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Determination of Air Pollution Concentrations from Motor Vehicles at Selected Stop-Points Along a Major Highway

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Abstract: Intensified traffic-related air pollution along major highway corridors in developing countries poses increasing risks to environmental quality and public health. This study investigated air pollutant concentrations from motor vehicles at selected stop-points (Locations A - D) along the Benin–Ore–Sagamu highway in southwestern Nigeria. Continuous monitoring was conducted for gaseous pollutants (CO, CO_2, SO_2), particulate matter (PM2.5 and PM10), inorganic ions (SO_4^{2-} and NO_3^-), and trace metals across four locations during wet and dry seasons. Traffic density was assessed through structured manual vehicle counts at each location, with vehicles categorized by type to assess traffic density and flow patterns. Traffic volume assessment identified Location D as the highest traffic hub, with seasonal variations influencing pollutant levels. Measured levels of CO, SO_2, PM2.5, and PM10 showed significant exceedances of WHO, NAAQS, and FMEnv guidelines, while trace metal analysis indicated extreme enrichment of Rh, Pt, Pd, and other metals, predominantly from vehicular emissions. In contrast, Fe, Zn, and Mn were predominantly derived from natural sources. Sulphate and nitrate exhibited strong dry-season correlations ($r = 0.991$, $p < 0.01$) and significant spatial variability, with ANOVA confirming the influence of location on concentrations. Wet-season deposition reduced pollutant concentrations, demonstrating the mitigating role of rainfall. The findings provide a seasonally resolved characterization of traffic-induced air pollution and emphasize the urgent need for regulatory enforcement, fuel quality improvement, and traffic management to protect public health along high-density highway corridors.

Keywords: Air pollution; Traffic density; Vehicular emissions; Enrichment; Particulate.

1. Introduction

Rapid urbanisation, population growth, and economic expansion have significantly increased road transport demand, making vehicular traffic a major contributor to atmospheric pollution in urban and peri-urban environments globally [1][2]. Motor vehicles emit complex mixtures of gaseous pollutants and particulate matter, including CO, SO_2, NO_x, $PM_{2.5}$, and PM_{10}, generated from fuel combustion, engine wear, and brake and tyre abrasion [3, 4]. Vehicular fine particulate matter exhibits high toxicity and chemical variability dependent on emission processes, highlighting the need for source-specific characterisation [4]. Exposure to traffic-related air pollutants is strongly associated with adverse respiratory, cardiovascular, neurological, and mortality outcomes [5-9].

In Nigeria and other developing countries, vehicular emissions are exacerbated by rapid motorisation, inadequate transport infrastructure, weak regulatory enforcement, poor vehicle maintenance, and continued use of low-quality, sulphur-rich fuels [10-13]. These factors elevate pollutant concentrations along highways and traffic stop points characterised by frequent idling, deceleration, and acceleration. Limited emphasis on vehicular emission control poses a significant challenge to public health protection and the attainment of Sustainable Development Goals 3, 11, and 13 [14]. Nigerian studies report elevated $PM_{2.5}$ and gaseous pollutant levels at major roadways, with strong associations to traffic intensity [13-16]. While satellite observations indicate persistently high tropospheric NO_2, SO_2, and CO across Nigeria, ground-based monitoring remains essential for resolving local-scale variations. Ground-level measurements further reveal pronounced seasonal and diurnal variability in particulate and gaseous pollutants linked to traffic activity. Characterisation of particulate inorganic ions, such as sulphates and nitrates, provides insight into both primary vehicular emissions and secondary aerosol formation. In addition, motor vehicles are significant contributors to environmental heavy metal burdens, which pose health risks even at low inhalation levels [17,18]. Trace metal enrichment factor analysis is therefore critical for distinguishing crustal and anthropogenic sources, including engine exhaust, brake linings, and tyre wear.

Despite growing research efforts, comprehensive Nigerian studies simultaneously assessing multiple gaseous pollutants, particulate matter fractions, seasonal variability, inorganic ions, and trace metals along major highway corridors remain scarce. Existing studies largely focus on urban road networks or isolated pollutants, limiting understanding of traffic-induced pollution dynamics at intercity stop points. To address this gap, the present study evaluates concentrations of key gaseous pollutants (CO, SO_2, CO_2), particulate matter ($PM_{2.5\ 10}$and PM_0), inorganic ions (SO_4^{2-} and NO_3^-), and trace metals at selected stop points along a major southwestern Nigerian highway corridor. Seasonal variations are analysed, pollutant levels are compared with air quality standards, and anthropogenic contributions are assessed using enrichment factor analysis. The study provides a seasonally resolved assessment of traffic-related air pollution to inform evidence-based policy and public health interventions in Nigeria.

