

Comparative Assessment of Seasonal Variation of Pollutants' Level and Air Quality of Otukpo Metropolis: Spatial Dynamics Analysis and Possible Health Risks

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DOI: <https://doi.org/10.5281/zenodo.18443247>

Published Date: 31-January-2026

Abstract: As the air that man breathes continues to play important roles in human health and well-being, assessment of the atmospheric air components is becoming more crucial in recent years as man seems to be chemically net-round by health-threatening chemical substances as components of the atmospheric air. In the current study, three hours' measurements of concentrations of particulate matters (PM_{2.5} and PM₁₀), gaseous pollutants (CO, CO₂, NO₂, SO₂, NH₃, O₃, and H₂S), and volatile organic compounds (methane-CH₄, and total volatile organic compounds-TVOC), using Digital 4-in-1 Gas Hand-held Monitors and Temtop Air-Quality Monitor while heavy metals were determined using Atomic Absorption Spectrophotometer. The results showed the highest PM_{2.5} of (6.35±0.20), (7.31±0.10), and (5.40±0.25), and PM₁₀ of (9.65±0.30), (10.62±0.10), and (7.68±0.40), for car parks, markets, and residential areas, respectively, in the dry season. Also, the highest CO₂ of (1330±1.10) and (1300±0.6) were recorded for markets and parks, (6.80±0.11) and (6.10±0.12) recorded for parks and markets, respectively, while concentrations of Fe (0.029±0.040), Zn (0.026±0.020), and Cu (0.025±0.030) were obtained in the dry season. In terms of particulates, (dust particle > metallic particle > other suspended solids), while gases (CO₂>CO>NH₃>O₃>NO₂>SO₂>H₂S). Generally, except for dust particles, CO₂, and CO, the concentrations of other pollutants were below the WHO and FME_{env} recommended limits. Additionally, the dry season recorded higher concentrations of particulate matter (PM₁₀ and PM_{2.5}), inorganic and organic gaseous pollutants, and heavy metals. These findings showed that Otukpo Metropolis is minimally polluted with dust, CO₂, and CO, thereby calling for urgent attention by governments at all levels.

Keywords: Particulates, Parks, Markets, Heavy Metals, Dry season.

1. INTRODUCTION

The current global trend in research courses on the assessment of air quality of certain atmospheric locations is towards an appreciation of the quality of life and the relevance of man's immediate environments, particularly the soil, water, and the atmospheric air in which man breathes. This of course could be aligned to the fact that in pursuance of urban development, agricultural mechanization, mineral exploration and exploitation, industrial and technological development for the well-being of human society, willingly or unwillingly the humans' occupants of the planet Earth have rendered the Earth ecosystem particularly the atmospheric air unfit for breathing to sustain human survival [1], due to introduction of harmful foreign matters into the atmospheric air, that deteriorate its quality and renders its inhalation detrimental to the human health. Now more than ever, the pages of medical history are filled and littered with stories about toxic heavy metals, particularly lead and mercury in the atmospheric air, and their grave consequences on human health. For instance, even before now, according to [2], hundreds of years ago, madness among the mirror-makers of Venice and the Hatters of London was linked to inhalation of mercury vapours, which were a by-product of the manufacturing process. By chemical scientific pollution sense, mercury is both a hazardous substance, as it can cause skin irritation, and also a toxin, as it can equally have deadly effects on the nervous system, where the latter is mercury's most well-known and serious threat to human health [2].

