presented. However, what has been reported by several authors [33-35] on the impact of RH on the collection efficiency of our sampler is that it occurs at RH values greater than 80%. The city average RH value during our baseline study was 55% (Fig. 3), hence we proceeded with the PM data obtained without any further correction factor applied. Furthermore, in a similar study at Ilorin Nigeria, Adeniran et al. [7] did not observe any significant difference in the calculated mean PM concentrations after introducing a correction factor for PM values measured above RH of 65%.

Baseline and background mass levels of $PM_{2.5}$ and PM_{10} and their interrelationships

Table 2 represents the statistics of the baseline $PM_{2.5}$ and PM_{10} mass levels collected in Benin City at the five sampling sites, AS1, AS2, AS3, AS4, AS5 and the background location AS6

Table 2. Baseline and background PM averages in comparison with WHO, USEPA 24h guidelines and some cities

Sampling site	$PM_{2.5}$ (μgm^{-3})			PM_{10} (μgm^{-3})			$PM_{2.5}/PM_{10}$ ratio		
	Mean	SD	P-value	Mean	SD	P-value			
ASI	42.40	3.13	0.000	52.40	5.27	0.000	0.81		
AS2	22.00	16.40		57.80	1.48		0.37		
AS3	46.20	4.15		57.00	5.52		0.81		
AS4	19.60	1.67		21.40	1.52		0.92		
AS5	27.20	3.11		33.60	2.70		0.81		
AS6 (Background)	16.40	0.89		17.80	1.10		0.92		
This study	**31.48**			**44.44**			**0.74**		
WHO 24hguideline	**25.00**			**50.00**			**0.50 - 0.80**		
USEPA24hguideline	**35.00**			**150.00**					
Ilorin (Nigeria)	70.30			451.50			0.16	Adeniran et al.	2017
Abuja (Nigeria)	29.00			75.00			0.38	Abiye et al.	2013
Aba (Nigeria)	100.00			550.00			0.18	Obioh et al.	2013
Zaria (Nigeria)	219.73			451.96			0.49	Aliyu and Botai	2018
Lagos (Nigeria)	272.80			617.40			0.44	Adeleke et al.	2011
Palermo (Italy)	33.70			44.20			0.76	Dongarra et al.	2010
Harare (Zimbabwe)	41.00			60.00			0.68	Kuvarega and Taru	2008
Cairo (Egypt)	85.00			170.00			0.50	Zakey et al.	2008
Dar es Salaam (Tanzania)	26.00			76.00			0.34	Mkoma et al.	2010
Contiguous (USA)	9.00			17.90			0.50	Alotaibi et al.	2019

The highest $PM_{2.5}$ mean value was observed at location AS3 (46.20 μgm^{-3}), which is one of the most heavily traffic – exposed sites in the city. This was followed by AS1 station (42.40 μgm^{-3}), with the highest traffic volume in the city (Table 1). The lowest concentration within the city was reported at AS4 (19.60 μgm^{-3}), one of the least traffic – exposed location in the city. As expected, the lowest average $PM_{2.5}$ level during the study was measured at the background station AS6 (16.40 μgm^{-3}). Table 2 also reflects the statistics of the baseline PM_{10} mass levels measured at the sampling stations. For the coarse PM, the highest mean concentration of 57.80 μgm^{-3} was reported at Upper Sakponba traffic intersection, site AS2. This sampling site is about 15m from Ekiosa open market, one of the largest open markets in the city with high volume of daily refuse incineration. The next highest mean PM_{10} concentration of 57.00 μgm^{-3} was measured at AS3. Just as observed with $PM_{2.5}$, sampling site AS1 with the highest traffic volume in the city, also recorded relatively high PM_{10} concentration (52.40 μgm^{-3}). The lowest mean concentration within the city was obtained at location AS4 (21.40 μgm^{-3}). The remote site created recorded expectedly the overall lowest mean background level (17.80 μgm^{-3}).

The observed spatial variability in the distributions of the PM fractions as outlined above, were statistically significant ($p<0.05$) (Table 2). Probable reasons for this variation are; differences in emission rate, emission height, emission conditions and atmospheric dispersion conditions. [36, 37] What differed in the sampling locations during the study was emission rate from the local sources of the primary PM fractions, such as vehicular traffic and refuse incineration. A correlation was observed between traffic volume and $PM_{2.5}$ levels in the city. Sampling locations AS1 and AS3 with the highest traffic volumes (Table 1), also recorded the highest mean concentrations of 42.40 μgm^{-3} and 46.20 μgm^{-3} respectively. Correlation between the PM_{10} concentrations and traffic intensity was also noticeable, with additional influence from refuse combustion from nearby open markets with large volumes of refuse generated daily. Thus, locations AS1, AS2, AS3 with the highest traffic volumes and close proximity to open markets, recorded the highest baseline concentrations of PM_{10}. Some of the reported studies on PM fractions in Nigeria [4, 7, 38-40] have also attributed measured $PM_{2.5}$ and PM_{10} levels to automobile exhausts and refuse incineration. In a similar study in Europe, Sundvor et al. [17] also reported that traffic contributes between 9 and 66% to $PM_{2.5}$ and 9 - 53% toPM_{10}. The correlation

analysis carried out on the fine and coarse PM data, revealed a positive linear correlation between the PM fractions (Figure 4), which further suggest similarities in their sources in the city.