2. Research and Methodology

2.1. Materials and equipment

The study was conducted along the Benin–Ore–Sagamu highway in southwestern Nigeria, a major intercity transportation corridor characterised by continuous vehicular flow, high traffic density, and a significant proportion of heavy-duty vehicles, making it an important source of traffic-related atmospheric emissions. Four highway locations were strategically selected for pollutant and traffic monitoring based on traffic intensity and their potential influence on near-road pollutant dispersion. Okada Junction (Location A; 6.3382° N, 5.6129° E) is dominated by intense intercity traffic, roadside commercial activities, and fuel stations, which contribute to sustained emission release. Ore (Location B; 6.7469° N, 4.8667° E) functions as a major highway interchange and transit node, characterised by traffic congestion, vehicle idling, refuelling operations, and goods handling activities. Ijebu-Ode (Location C; 6.8222° N, 3.9217° E) represents an urbanised highway corridor with mixed residential and commercial land use, where both intra- and intercity traffic, roadside trading, and pedestrian activities influence emission variability. Sagamu (Location D; 6.8093° N, 3.3321° E) is an industrially influenced highway corridor linking Lagos to other regions, characterised by high volumes of heavy-duty vehicles and freight movement, making it suitable for assessing highway-induced pollutant dispersion under varying traffic conditions.

Specialised handheld air quality monitoring instruments were used to ensure accurate and reliable air quality measurements. Carbon monoxide (CO) concentrations were measured using a BH-4S portable multi-gas detector equipped with a high-sensitivity natural sensor, a response time of less than 30s, a detection range of 0–1000 ppm, and a resolution of 1 ppm. Particulate matter ($PM_{2.5}$ and PM_{10}) was monitored using a JBL-B600 multifunction air quality detector incorporating a high-performance intelligent electrochemical independent sensor, with a detection range of 0–999 μg/m³ and a response time of 5s.

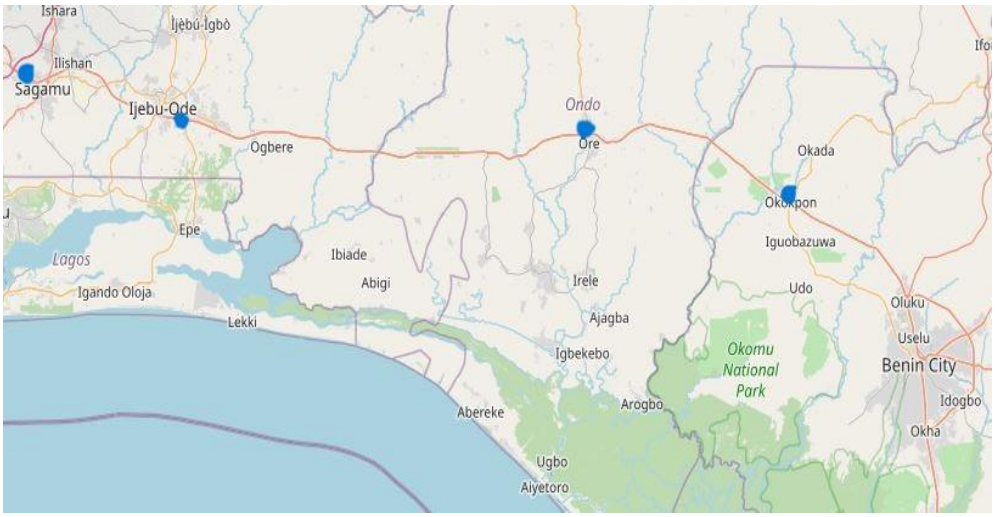

Figure 1. The Sampling Locations (Sagamu, Ijebu-Ode, Ore, and Okada (Benin City))

Carbon dioxide (CO_2) concentrations were determined using a UNI-T A37 detector with a detection range of 0–1000 ppm and a resolution of 1 ppm. Sulphur dioxide (SO_2) was measured using a PDM+ Single Sustainable Gas Detector (model SP-SGTP) fitted with an electrochemical cell sensor, offering a detection range of 0–50 ppm and a resolution of 0.1 ppm. All instruments provided real-time measurements with high sensitivity and accuracy. This approach aligns with established methodologies for portable air quality monitoring [19] and recent advancements in the deployment and performance evaluation of handheld and low-cost air quality sensors for ambient air pollution assessment [20][21]. Measurements were taken on an hourly basis from Monday to Friday to represent weekdays, and on Saturday and Sunday to capture weekend conditions, over a one-month period during both the wet and dry seasons. All data were recorded in a worksheet, and the hourly pollutant concentrations were subsequently extrapolated to 24-hour and annual averages using the atmospheric stability equation (Equation 1). This relationship follows a power-law form and is consistent with established atmospheric dispersion theory (Turner,1994).

$$\frac{C_2}{C_1} = \left(\frac{t_1}{t_2}\right)^{0.28} \quad (1)$$

Where C_2 is the estimated concentration for the new averaging time t_2, C_1 is the concentration measured over the original averaging time t_1, and 0.28 is a stability-dependent exponent commonly applied in air quality studies, particularly under neutral to stable atmospheric conditions.