Notably, in the atmosphere, heavy metals can exist in several elemental forms and chemical compositions, including particulate forms, vapour, and in combination with ions such as sulphides (S^{2-}), carbonates (CO_3^{2-}), and oxides (O_2^{2-}) [3]. Primarily, this difference in the composition of metals for different forms (phylogenesis) has been reported to affect various atmospheric natural chemical processes, such as electron-transfer reactions, atmospheric molecular deposition, diffusivity, precipitation equilibria, and the solubility of substances in saturated atmospheric water vapour [3]. More often, however, the heavy metal ions can also get accumulated in the atmosphere through certain chain reactions, thereby contaminating various natural processes, and stimulate degradation of the environment and human health [3,4,5]. Apart from heavy metals, other substances known to be present in atmospheric air may include organic molecules such as volatile hydrocarbons, dust particles, volatile herbicide and pesticide compounds, and even pathogenic agents, as well as chlorofluorocarbons. Although it has become a common knowledge that natural phenomena such as Earth quake, hurricane, whirlwinds, and evaporation are among the known natural phenomena that contribute immensely to the global air pollution problems, it is equally important to note that, outdated agricultural practices such as bush burning, vehicular movement activities, domestic and industrial generating plants and various industrial processes are often the key identified anthropogenic processes that usually lead to the introduction of foreign air components. Based on the foregoing, it has been reported that heavy metals are wholly discharged into the environment through vehicular and other combustion engine emissions [6].

Furthermore, among the various industrial processes that have been identified as anthropogenic means of introducing gaseous foreign substances into the atmosphere in concentrations that become harmful to man and other living organisms, including refinery operations, foundries, blasting, metallurgy, and a lot others, there is also a general recognition that mining and mineral processing operations present, in general large volumes of tailings and gaseous emissions into the atmospheric, besides several environmental impacts [7,8]. So far, previous studies on the assessment of the pollution level and air quality in the literature on the Benue region in particular and Nigeria at large have highlighted the general concerns regarding air quality, noting that the ambient air often falls below national and international standards [9,10]. Also, Nwachukwu and Ugwuanyi [11] have reported a survey of health effects of air pollution on peasant farmers in Benue State, Nigeria, while Ugwuanyi and Sombo [12], reported fine particulate pattern distribution in Makurdi and Otukpo Metropolis, Benue State, Nigeria. In another study, Ameh *et al.* [13] reported on the assessment of some gaseous emissions in traffic areas in Makurdi Metropolis, Benue State, Nigeria, while Adebayo [14] reported a concise review on urban air pollution and its effects on health, safety, and the environment in Nigeria, and Ndubueze *et al.* [15], reported the assessment of air quality parameters in the vicinity of selected dumpsites in Owerri Metropolis, Imo State, Nigeria. In addition, Onoja *et al.* [16], have reported on the assessment of air quality levels in the major towns across Benue Zone C, Nigeria, and the concentrations of air pollutants in Otukpo were related to temperature and relative humidity. In that study, Onoja *et al.* [16] concluded that the mean concentrations of some of the pollutants increase with the temperature and relative humidity.

Meanwhile, within different time frames, various techniques have come into use and have been extensively utilized for analysis of the atmospheric air quality [3]. Among the commonest techniques often used for the analysis of gaseous air pollutants are the use of direct-reading instruments, such as hand-held gas monitors and the Haz-Dust Sampler [9, 12]. In

Onoja *et al.* [16], air pollutant concentrations were monitored using direct-reading instruments, such as Gasman Hand-held Gas Monitors and JLDG Air Quality Tester.

In an effort to raise awareness about the perils caused by natural phenomena such as earthquakes, hurricanes, whirlwinds, and other natural processes that emit hazardous chemical substances into the atmospheric air, the global interest and relentless drives towards the assessment of global air quality have been rekindled. This interest has also grown in terms of academic research on how air quality affects the public health of the general population living in a particular location. In that regard, there is no doubt that the various reports or researchers have contributed to the acknowledgement of air quality as a prerequisite for the sustenance of human good health. In fairly recent times, particularly in Benue State, Nigeria, interest has also grown in terms of academic research on how to assess and establish quantitatively the quality of air that the generality of the human population in Otukpo metropolis breathes. Even as such scientific efforts were being made in the past, with researchers only identifying the air pollutants, there appears to be no study or information available in the literature on the spatial dynamics and seasonal variation of air pollutants of Otukpo Metropolis. Nevertheless, a detailed analysis of the spatial distribution of key pollutants across Otukpo's distinct urban micro-environments (e.g., garages and suburbs) is crucial for developing effective, localized mitigation policies. This paper therefore addresses this gap by assessing the pollution levels of particulate matter (PM), inorganic gaseous pollutants, carbon (II) oxide (CO), nitrogen (IV) oxide (NO₂), and sulphur (IV) oxide (SO₂) and organic gaseous pollutants (formaldehyde, total volatile organic compounds, and methane), across varying land-use/land-cover (LULC) types in Otukpo and analysing their temporal, seasonal and spatial dynamics. Additionally, heavy metal concentrations in the ambient air of Otukpo Metropolis are analysed. Following a stronger global concern for air quality to improve human health conditions, the determination of heavy metals' concentrations in the air is also essential to possibly diminish their toxic effects and the ill effects of heavy metal ions on living beings and the environment.