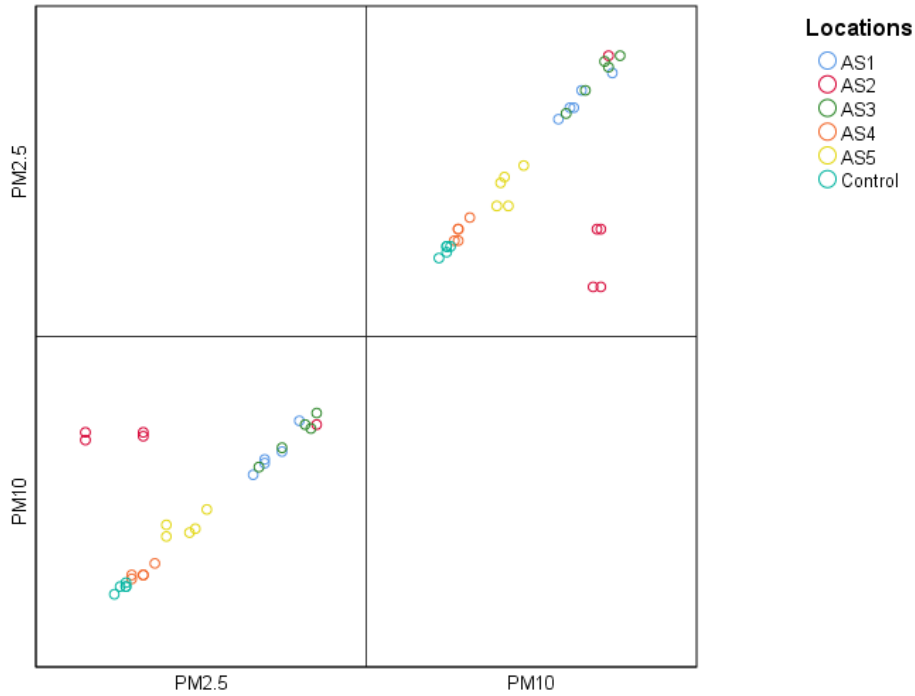

Figure 4. Correlation matrix between $PM_{2.5}$ and PM_{10}

Guided by health and safety considerations, the measured fine and coarse PM were compared with regulatory limits. The Nigeria Federal Ministry of Environment (FMEnv) has no set regulatory limits for PM fractions. Consequently, our measured data were compared with the 24 hr threshold limits set by the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA). At locations AS1, AS3 and AS5, the WHO fine PM24 hr limit (25 μgm^{-3}) was exceeded (Figure 5). At the other two locations (AS2 and AS4), a perfect compliance with the WHO limit was observed. The USEPA 24 hr limit (35 μgm^{-3}) for fine PM was complied with at all locations except at locations AS1 and AS3. The city averaged $PM_{2.5}$ concentration (31.48 μgm^{-3}) was a factor of 1.25 higher than the WHO regulatory limit but was within the USEPA limit. The obtained average background $PM_{2.5}$ of 16.40 μgm^{-3} compared well with the Guildford UK urban background concentration of 16μgm^{-3} [24] but a factor of 2 lower than the urban background value of 34 μgm^{-3} for Nairobi, Kenya.[41] The city average PM_{10} concentration (44.44 μgm^{-3}) was within the WHO (50 μgm^{-3}) and USEPA (150 μgm^{-3}) threshold limits. However at locations AS1, AS2 and AS3, the WHO limit was slightly exceeded but complied perfectly with the USEPA standard (Figure 5). At locations AS4 and AS5, the obtained coarse PM fractions were factors of 2.3 and 1.5 lower than the WHO limit respectively.

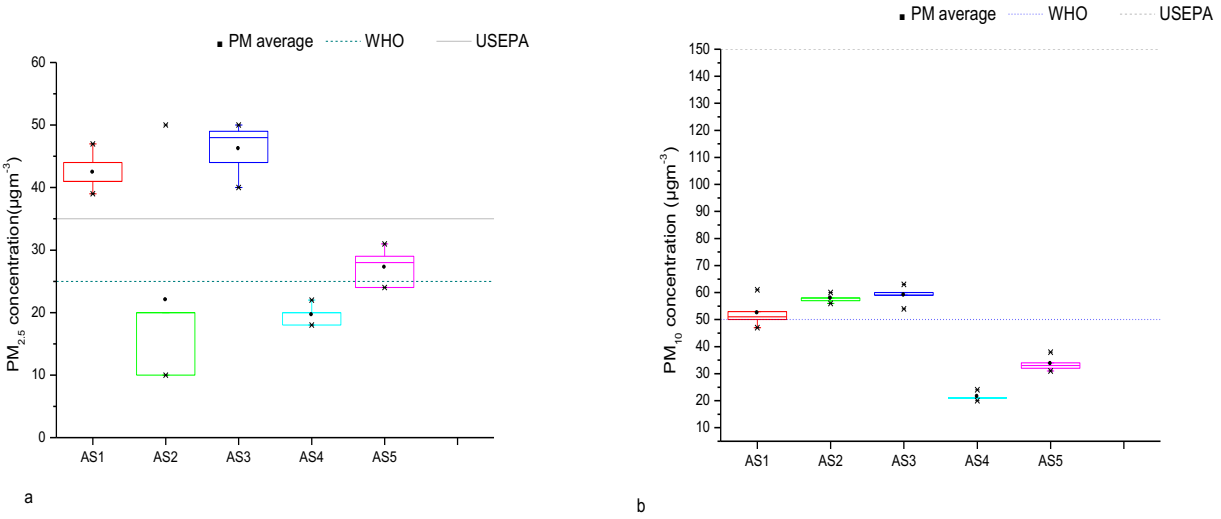

Figure 5. Box plots of PM concentrations from the 5 sample sites showing the performance against WHO/USEPA stipulated limits.