2.2 Experiments

The traffic data for this study were collected through manual vehicle counts at selected highway segments, intersections, and access roads. Observations were recorded on tally sheets, with vehicles classified into four categories: motorcycles, cars, buses, and trucks/trailers. Counts were conducted hourly, and the data were used to estimate average daily traffic flow, which was subsequently

extrapolated to derive the average annual traffic volume. Monitoring was carried out over one-month periods during the dry season, with weekdays defined as Monday to Friday and weekends as Saturday and Sunday. For the purpose of the study, vehicles were assumed to be powered either by gasoline or diesel. No abnormal events, such as road closures or accidents, were reported during the monitoring periods, ensuring that the collected data accurately represent typical traffic conditions. The resulting traffic dataset provides a reliable basis for evaluating traffic flow patterns and their influence on near-road pollutant dispersion along the study highway.

The concentrations of sulphate (SO_4^{2-}), nitrate (NO_3^-), and trace metals at the sampling locations were determined by collecting airborne particulate matter using a size-selective air sampler equipped with a $PM_{2.5}$ inlet. Samples were collected on 47 mm diameter quartz fiber filters, with each sampling session lasting 60 minutes, corresponding to a total sampled air volume of approximately 4.2 m^3 per session. The sampler operated at a calibrated flow rate of 70 L min^{-1}, with a volumetric error maintained within ±2%. It was positioned 2 m above ground level and 2 m from the roadside to represent ambient exposure conditions. Sampling was conducted on weekdays and weekends at three intervals: morning (08:00–09:00), noon (12:00–13:00), and evening (16:00–17:00), yielding at least 24 samples per location for a period of one month for wet and dry seasons. Each filter was conditioned under controlled temperature and relative humidity before and after sampling and handled with flat-tipped forceps, stored in cassettes, wrapped in aluminum foil to prevent photo-oxidation, and transported to the laboratory. The gravimetric method was employed, in which filters were weighed using a high-precision analytical balance (±0.01 mg) to determine the mass of collected particulate matter, with field blanks used to account for background contamination. Collected filters were analyzed for inorganic ions (SO_4^{2-} and NO_3^-) and trace metals using standard laboratory techniques.

Sulphate and nitrate concentrations were determined using turbidity and colorimetric methods, respectively. For SO_4^{2-}, filtered samples were reacted with glycerol, hydrochloric acid, and sodium chloride, and absorbance was measured at 420 nm against a sodium sulphate standard curve. For NO_3^-, samples were reacted with $CuSO_4$, sulfanilamide, and N-1-naphthylethylenediamine dihydrochloride (NED), and absorbance was measured at 540 nm, using a sodium nitrate standard curve for quantification. Heavy metals were analyzed using a Thermo Scientific Niton XL2 Energy Dispersive X-ray Fluorescence Spectrometer (EDXRF) at the Central Research Laboratory, Tanke, Ilorin. The EDXRF detects up to 92 elements from Be to U and provides qualitative and quantitative analysis by measuring characteristic X-rays emitted when samples are bombarded with a focused electron beam. Metal concentrations were determined from the X-ray intensity through the filter paper based on counts per second.

2.3 Statistical and pollution assessment methods

Correlation analysis was selected due to its suitability for assessing linear associations between secondary inorganic aerosols with potentially shared emission sources. Pearson's correlation coefficient (r) was employed to examine the strength and direction of the linear relationship between sulphate (SO_4^{2-}) and nitrate (NO_3^-) concentrations. Seasonal mean concentrations obtained from four sampling locations (n = 4) were used for the analysis. The statistical significance of the correlation coefficients was evaluated using a two-tailed t-test at a 95% confidence level ($\alpha = 0.05$), with degrees of freedom calculated as $df = n - 2$. This analysis was conducted to provide insight into the possible common sources or similar atmospheric processes influencing the distribution of sulphate and nitrate in the study area.

The Enrichment Factor (EF) method is widely used to differentiate between crustal and non-crustal sources of trace metals in airborne particulate matter, providing a quantitative assessment of

anthropogenic metal pollution in the study area. This method compares the concentration of metals in the sample with their average abundances in the Earth's crust, using a reference element for normalization. In this study, Titanium (Ti) was selected as the reference element due to its geochemical stability and ubiquitous presence in the environment [23]. Concentration data for the Earth's crust were obtained from the handbook by [24]. The EF for a given metal is calculated using Equation 2:

$$EF_i = \left(\frac{C_i}{C_{ref}}\right)_s / \left(\frac{C_i}{C_{ref}}\right)_{crust} \quad (2)$$

Where EF_i is enrichment factor of metal i, C_i and C_{ref} represent the concentrations (μg/m^3) of the target metal and reference element, respectively, and the subscripts “s” and “crust” refer to their concentrations in the particulate matter and Earth’s crust. Pollution levels are categorized based on EF values as follows: EF ≤ 1, no enrichment; 1 < EF ≤ 3, minor enrichment; 3 < EF ≤ 5, moderate enrichment; 5 < EF ≤ 10, moderately severe enrichment; 10 < EF ≤ 25, severe enrichment; 25 < EF ≤ 50, very severe enrichment; and EF > 50, extremely severe enrichment [25].