A meaningful correlation requires that a reasonable range of parameters should be explored and it is traditionally relevant to establish that the spatial dynamics of the study is intended to establish correlations between air pollutants and their possible sources and the quantities as research reports have not always agreed as to the exact quantity of these air pollutants could be harmful to people and researchers are usually differing in what they consider important and concentration capable of being harmful to man health [2,17]. In this regard, it is also important to emphasise that the present study is not intended to discourage the publication of air pollution assessment reports by any group of researchers, government agencies, or companies. Quite the contrary, it is necessary to continue generating valuable information, but with a greater rigour and transparency, particularly concerning the data of quantitative air quality, spatial dynamics, and seasonal variation of concentrations of air pollutants in the ambient air of Otukpo Metropolis, Benue State, Nigeria. Again, it should, however, be established that a comprehensive knowledge of the chemical composition of various constituents in the ambient air of Otukpo Metropolis is crucial and of high necessity, not only to establish the data base of air quality of the Metropolis, but to avert the possible danger and challenges to human health. In efforts to avert these dangers, and coupled with the fact that scientists have long known that human health is often affected by complex, interrelated factors of heredity and environment [2,17]. As the indigenous dwellers of Otukpo Metropolis are known for economic and agricultural activities, engaging in certain economic activities and agricultural practices may have also led to the release of an enormous quantity of air pollutants into the atmosphere. Nevertheless, to reduce such a volume of air pollutants, there must be an appropriate urban planning so that the air quality of the area can be preserved.

In recent times, air pollution has continued to present one of the most critical environmental challenges in rapidly urbanising cities in the developing nations of the world, particularly across Nigeria, contributing significantly to morbidity and premature mortality rates in the country [18]. Otukpo, a major town in Benue State, Nigeria, located in Benue Southern Senatorial Zone (Zone C), which serves as a vital commercial and transportation hub in the North Central region of Nigeria, is currently experiencing increasing urbanization and vehicular traffic, reconstruction of the major Federal Government road (highway) linking the East, West and the Southern part of Nigeria, and influx of people especially staff and students due to the establishment of a new Federal University, thereby leading to concerns about its ambient air quality. Sincerely, it is believed that the rapid urbanisation of Otukpo Metropolis, coupled with poor infrastructural development of the area, reliance on combustion-based energy sources (e.g., generators, firewood, and refuse burning), and an ageing vehicular fleet, may suggest a high potential for detrimental air quality [13,19]. This paper, therefore, presents a comprehensive assessment of air quality and pollution levels in the Otukpo metropolis, with a specific focus on spatial variation and the concentration of Particulate Matter (PM) and gaseous pollutants.

2. MATERIALS AND METHODS

Study Location

The present study was carried out in Otukpo Metropolis in Otukpo Local Government Area of Southern Senatorial Zone (Zone C), of Benue State, Nigeria, where certain locations in the Metropolis were chosen for data collection. Hence, the work was conducted at very busy motor parks, markets, and in densely populated residential areas in Otukpo Metropolis and its environs. For each study location, four park/busy road locations, four marketplaces, and four residential areas were considered, and the GPS coordinates of the study locations are shown in Table 1. Also, Figure 1 shows the location of Otukpo, in Benue State, Nigeria, where the study was conducted.