The background PM_{10} mean concentration (17.80 µgm^{-3}) was a factor of 2.5 lower than the city average concentration but compared well with Guildford UK urban background concentration of 22 µgm^{-3}.[24] An urban PM_{10} concentration (93 µgm^{-3}) with a factor of 5 higher than that obtained in Benin City exist in the literature for Cairo, Egypt.[42] Though the baseline average $PM_{2.5}$ concentration (31.48 µgm^{-3}) reported in this study breached the WHO threshold limit (25 µgm^{-3}) with a factor of 1.25 and with the likelihood of grave health implications, it is however one of the lowest fine PM value that exist in the literature (Table 2). Except in Abuja (Nigeria), Dar es Salaam (Tanzania) and the contiguous states of USA with mean $PM_{2.5}$ values of 25 µgm^{-3}, 26 µgm^{-3} and 9 µgm^{-3} respectively (Table 2), other Nigerian and African cities have values with several factors higher than that reported in this study (Table 2). Furthermore, the baseline average PM_{10} level (44.44 µgm^{-3}) reported in this study is about the lowest ever measured in a Nigerian city and one of the lowest reported globally (Table 2; Figure 6). The relatively low fine and coarse PM measured in Benin City (Figure 6) can probably be attributed to the traffic control measures that were recently introduced in the city. The measures include - installation of traffic light signals at busy road junctions and intersections, relocation of various commercial bus terminals from the city centre, restriction from indiscriminate picking of passengers outside of the designated bus stops, expansion, rehabilitation and resurfacing of the road network and finally the establishment of a special traffic management unit. These measures have led to a remarkable improvement on traffic congestion and traffic flow within the city. The co – effects of traffic de-congestion and traffic flow improvement are apparent in the baseline PM fractions measured in this study. The positive effects of these traffic control measures on TSP and CO distributions in Benin City have been reported elsewhere.[43, 44] Effective traffic control measures have also been adduced for the low PM fractions in Abuja (Nigeria)[39] and lower PM pollutant levels in high – income nations of the world.[45, 46] Traffic congestion is associated with more concentrated pollution levels from vehicles idling.[47]