3. Results and Discussion

3.1. Traffic volume data

Figure 2 illustrates the annual traffic volumes across the various vehicle categories. The highest annual traffic volume of 58,386,432 vehicles was recorded at Sagamu. During the dry season, motorcycles accounted for 15,656,160–18,280,704 vehicles, cars for 4,019,808–5,989,152, buses for 1,795,872–3,146,208, and trucks/trailers for 2,706,912–3,534,336, while in the wet season, motorcycle traffic ranged from 9,049,248 to 11,764,896, cars from 3,223,584 to 12,944,256, buses from 1,508,832 to 2,357,472, and trucks/trailers from 1,528,800 to 4,183,296. These volumes substantially exceed the daily average of 18,851 vehicles (6,880,615 per year) reported by [26] for the Benin-Ore-Sagamu expressway in 2019, likely due to their reliance on nodal traffic counts, and are also higher than values reported by [27] for major highways in Makurdi, highlighting Sagamu as a major transportation hub. Seasonal variations, with higher motorcycle and bus traffic during the dry season, may reflect improved road conditions and reduced travel disruptions, while the variability in car and truck traffic during the wet season likely indicates commercial and freight transport patterns. These elevated traffic volumes have important implications for air quality, as they contribute to increased emissions of particulate matter and gaseous pollutants, emphasizing the need for traffic management strategies and mitigation measures to reduce vehicular pollution in this high-density corridor.

3.2. Seasonal air pollutant concentrations and Comparison with air quality standards

The seasonal concentrations of key air pollutants, carbon monoxide (CO), sulphur dioxide (SO_2), carbon dioxide (CO_2), and particulate matter ($PM_{2.5}$ and PM_{10}), expressed in micrograms per cubic meter, measured across the four study locations are summarized in Tables 2 to 6. These values were compared with international guidelines, including the World Health Organization (WHO) and the National Ambient Air Quality Standards (NAAQS), as well as national limits set by the Federal Ministry of Environment (FMEnv). Table 2 shows the mean seasonal concentrations of carbon monoxide (CO) across all sampling locations for 1-hour, 8-hour, and 24-hour averaging periods. CO levels were consistently higher during the dry season, with 1-hour concentrations ranging from 46.30 to 60.82 × 10³ μg/m³, exceeding WHO (35 × 10³ μg/m³) and NAAQS (40 × 10³ μg/m³) limits, and peaking at Location D (60.82 × 10³ μg/m³). In contrast, wet season 1-hour concentrations generally remained

below the standards, except at Location D (4.19 × 10³ µg/m³). For the 8-hour period, all locations exceeded the 10 × 10³ µg/m³ guideline in both seasons, with Location D recording the highest levels (34.06 × 10³ µg/m³ dry; 24.75 × 10³ µg/m³ wet).

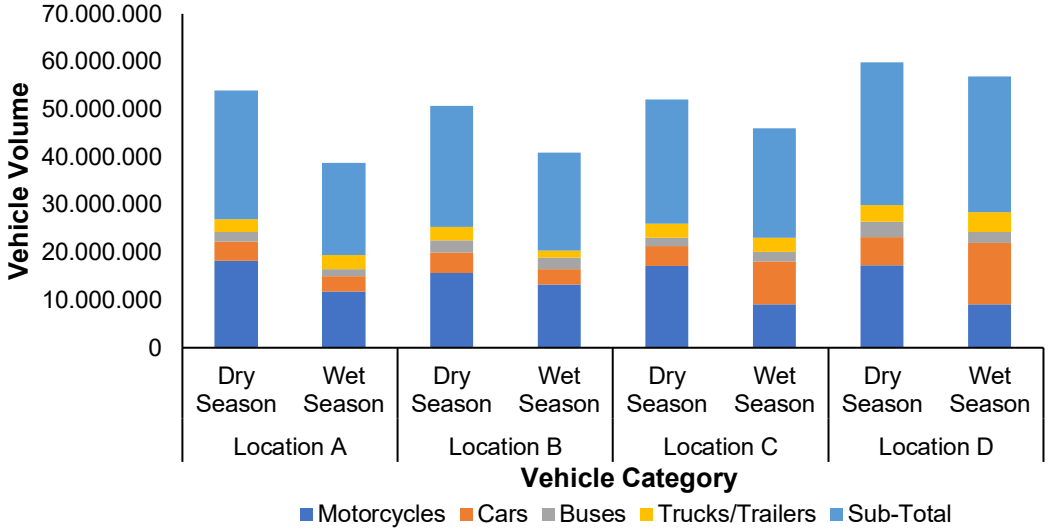

Figure 2. Annual Traffic Volume of Different Categories of Vehicles

Similarly, 24-hour dry season CO concentrations (18.88–24.93 × 10³ µg/m³) surpassed the FMEnv limit of 11.4 × 10³ µg/m³, while wet season values (13.34–18.12 × 10³ µg/m³) remained above the WHO limit of 4 × 10³ µg/m³. These patterns indicate a clear seasonal effect, with dry conditions favouring higher CO accumulation, likely due to increased traffic emissions and reduced atmospheric dispersion. Location D consistently exhibited the highest concentrations, highlighting it as a pollution hotspot. The observed levels pose significant health risks, including headaches, dizziness, cardiovascular stress, and impaired oxygen delivery, underscoring the need for targeted air quality management in high-traffic corridors