Table 1: GPS Coordinates of Study Locations in Otukpo Metropolis, Benu State

GPS Coordinates of Study Locations in Otukpo Metropolis, Benu State		
Location	Latitude	Longitude
Parks A by Joy FM	7.2169°N	8.1226°E
Parks B by the Railway	7.2150°N	8.1247°E
Parks C by Conoil	7.2086°N	8.1322°E
Parks D by E. R	7.1982°N	8.1393°E
Tiv Market	7.2159°N	8.1237°E
Main Market	7.2135°N	8.1290°E
Rice Mill Market	7.1920°N	8.1475°E
Market by E. R	7.1985°N	8.1390°E
GRA	7.1930°N	8.1464°E
Effa Quarters	7.2180°N	8.1213°E
St Francis	7.1986°N	8.1390°E
Otada Village	7.2167°N	8.1500°E

Sample Collection

In each case, 250 g of settled dust samples were collected from the top of buildings at motor parks/busy roads, marketplaces, and residential areas in sterilised polyethene bags, and the samples were taken to FUHSO Chemistry/Biochemistry Laboratory and then were stored under regulated temperature for 48 hours before they were prepared for heavy metal analysis. Meanwhile, dust samples were collected each month between the months of October and March, for the six-month dry season investigation, while the rainy season samples were collected between the months of April and September.

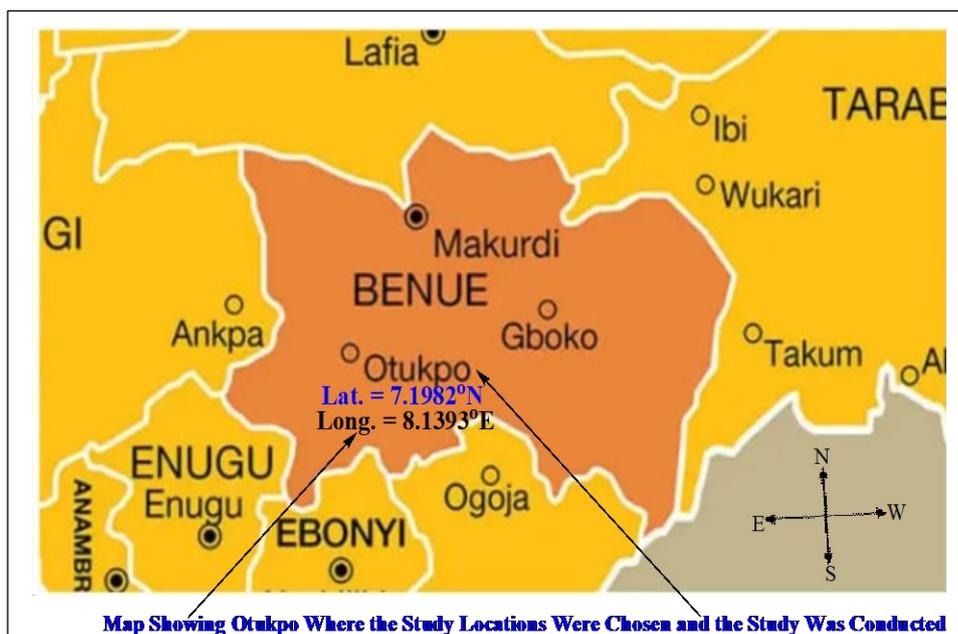


Figure 1: Map of Benue State, Nigeria, Showing Otukpo Local Government Area

Sample Preparation

Analysis of heavy metals was done using dust samples collected from different study locations. The dust samples were air-dried, screened, sieved, and digested. Thereafter, the different dust samples were digested and extracted using 0.1 % perchloric acid. Then, the dust extracts were analysed for heavy metals using the BUK Atomic Absorption Spectrophotometer.

Determination of Heavy Metals

A total of eleven heavy metals including Chromium (Cr), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Arsenic (As), Cadmium (Cd), Mercury (Hg) and Lead (Pb) were analysed to determine their presence in the digested samples using BUK Atomic Absorption Spectrophotometer (Model AAS-205) by selecting appropriate wavelength for each element [20].