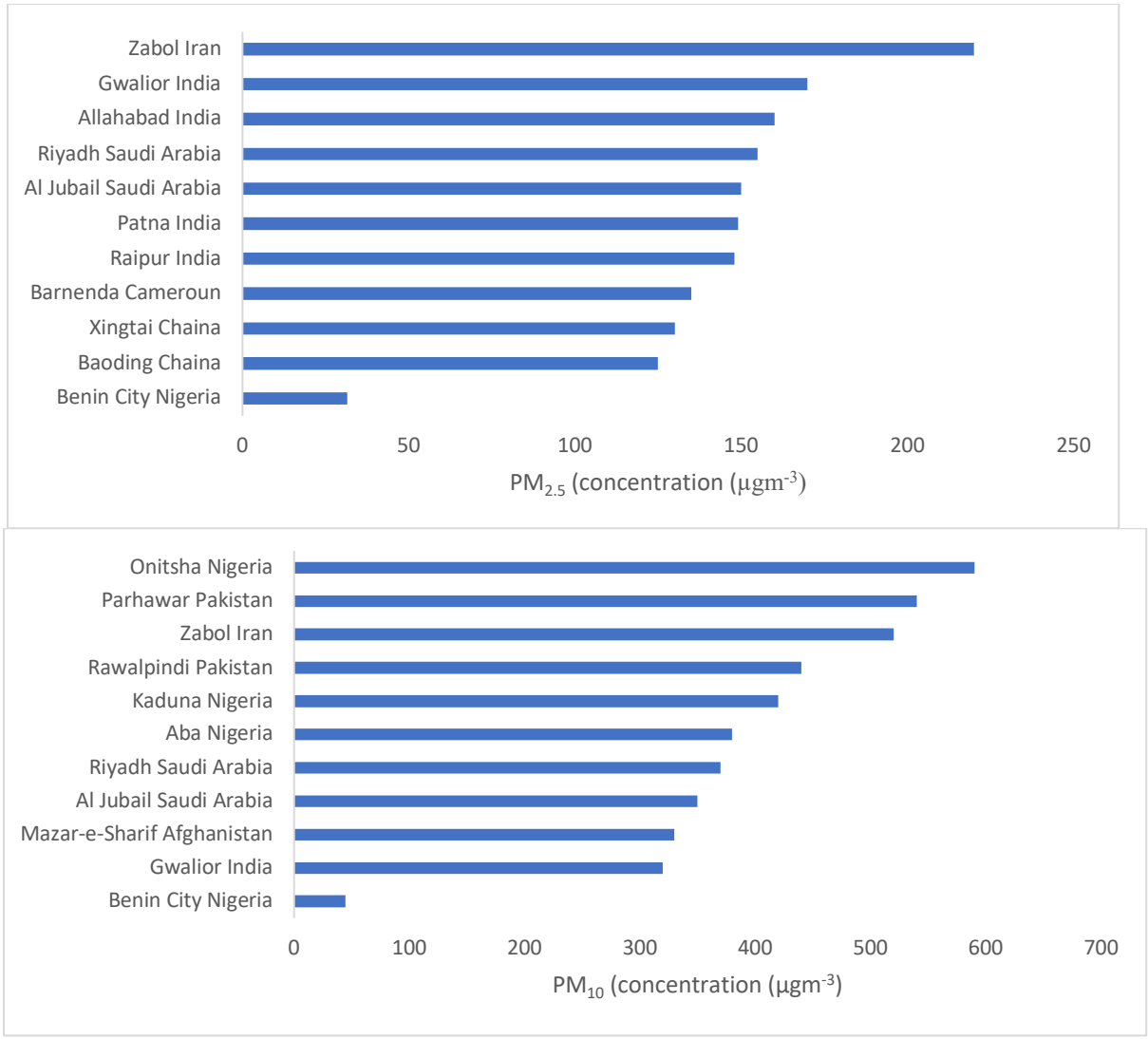

Figure 6. Average concentration of (a. PM2.5; b.PM10) for Benin City in contrast with 10 most polluted cities of the world. This is, modify after the WHO, 2016

Moreover, transport has severally been reported as a major contributor to urban ambient PM levels.[7, 8, 48]

The descriptive statistics of the obtained $PM_{2.5}/PM_{10}$ ratio are shown in Table 3. The ratio of $PM_{2.5}/PM_{10}$ is critical and important in establishing the emission sources of PM. High ratio of $PM_{2.5}/PM_{10}$ implies the dominance by fine particles while low ratio indicates domination by coarse particles. Statistically significant ($p<0.05$) spatial variations were observed in the obtained ratio (Table 3) with location AS2 ratio (0.37) significantly lower than the other sites. However, the results obtained for $PM_{2.5}/PM_{10}$ ratio (range: 0.37 – 0.92) in this study are typical of urban scenarios as shown in Table 2 and to some extent within the limits specified by WHO guidelines. The obtained ratio in AS2 suggested the dominance of the PM by coarse fraction, similar to the observations of Obioh *et al*.[8] and Adeniran et al.[7] who measured similar ratios in Nigerian megacities and Ilorin respectively. The dominance of coarse PM at AS2 further suggest that most of the measured PM came from refuse combustion at Ekiosa open market as reported previously for Warri metropolis.[38] The $PM_{2.5}/PM_{10}$ ratio range (0.81 – 0.92) obtained at locations AS1, AS3, AS4 and AS5, clearly indicate the dominance of fine particles in the PM obtained from these locations. Fine particles are known to primarily originate from vehicular exhaust.[31, 49] We therefore presume that vehicular traffic accounted for the dominance of fine particles in those locations. The dominance of $PM_{2.5}$ in AS1, AS3, AS4 and AS5 is particularly worrisome as its fine nature could accentuate the ease of its lodgement into the respiratory system inducing negative health impacts.[50]

Table 3. Descriptive statistics of $PM_{2.5}/PM_{10}$ ratio in the receptor sites studied

Location	Minimum	Maximum	Median	Mean	Std. Deviation	F	p
AS 1	0.83	0.77	0.82	0.81a	0.03	15.284	0.000
AS 2	0.83	0.17	0.34	0.37b	0.27		
AS 3	0.83	0.79	0.81	0.81a	0.02		
AS 4	0.95	0.86	0.92	0.92a	0.04		
AS 5	0.88	0.71	0.82	0.81a	0.07		
Control	0.94	0.89	0.94	0.92a	0.03		

The table above shows that there is significant spatial variation in $PM_{2.5}/PM_{10}$. Location AS2 showed significantly lower $PM_{2.5}/PM_{10}$ ratio than other sites.

Exposure assessment

The respiratory deposition dose (RDD) rate of the measured fine and coarse PM along the respiratory pathways are presented in Figure 7. The data indicate that the $PM_{2.5}$ mean deposition rate ranged from 1.71 – 7.60 μghr^{-1}, 0.96 – 4.28 μghr^{-1} and 10.93 – 48.51μghr^{-1} at the alveolar, tracheobronchial and head airway regions respectively and a mean range of 13.86 – 61.53μghr^{-1} for $PM_{2.5}$ RDD_T (Fig. 7a-d). For the coarse PM, the average deposition rate ranged from 0.34 –1.11 μghr^{-1}, 0.27 –0.87 μghr^{-1} and 14.55 – 48.70μghr^{-1} at the alveolar, tracheobronchial and head airway regions respectively and a range of 15.00 – 48.70μghr^{-1} for the PM_{10} RDD_T. The above RDD data are consistent with data obtained in Ilorin (Nigeria).[7] The calculated regional percentage deposition of the fine and coarse PM shows that the tracheobronchial region had the least deposit of 6.96% followed by alveolar with 12.36% and the head airway region with the highest (78.86%). The above observation agrees with the deposition process and equation as explained by Hinds [25] and the Bailey [51] particulate deposition model.