Table 2. Carbon Monoxide (CO). Concentration in (µg/m^3) x 10^3

Location	1-h		8-h		24h	
	Dry	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
A	47.45	35.51	26.57	19.89	19.45	14.56
B	46.3	32.53	25.93	18.21	18.88	13.34
C	47.48	32.54	26.59	18.22	19.47	13.34
D	60.82	44.19	34.06	24.75	24.93	18.12
WHO	35		10		4	
FMEnv	-		-		11.4	
NAAQS	40		10		-	

Table 3 presents the 1-hour, 8-hour, and 24-hour average concentrations of sulphur dioxide (SO_2) across the four study locations. During the dry season, SO_2 levels peaked at 3470 µg/m³ at Location D (Sagamu), far exceeding guideline limits set by FMEnv (260 µg/m³) and NAAQS (197 µg/m³) for the 1-hour average, as well as WHO (40 µg/m³), NAAQS (50 µg/m³), and FMEnv (26 µg/m³) for the 24-hour average, and surpassing the 225.4 ± 57.9 µg/m³ previously reported by [28]. These elevated concentrations are largely driven by the combustion of sulphur-rich fuels, particularly diesel, which is commonly used in vehicles along this corridor; Nigerian diesel contains up to 3000 ppm

sulphur, compared to the 10 ppm standard in developed countries. Such high SO_2 levels are a serious public health concern, particularly for children, the elderly, and individuals with pre-existing respiratory conditions, who are at increased risk of bronchitis, asthma exacerbation, and irritation of the respiratory tract. The results highlight a clear seasonal effect, with dry conditions favouring accumulation of SO_2, and underscore the urgent need for improved fuel quality standards and emission control measures in high-traffic areas.

Table 3. Sulphur Dioxide (SO_2). Concentration in ($\mu g/m^3$)

Location	1-h		8-h		24-h	
	Dry	Wet	Dry	Wet	Dry	Wet
A	2090	1330	1420	740	860	550
B	2730	1790	1145	520	1120	640
C	2940	1560	1610	880	1210	650
D	3470	1850	2140	950	1160	760
WHO	-		-		40	
FMEnv	260		-		26	
NAAQS	197		-		50	

The seasonal average concentrations of $PM_{2.5}$, summarized in Table 4, reveal significant spatial and temporal variability across the study locations. During the dry season, hourly $PM_{2.5}$ concentrations at Locations A, B, C, and D were 834.68, 992.52, 748.60, and 1181.68 $\mu g/m^3$, respectively, while corresponding daily averages were 414.59, 238.41, 262.88, and 337.01 $\mu g/m^3$. These values substantially exceed regulatory standards, including the FMEnv hourly limit (250 $\mu g/m^3$), the WHO 24-hour guideline (25 $\mu g/m^3$), and the NAAQS 24-hour standard (35 $\mu g/m^3$), with Location D exhibiting particularly high levels. The elevated concentrations at Location D are likely attributable to the dense traffic of heavy-duty diesel vehicles, which are major sources of fine particulate emissions due to incomplete combustion. Comparative analysis across seasons shows a marked reduction in $PM_{2.5}$ levels during the wet season, which can be attributed to wet scavenging processes, including washout and rainout, effectively decreasing the atmospheric particulate load. This seasonal pattern aligns with previous studies highlighting the mitigating effect of precipitation on air pollution, emphasizing the combined influence of traffic density, fuel type, and meteorological conditions on ambient $PM_{2.5}$

Table 4. Particulate Matter ($PM_{2.5}$). Concentrations in ($\mu g/m^3$)

Location	1-h		8-h		24-h	
	Dry	Wet	Dry	Wet	Dry	Wet
A	835	1011	512	755	342	415
B	993	581	710	345	407	238
C	749	641	525	414	307	263
D	1182	822	834	670	484	337
WHO	-		-		25	
FMEnv	250		-		-	
NAAQS	-		-		35	

The data in Table 5 indicate that all measured pollutants frequently exceeded regulatory standards, particularly during the dry season. CO levels at all locations exceeded WHO and NAAQS limits for both 1-hour and 24-hour averages, with Location D recording the highest concentrations (60.82 × 10^3 µg/m³ dry season). SO_2 concentrations peaked at 3470 µg/m³ at Location D, far above FMEnv and NAAQS limits, largely due to the use of high-sulphur diesel fuel. Fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}) also exceeded WHO, NAAQS, and FMEnv standards across all locations, with the highest levels observed at Location D ($PM_{2.5}$: 1181.68 µg/m³; PM_{10}: 1620 µg/m³). Wet season concentrations were generally lower, reflecting the mitigating effects of rainfall through wet scavenging processes, although values still exceeded WHO and NAAQS limits at most sites. Across all pollutants, Location D consistently emerged as a hotspot, emphasizing the role of high traffic density, especially heavy-duty diesel vehicles, in driving ambient air pollution. These elevated pollutant levels pose significant health risks, including respiratory irritation, cardiovascular stress, and exacerbation of chronic conditions, highlighting the urgent need for stricter emission controls, fuel quality regulations, and traffic management in high-density corridors.