Measurement/Determination of Concentration of Pollutants

Three hours’ measurement of concentrations of particulate matters (fine particulate matter-PM_{2.5} and inhalable coarse particulate matter-PM₁₀), inorganic gaseous pollutants (carbon (II) oxide-CO, Carbon (IV) oxide-CO₂, Nitrogen (IV) oxide-NO₂, Sulphur (IV) oxide-SO₂, Ammonia-NH₃, ozone-O₃, and Hydrogen sulphide-H₂S), and volatile organic compounds (methane-CH₄, Formaldehyde-HCHO, Total Volatile Organic Compounds-TVOC) for data collection during the study period were done between the hours of 7-9 am, 12-3 pm and 5-8 pm using Digital Compound 4 in 1 Gas Hand-held Monitors (coloured LCD India) and Temtop Air Quality Monitor CO₂ Detector (M2000 2nd, Temtop PMD331) Portable Particle Counter – Handheld, USA). The total number of days, months, and readings taken per day, as well as the readings taken during the dry and rainy seasons, are shown in Table 2.

Table 2: The Total Number of Days, Months, and Instrumental Readings Taken During the Study Period

Items	Time of Taking Readings at Four Study Locations Each Day					
	Morning Data Collect.		Afternoon Data Collect.		Evening Data Collect	
Time	DS	RS	DS	RS	DS	RS
Season						
Duration	6-Month	6-Month	6-Month	6-Month	6-Month	6-Month
Days/Wk	6	6	6	6	6	6
Days/Month	24	24	24	24	24	24
Total Days	144	144	144	144	144	144
No. of Reading	6	6	6	6	6	6
Total Readings	20,736	20,736	20,736	20,736	20,736	20,736

DS = Dry Season; RS = Rainy Season

A total of six (6) readings were taken at each location, morning, afternoon, and evening, giving a total of twenty-four readings (24) per day and a total of 144 readings in 6 days of the week, considered in this study. Thereafter, and thereafter the mean value was evaluated. While the Digital Compound 4 in 1 Gas Hand-held Monitors (coloured LCD India) were used for measuring the concentration of inorganic gaseous pollutants and particulates (H₂S, CO, NO₂, SO₂, NH₃, and O₃), and (PM_{2.5} and PM₁₀), the Temtop Air Quality Monitor CO₂ Detector (M2000 2nd, Temtop PMD331) Portable Particle Counter – Handheld, USA) was used for measuring the concentrations of HCHO, TVOC, and CO₂.

Statistical Analysis

All data in this work are presented as means ± Standard Deviation. The means and standard deviations were determined for each sample, and the standard deviation was obtained using the formula: Standard Deviation (SD) = $\sqrt{\sum(xi-\bar{x})^2/N-1}$ or

$$\sqrt{\frac{\sum (xi - \bar{x})^2}{N - 1}} \dots\dots\dots \text{(Equ. 1). Where } xi = \text{Individual value; } \bar{x} = \text{Mean value, and } N = \text{Number of}$$

measurements/observations [20]. The data obtained for each pollutant were computed and statistically analysed using Analysis of Variance (ANOVA) to test for significant differences across seasons and sampling locations, thereby establishing the spatial dynamics of pollution, and the results were compared with national and international recommended standard values for drawing accurate inferences [9].

3. RESULTS AND DISCUSSION

(i) Particulate Matters (PM_{2.5} and PM₁₀)

The results of the mean concentration of particulate matters (fine particulate matter-PM_{2.5}) and (inhalable coarse particulate matter-PM₁₀) for car parks and busy roads in table 3, obtained in the dry season (six months), have shown that the mean concentration of dust particles is much higher than that of metallic particles and that of other suspended particles (dust particles > metallic particles > other suspended particles). From the results obtained in this study, it has been observed that the mean concentrations of the inhalable coarse particulate matter (PM₁₀) in the car parks/busy roads are in the range of 0.046-0.048 mg/m³, and therefore were above the Nigerian Federal Ministry of Environment’s recommended limit of 0.23 mg/m³ for 1 hour and 0.15 mg/m³ for the 24 hours duration. However, the obtained results are below 50 µg/m³ and fall within the 45 µg/m³ recommended permissible limit by FMEnv and WHO, respectively. Furthermore, the values of inhalable coarse particulate matter (PM₁₀) obtained in this study for metallic particles and other suspended solid particles were within the recommended permissible limit of 0.05 mg/m³ by the Nigerian Federal Ministry of Environment and 0.045 mg/m³ recommended by WHO [21]. Similarly, the results of fine particulate matter (PM_{2.5}) obtained in the present study for dust particles are much higher than the 15 µg/m³ (or 0.015 mg/m³) recommended permissible limit by WHO and 35 µg/m³ (or 0.035 mg/m³) recommended permissible limit by FMEnv.