A comparison of the obtained RDD results with the computed RDDs using WHO regulatory limits of 25μgm^{-3} ($PM_{2.5}$) and 50μgm^{-3} (PM_{10}), revealed that the $PM_{2.5}$ limit was violated at all the sampling locations with location AS2 having the highest aberration of 180% (Fig. 7a-d). For the coarse PM, compliance with the predicted RDD was only observed at locations AS4 and AS5 (Fig. 7e-h), with the highest violation of 15.6% at location AS2. The box plot (Fig. 7) also confirms that the lower the particle sizes the higher the penetrating ability as indicated by Hinds.[25] The RDD of the alveolar deposit obtained at AS2 indicates that the people who spend most of their time in this location may be at a high risk of cardiovascular problems with time. Notably, previous studies of PM fractions have shown that short term peak exposure levels may trigger acute health condition such as sneezing, coughing and asthma,[52] and have been associated with short-term cardiovascular and respiratory health effects.[53] $PM_{2.5}$ are inhaled deeply into the alveoli of the lungs causing extensive damage to the body. PM_{10} are generally associated with inflammatory responses. [54]

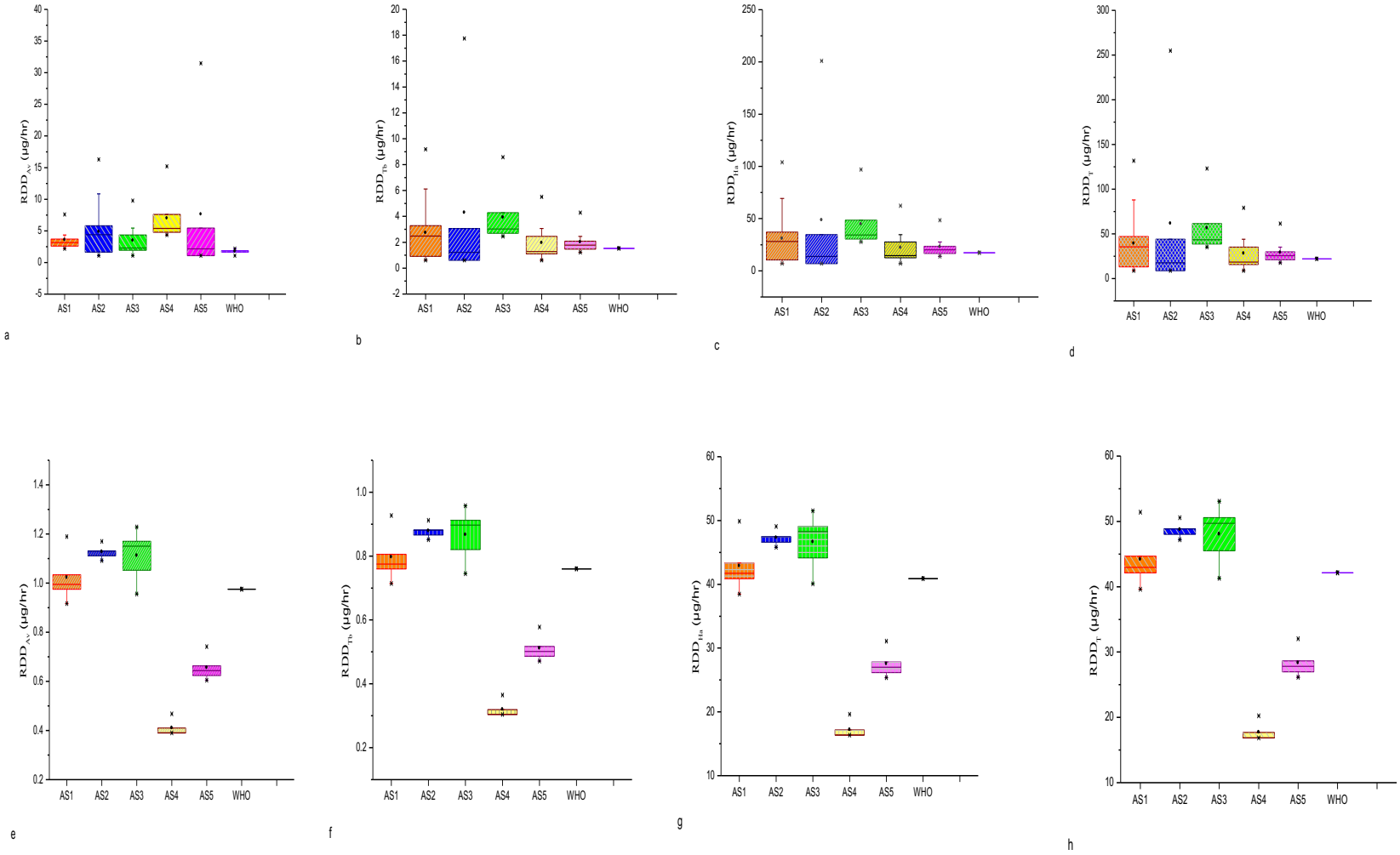

Figure7. RDD box plots for $PM_{2.5}$ in the respiratory tract (a: alveolar, b: tracheobronchial, c: head airway, d: total) and PM_{10} in (e: alveolar, f: tracheobronchial, g: head airway, h: total)