Table 5. Particulate Matter (PM_{10}). Concentrations in (µg/m^3)

Location	1-h		8-h		24-h	
	Dry	Wet	Dry	Wet	Dry	Wet
A	1197	1186	795	820	491	491
B	1454	651	854	335	596	267
C	1006	790	678	528	413	324
D	1620	1353	990	832	664	555
WHO	-		-		50	
FMEnv	250		-		-	
NAAQS	-		-		150	

Table 6 presents the seasonal 1-h, 8-h, and 24-h average concentrations of carbon dioxide (CO_2) across the four study locations, compared with the WHO guideline value of 1796 × 10^3 µg/m³. During the dry season, 1-h CO_2 concentrations ranged from 1687 to 2357 × 10^3 µg/m³, with exceedances observed at Locations A (2110 × 10^3 µg/m³), B (1801 × 10^3 µg/m³), and D (2357 × 10^3 µg/m³), while Location C remained below the guideline. In contrast, wet season 1-h concentrations (1329–1667 × 10^3 µg/m³) were below the WHO limit at all locations. For the 8-h and 24-h averaging periods, CO_2 concentrations in both seasons (8-h: 795–1562 × 10^3 µg/m³; 24-h: 545–980 × 10^3 µg/m³) complied with the WHO guideline across all sites. The observed short-term exceedances during the dry season, particularly at Location D, indicate intense combustion activity and limited atmospheric dispersion. The spatial and seasonal distribution of CO_2 closely aligns with trends observed for CO, SO_2, $PM_{2.5}$, and PM_{10}, suggesting a dominant influence of traffic-related emissions. Although CO_2 is not acutely toxic at ambient concentrations, elevated short-term levels serve as a useful indicator of combustion intensity and the potential accumulation of co-emitted pollutants with established health impacts.

Table 6. Carbon Dioxide (CO_2). Concentration in ($\mu g/m^3$) x 10^3

Location	1-h		8-h		24-h	
	Dry	Wet			Dry	Wet
A	2110	1667	1350	980	865	684
B	1801	1543	1010	893	738	633
C	1687	1329	874	912	692	545
D	2357	1611	1562	795	967	660
WHO ($\mu g/m^3$)					1796	

3.3 Results of trace metals characterization in Samples

Table 7 presents heavy metal concentrations across four sampling locations in both the dry and wet seasons. The analysis reveals significant variations in metal concentrations, with elements like Iron (Fe) reaching a peak concentration of 9.318 × 10^3 µg/m³ at Location D during the dry season, and Titanium (Ti) exhibiting the highest overall concentration of 62.685 × 10^3 µg/m³ in the wet season at the same location. Toxic heavy metals such as cadmium (Cd) and lead (Pb) exhibit notable fluctuations; Cd reaches 8.688 × 10^3 µg/m³ in the dry season at Location C, while Pb, known for its severe health effects, shows its highest wet season concentration at Location D (3.611 × 10^3 µg/m³), The high concentration of Pb obtained in this work is consistent with the findings of the preceding study by [29]. This implies that, despite the ban of leaded gasoline, Nigerian fuel still contains an appreciable amount of Pb. Additionally, rhodium (Rh), often linked to vehicular catalytic converters, remains elevated at all locations, with a maximum of 10.647 × 10^3 µg/m³ in the wet season at Location B, further underscore traffic-related emissions. Rh, Fe, In, Cd and Sn were the 2nd, 3rd, 4th, 5th and 6th largest pollutants in the study area while Ga, Ga, Ir and Pt were the smallest pollutants. The twenty-one metals detected followed a descending order of Ti > Rh > Fe > In > Cd > Sn > Cr > Ag > Pd > Mn > Ni > Ru > Cu > Pb > W > Co > Zn > Ga > Ge > Ir > Pt. A comparison of the findings of this study with those reported by [29][30][31][32][33] shows a consistent observation of seasonal variations in metal concentrations, which were attributed to changes in vehicular traffic density. These seasonal shifts are also reflected in Table 7, where metals show fluctuations, with the dry season generally exhibiting higher concentrations due to reduced wet deposition and increased atmospheric particulate resuspension, indicating the potential influence of vehicular emissions.