Table 3: Results of Concentrations of Particulates Measured at Car Parks and Busy Roads During Dry Season

Study Location (mg/m ³)	Results of Concentrations of Particulates Measured in Parks in the Dry Season					
	Dust Particles		Metallic particle		Other Suspend Solids	
	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀
Parks A	0.033±0.50	0.047±0.12	0.024±0.02	0.044±0.2	0.011±0.01	0.028±0.01
Parks B	0.034±0.20	0.046±0.60	0.01±0.010	0.02±0.10	0.014±0.00	0.036±0.00
Parks C	0.0332±0.10	0.048±0.30	0.032±0.01	0.049±0.0	0.007±0.02	0.025±0.02
Parks D	0.032±0.15	0.046±0.25	0.018±0.02	0.026±0.1	0.020±0.01	0.048±0.01

Results presented in Means ± Standard Deviation; Parks A= By Joy FM; Parks= By Railway; Parks C= By Conoil; Parks D= By Enugu Roundabout; Results differences were significant at p<0.05

Meanwhile, the results obtained in this investigation, as concentrations of particulate matter (fine particulate matter-PM_{2.5}) and (inhalable coarse particulate matter-PM₁₀) for car parks and busy roads are higher than 3.98 µg/m³ and 6.30 µg/m³ of fine particles matters (PM_{2.5}) and 6.60 µg/m³ and 9.60 µg/m³ of inhalable coarse particulate matter (PM₁₀) reported by Onoja *et al.* [16], for busy roads and garages, respectively. Nevertheless, the results obtained for PM_{2.5} and PM₁₀ in this study are lower than the 0.168 mg/m³ and 0.148 mg/m³ reported by Ndubueze *et al.* [15] for Owerri roads dumpsites, lower than those reported by Abulude *et al.* [22] for Ibadan, but higher than those of Abeokuta, Ado-Ekiti, Akure, and Osogbo reported by Abulude *et al.* [22]. Likewise, the results obtained in the current study are consistent with those reported by Odubanjo *et al.* [19] for Abuja (50.77 µg/m³), Lagos (43.88 µg/m³), Benin City (56.43 µg/m³), Osogbo (36.68 µg/m³), and Anyigha (16.11 µg/m³).

Table 4: Results of Concentration of Particulates Measured at Car Parks and Busy Roads During Rainy Season

Study Location (mg/m ³)	Results of Concentrations of Particulates Measured in Parks in Dry Season					
	Dust Particles		Metallic particle		Other Suspend Solids	
	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀
Parks A	0.022±0.10	0.038±0.15	0.016±0.01	0.035±0.02	0.011±0.03	0.017±0.02
Parks B	0.0218±0.50	0.0375±0.40	0.01±0.015	0.03±0.015	0.012±0.02	0.022±0.01
Parks C	0.0215±0.30	0.0383±0.20	0.020±0.02	0.037±0.01	0.006±0.00	0.018±0.05
Parks D	0.0210±0.11	0.038±0.12	0.015±0.01	0.028±0.02	0.016±0.02	0.028±0.0

Results presented in Means ± Standard Deviation; Parks A= By Joy FM; Parks= By Railway; Parks C= By Conoil; Parks D= By Enugu Roundabout; Results differences were significant at p<0.05