Source Identification and Apportionment of the measured PM

To be able to design a more informed and sustainable PM pollution control strategy, a study on the anthropogenic contributing sources of PM fractions in Benin City was undertaken. Principal Component Analysis (PCA) and Multiple Linear Regression (MLR), vis-à-vis PCA-MLR method was employed.[21, 55] The $PM_{2.5}$ and PM_{10} data were first subjected to communality studies to establish their suitability for PCA analysis. The communality tables (Tables 4 & 5) show that the variables entered were suitable for PCA since the extracted communalities were greater than 0.3.[56]

Table 4. Communalities of $PM_{2.5}$ at the different sampling sites.

	Communalities	
	Initial	Extraction
AS1	1.000	.989
AS2	1.000	.978
AS3	1.000	.892
AS4	1.000	.741
AS5	1.000	.862

Table 5. Communalities of PM_{10} at different sampling sites.

	Communalities	
	Initial	**Extraction**
AS1	1.000	.910
AS2	1.000	.975
AS3	1.000	.805
AS4	1.000	.824
AS5	1.000	.971

Consequently, the fine and coarse PM were extracted for analysis using PCA. Two components were extracted for $PM_{2.5}$ (Table 6), explaining 89.22% of the total variance.

Table 6. Total variance of $PM_{2.5}$ explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.822	56.450	56.450	2.822	56.450	56.450	2.584	51.682	51.682
2	1.639	32.770	89.220	1.639	32.770	89.220	1.877	37.538	89.220
3	.493	9.863	99.083						
4	.046	.917	100.000						
5	-1.527E-16	-3.055E-15	100.000						

Extraction Method: Principal Component Analysis.

Table 7. Total variance of PM_{10} explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.836	56.711	56.711	2.836	56.711	56.711	2.830	56.592	56.592
2	1.650	33.000	89.711	1.650	33.000	89.711	1.656	33.119	89.711
3	.461	9.217	98.928						
4	.054	1.072	100.000						
5	4.457E-16	8.913E-15	100.000						

Extraction Method: Principal Component Analysis.

This indicates two sources of $PM_{2.5}$ in the sampling locations. Similarly, two components were extracted for PM_{10}, explaining 89.71% of the total variance. This again suggests two main sources of the coarse particles measured in the sampling stations. The rotated component matrix (using Varimax with Kaiser Normalization) for $PM_{2.5}$ (Table 8), shows that locations AS1, AS2 and AS5 have loading scores above 0.5 on component 1 (suggesting similar sources of fine PM pollution in those locations), while AS3 and AS4 have loading scores greater than 0.5 on component 2.

Table 8. Rotated component Matrix[a] for $PM_{2.5}$

	Component	
	1	**2**
AS1	.946	.305
AS2	.922	-.359
AS3	.075	-.941
AS4	.338	.792
AS5	.848	.377

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 3 iterations.

The differences in loading is further shown in Figure 8.