Table 7. Metal Concentrations in ($\mu g/m^3$) x 10^3

Elements	Location A		Location B		Location C		Location D	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Fe	7.944	5.969	7.541	7.706	7.215	8.164	9.318	8.362
Ag	5.087	6.921	5.736	5.214	6.019	5.511	6.166	5.892
Pt	-	-	-	-	-	1.106	1.123	1.423
Pd	4.758	4.222	5.613	4.451	4.883	4.968	6.894	5.282
Rh	9.764	8.126	9.047	10.647	9.132	9.358	7.577	8.243
Ru	2.005	3.47	3.105	2.965	3.075	3.064	2.994	2.978
Ir	0.0026	1.141	1.134	-	-	-	1.268	1.026
Cd	6.767	7.352	6.278	6.944	8.688	7.302	8.999	7.393
Ga	0.215	1.154	2.102	-	1.512	-	1.062	1.106
Ge	0.221	0.001	1.451	-	1.007	1.022	1.029	1.356
Mn	4.432	4.378	5.232	3.683	4.231	3.777	5.381	6.119

Elements	Location A		Location B		Location C		Location D	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Ni	3.419	3.427	6.587	2.102	4.212	4.117	3.674	4.281
Co	1.573	1.472	1.541	1.294	1.563	1.893	2.358	2.025
Cr	5.619	6.125	5.909	5.226	5.909	5.441	6.564	8.995
Zn	1.585	1.361	1.606	1.681	1.573	1.623	1.692	1.671
In	6.821	7.59	7.993	6.572	7.988	6.967	8.885	7.605
Sn	6.451	4.264	6.678	6.257	6.843	6.919	7.721	7.825
W	2.098	1.063	2.113	1.274	2.906	1.074	3.801	2.513
Cu	2.641	2.405	2.449	2.592	2.549	2.319	2.357	3.215
Ti	55.672	54.543	51.837	57.424	53.624	54.845	60.329	62.685
Pb	2.396	1.835	2.589	1.665	1.915	1.368	3.017	3.611

3.4 Pollution assessment of heavy metals

The study analyzed the Enrichment Factor (EF) of various metals during the wet and dry seasons, revealing different levels of anthropogenic influence. Some of the metals that exhibited extreme enrichment include, Platinum (219.15–744.39), Palladium (37,012.18–59,922.57), Rhodium (344,070–535,588.6), Iridium (46.39–7,521.24), Cadmium (1,909.11–2,844.81), Indium (1,108.28–1,477.81), Tin (94.85–135.32), Tungsten (1.67–65.62), and Ruthenium (exceeding 50, at 148,891.7). They are primarily linked to vehicular emissions such as, brake wear and catalytic converters. While Chromium (5.226 – 8.995), Germanium (0.4 – 25.02), Gallium (0.21 – 3.86), Cobalt (1.14 – 4.96), Nickel (2.91– 4.03), Copper (2.319 – 3.215), and Lead (0.77 – 4.64) showed minor to moderate enrichment. In contrast, Iron (0.01), Zinc (0.48 – 0.86), and Manganese (0.29 – 0.5) displayed no enrichment, indicating a natural crustal origin. These findings reveal that Platinum, Palladium, Rhodium, Iridium, Cadmium, Indium, Tin, Tungsten, and Ruthenium are extremely enriched, indicating strong anthropogenic inputs, mainly from vehicular emissions such as brake wear and catalytic converter degradation. Conversely, metals like Germanium, Gallium, Cobalt, Nickel, and Lead exhibited minor to moderate enrichment, suggesting mixed sources that may include limited human activity. Meanwhile, the near absence of enrichment in Iron, Zinc, and Manganese suggests their predominant origin from natural crustal materials. These distinctions highlight the pressing need for targeted air quality management strategies focused on curbing vehicular pollution and mitigating the health and environmental risks associated with heavy metal accumulation.

3.5 Results of the characterization of inorganic ions in particulate matter

Table 8 provides a detailed analysis of sulphate (SO_4^{2-}) and nitrate (NO_3^-) concentrations in particulate matter under dry and wet conditions across various locations, highlighting significant variations and their associated errors. Sulphate levels show a significant reduction in wet conditions, decreasing from 117.30 ± 32.06 µg/m³ to 54.12 ± 11.78 µg/m³ (53.9%) in Location A, 126.69 ± 11.63 µg/m³ to 55.68 ± 31.10 µg/m³ (56.0%) in Location B, 136.25 ± 55.53 µg/m³ to 51.78 ± 25.43 µg/m³ (61.9%) in Location C, and 445.54 ± 98.86 µg/m³ to 173.58 ± 71.97 µg/m³ (61.0%) in Location D. In dry conditions, sulphate levels are highest at Location D (445.54 ± 48.86 µg/m³), approximately 280% higher than at Location A (117.30 ± 32.06 µg/m³). This indicates a significant contribution to traffic emissions from diesel-powered vehicles, which are known to have high sulphur content. Nitrate concentrations follow a similar trend, with the highest values observed in Location D (207.84 ± 36.03 µg/m³), which is over 100% greater than in Location A (72.43 ± 8.11 µg/m³). The sulphate-to-nitrate ratio remains consistently high across all locations, reinforcing the dominance of sulphur-rich

emissions, majorly from fossil fuel combustion.The significant decrease in concentrations under wet conditions suggests variability in emissions or atmospheric washout rates, highlighting the role of precipitation in effectively removing particulate pollutants from the air. These findings emphasize the need for stricter air quality management, especially in high-emission areas, to mitigate the health and environmental impacts of sulphate- and nitrate-rich particulate matter.