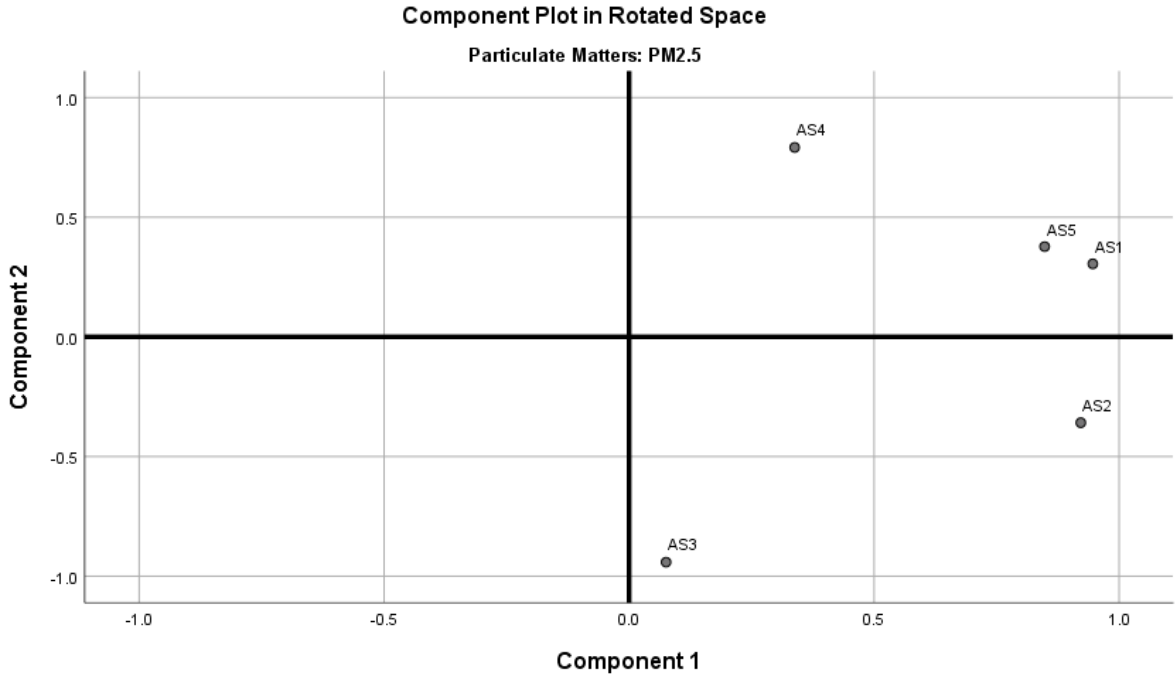

Figure 8. PCA Component Plot in Rotated Space for $PM_{2.5}$

From our field observations, we attributed component 1 to contributions from vehicular emissions (77.3%) and component 2 to contributions from refuse combustion (22.7%) (Figure 9). The rotated component matrix for the coarse particles revealed that locations AS1, AS2 and AS5 loaded highest on component 1 (Table 9) (suggesting once again similar sources of coarse PM pollution).

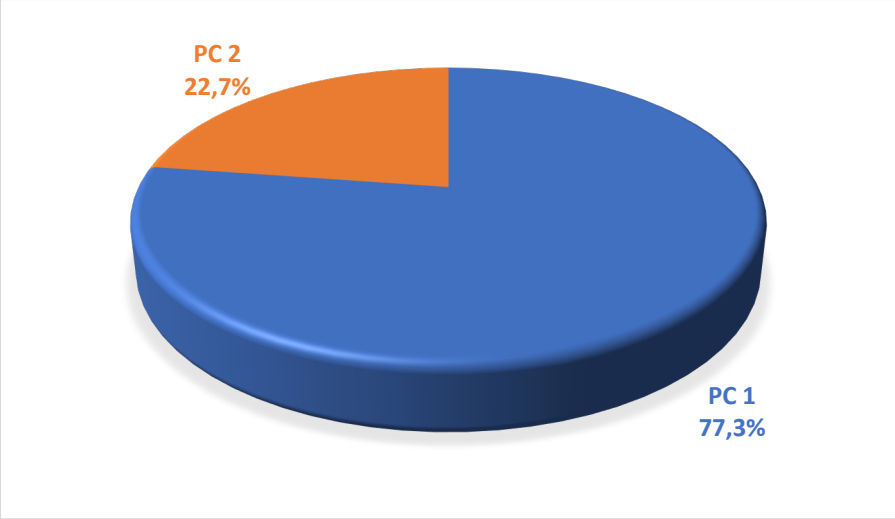

Figure 9. Source apportionment for $PM_{2.5}$

Table 9. Rotated Component Matrix[a] for PM_{10}

	Component	
	1	2
AS1	.953	-.042
AS2	.975	.158
AS3	-.054	-.896
AS4	-.025	.907
AS5	.984	-.057

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 3 iterations.

Sites AS3 and AS4 had loadings greater than 0.5 on component 2. The dichotomy in loading was further explained in Figure 10.

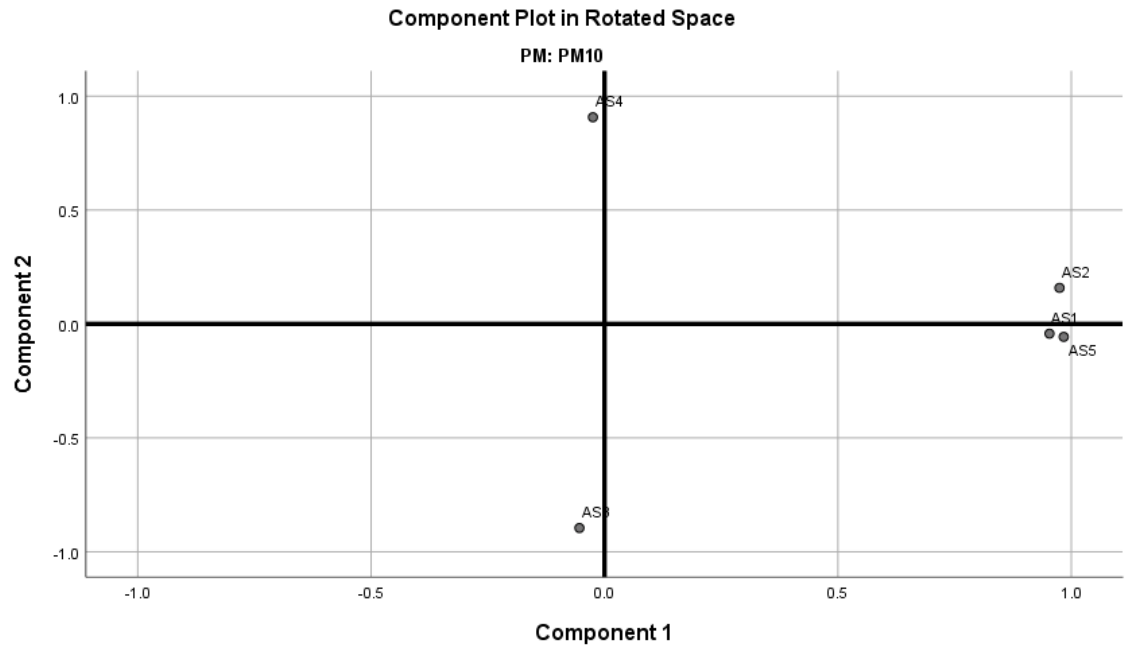

Figure 10. PCA Component Plot in Rotated Space for PM_{10}

From our field observations, we attributed component 1 to contributions from vehicles (70%) and component 2 to the coarse fractions that came from refuse combustion (30%) (Figure 11). The similarities in the sources of fine and coarse PM in this study was first noticed from the correlation analysis on the measured $PM_{2.5}$ and PM_{10} data (Fig. 4). In a similar study in Europe, Sundvor et al. [17], demonstrated that between 9 and 66% of $PM_{2.5}$ and 9-53% of PM_{10} came from traffic. In London, UK, more than 80% of PM is from road traffic.[57] Also in Athens, Greece, the contribution of road traffic to total $PM_{2.5}$ emission is estimated to be 66.5%.[58]

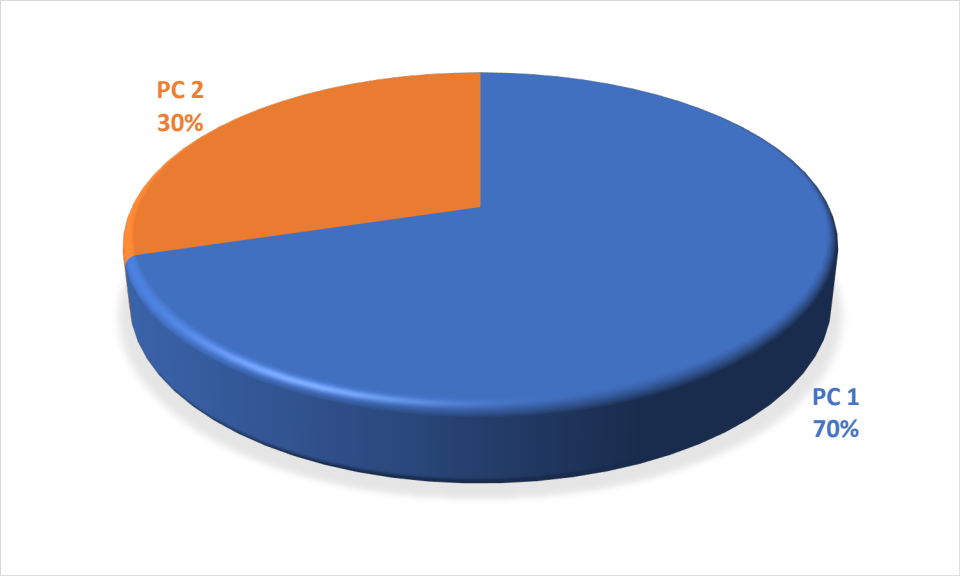

Figure 11. Source apportionment for PM_{10}

Strengths and weaknesses

This present study has filled a major information gap on the baseline and background levels of PM fractions in Benin City with a population of over one million people. It has also been able to establish the effectiveness of simple traffic control measures on PM pollution in a tropical urban centre. Furthermore, the information on the contributions of the different sources to PM fractions in the city is sufficient to initiate policy on the development of mitigation measures. Finally, the data on the respiratory deposition dose (RDD) is quite apt on the need for urgent precautionary measures on PM emissions. A major limitation of this study is the period of sampling; covering just the wet season months of the year. However we do not anticipate significant temporal variations in the PM data because of the impact of climate change on rainfall that is now almost all year round in the city. Secondly is the lack of time weighted average (TWA) data from fixed PM monitors in Benin City that denied us the opportunity of a more robust and comparative analysis of the obtained data.

CONCLUSION

The baseline and background levels of fine and coarse PM fractions in Benin City have been provided. The obtained average urban $PM_{2.5}$ and PM_{10} background concentrations for the city were found to be 16.40 μgm^{-3} and 17.80μgm^{-3} respectively. The measured baseline mean $PM_{2.5}$ concentration for the city was 31.48 μgm^{-3} and it breached the WHO threshold limit by a factor of 1.25. Remarkably, the average baseline PM_{10} level obtained for the city (44.44 μgm^{-3}) was within the WHO and USEPA regulatory limits. When compared with the $PM_{2.5}$ and PM_{10} data available nationally, continentally and globally, we concluded that the implemented traffic control measures in the city have positively impacted on PM pollution within the city. The results obtained for $PM_{2.5}/PM_{10}$ ratio (range: 0.37 – 0.92) in this study are typical of urban scenarios but revealed the dominance of the PM by fine particles in 80% of the sampling locations. The average on – road respiratory deposition dose (RDD) rates analysis estimated that 6.96% of the measured PM were lodged in the tracheobronchial region, 12.36% in the alveolar and 78.86% in the head airway of the commuters and pedestrians in the city. The source identification and apportionment studies by Principal Component Analysis (PCA) and Multiple Linear

Regression (MLR) suggested that vehicles was the major source of $PM_{2.5}$ (77.3%) and PM_{10} (70%) in the city with the remainder coming from refuse combustion.

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