Table 8. Characterization Results of Sulphates and Nitrates in Particulates (µg/m^3)

Location	Reading	SO_4^{2-}		NO_3^-	
		Dry	Wet	Dry	Wet
A	1	130.5 ± 9.33	51.01 ± 26.88	70.45 ± 1.40	50.85 ± 0.34
	2	80.75 ± 25.84	44.21 ± 21.68	81.35 ± 6.31	49.55 ± 0.58
	3	140.64 ± 16.50	67.15 ± 35.46	65.49 ± 4.91	50.7 ± 0.23
	Average	117.30 ± 32.06	54.12 ± 11.78	72.43 ± 8.11	50.37 ± 0.75
B	1	120.45 ± 4.41	20.04 ± 25.20	97.4 ± 0.91	39.41 ± 2.29
	2	140.11 ± 9.49	69.65 ± 9.87	105.2 ± 6.43	25.55 ± 7.51
	3	119.5 ± 5.08	77.34 ± 15.31	85.72 ± 7.35	43.56 ± 5.23
	Average	126.69 ± 11.63	55.68 ± 31.10	96.11 ± 9.80	36.17 ± 9.43
C	1	111.23 ± 17.69	45.44 ± 4.48	65.26 ± 14.04	22.4 ± 9.93
	2	199.89 ± 45.00	79.78 ± 19.79	104.1 ± 13.43	47.4 ± 7.75
	3	97.64 ± 27.30	30.11 ± 15.32	85.97 ± 0.61	39.52 ± 2.18
	Average	136.25 ± 55.53	51.78 ± 25.43	85.11 ± 19.43	36.44 ± 12.78
D	1	345.54 ± 50.71	115.31 ± 41.20	145.33 ± 44.20	55.96 ± 6.77
	2	543.21 ± 49.06	254.03 ± 46.88	253.54 ± 32.31	65.14 ± 0.29
	3	447.86 ± 5.38	151.4 ± 15.68	224.66 ± 11.89	75.53 ± 7.06
	Average	445.54 ± 48.86	173.58 ± 31.97	207.84 ± 36.03	65.54 ± 9.79

3.6. Correlation Analysis of SO_4^{2-} and NO_3^- with Significance Testing

Tables 9 and 10 present the Pearson correlation matrix and one-way ANOVA results for sulphate and nitrate concentrations across study locations and seasons. The statistically significant dry-season correlation (r = 0.991, p = 0.009) indicates that sulphate and nitrate are strongly coupled during periods of limited atmospheric removal. This suggests a commonality in emission sources and atmospheric formation pathways**,** most likely linked to anthropogenic activities such as vehicular emissions, fossil fuel combustion, and secondary aerosol formation from SO_2 and NO_x precursors. The stability of the dry atmosphere enhances accumulation and favours synchronized increases in both ionic species. In contrast, the wet-season correlation, while strong (r = 0.881), was not statistically significant (p = 0.12). This reduction in statistical significance can be attributed to enhanced wet deposition, dilution effects, and differential scavenging efficiencies of nitrate and sulphate aerosols. Nitrate particles, being more volatile, are more readily removed during rainfall events, thereby weakening the linear association with sulphates despite shared sources.The contrasting seasonal behaviour underscores the dominant role of meteorological controls in modulating particulate chemical composition during the wet season, whereas source-driven processes prevail during the dry season. These findings reinforce the importance of season-specific air quality management strategies, particularly in pollution hotspots where dry-season accumulation can significantly elevate health and environmental risks.

Table 9. Pearson Correlation Matrix Between SO_4^{2-} and NO_3^- Concentrations

Season	Variable	SO_4^{2-}	NO_3^-
Dry	SO_4^{2-}	1	0.991
	NO_3^-	0.991	1
Wet	SO_4^{2-}	1	0.881
	NO_3^-	0.881	1

Table 10. One-Way ANOVA for Spatial Variation of SO_4^{2-} and NO_3^- Concentrations

(a) Dry Season

Parameter	Ion	F-value	p-value	Significance
Location	SO_4^{2-}	18.6	< 0.01	Significant
Location	NO_3^-	15.2	< 0.01	Significant

(b) Wet Season

Parameter	Ion	F-value	p-value	Significance
Location	SO_4^{2-}	6.9	< 0.05	Significant
Location	NO_3^-	4.1	> 0.05	Not significant

4. Conclusion

Motor vehicles are major contributors to air pollution along the Benin–Ore–Sagamu highway, with pollutant levels frequently exceeding national and international standards. CO, SO_2, $PM_{2.5}$, and PM_{10} concentrations were elevated, while heavy metals such as Rh, Pt, Pd, and Cd indicated predominant vehicular sources. Seasonal variations were observed for inorganic ions, with wet-season precipitation reducing concentrations by 60 %. These results highlight the significant health risks posed by traffic emissions and underscore the urgent need for integrated mitigation measures, including emission controls, improved fuel quality, and targeted traffic management.

Conflict of Interest: The authors declare no conflicts of interest.

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