The results of the mean concentration of particulate matters (fine particulate matter-PM_{2.5}) and (inhalable coarse particulate matter-PM₁₀) for car parks and busy roads obtained during the six months' rainy season in table 4, have shown that the mean concentration of dust particles was still higher than that of the metallic particulates and other suspended particles in the order of (dust particles > metallic particles > other suspended particles). Comparatively, the results obtained in Table 4 showed that particulate concentrations decrease drastically during the rainy season compared to those in the dry season. This observation on the seasonal spatial variation of concentration of particulate matter (PM) is consistent with the report of [12], and ordinarily, the simplest explanation to this observation and the cause of such a decrease in the concentration of the particulates in the rainy season may be attributed to reduced harmattan dust and biomass burning. Additionally, the authors have argued that rainwater, due to increased rainfall, may have washed away some particulates, especially the dust particles, during the rainy season. More importantly, it is imperative to equally establish that the results obtained in the rainy season are within the standard recommended permissible limit of 40 µg/m³ by FME_{env}, 15 µg/m³ by WHO, and 35 µg/m³ by NAAQS, for fine particulate matter (PM_{2.5}), while the values of inhalable coarse particulate matter (PM₁₀) are below the standard recommended permissible limit of 150µg/m³ by FME_{env}, 45 µg/m³ by WHO, and 150 µg/m³ by NAAQS.

Table 5: Results of Concentration of Particulates Measured at Markets During Dry Season

Study Location (mg/m ³)	Particulates and Concentrations Measured in the Rainy Season					
	Dust Particles		Metallic particle		Other Suspend Solids	
	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀
Market M _A	0.043±0.40	0.050±0.3	0.028±0.01	0.042±0.01	0.015±0.02	0.032±0.00
Market M _B	0.041±0.10	0.051±0.5	0.012±0.00	0.03±0.010	0.018±0.01	0.041±0.02
Market M _C	0.045±0.30	0.052±0.10	0.026±0.02	0.042±0.04	0.010±0.00	0.029±0.01
Market M _D	0.041±0.25	0.048±1.50	0.012±0.01	0.032±0.02	0.015±0.01	0.034±0.05

Results presented in Means ± Standard Deviation; Market M_A=Tiv Market; M_B=Main Market; M_C=Rice Mill Market and M_D=Market by Enugu Roundabout; Results differences were significant at p<0.05

The results of the mean concentration of particulate matters (fine particulate matter-PM_{2.5}) and (inhalable coarse particulate matter-PM₁₀) for markets obtained during the six months' dry season in table 5, showed that the mean concentration of dust particles was higher than that of the metallic particulates and other suspended particles in the order of (dust particles > metallic particles > other suspended particles). However, the results of fine particulate matter (PM_{2.5}) dusts, obtained in this study in markets in Otukpo Metropolis, are in the range of 0.043-0.045 mg/m³, while those of inhalable coarse particulate matter (PM₁₀) are in the range 0.048-0.052 mg/m³. These obtained results showed that the fine particulate matter (PM_{2.5}) values are higher than the standard recommended permissible limit of 40 µg/m³ by FME_{env}, 15 µg/m³ by WHO, and 35 µg/m³ by NAAQS, while the values of inhalable coarse particulate matter (PM₁₀) are below the standard recommended permissible limit of 150 µg/m³ by FME_{env} and NAAQS but higher than 45 µg/m³ recommended by WHO. Still, the results of concentrations of particulate matters; fine particulate matter (PM_{2.5}) and inhalable coarse particulate matter (PM₁₀) for markets in Otukpo Metropolis obtained in this study are higher than 9.50 µg/m³ of fine particles matters (PM_{2.5}) and 8.70 µg/m³ of inhalable coarse particulate matter (PM₁₀) reported by Onoja *et al.* [16], for busy road and garage respectively. Interestingly, the results of particulate matter (PM_{2.5} and PM₁₀) obtained in this study are consistent with PM_{2.5}=40.80/PM₁₀=50.77 for Abuja, PM_{2.5}=37.39/PM₁₀=43.88 for Lagos, PM_{2.5}=46.19/PM₁₀=56.43 for Benin City, PM_{2.5}=28.88/PM₁₀=36.68 for Osogbo, and PM_{2.5}=14.36/PM₁₀=16.11 µg/m³ for Anyigha reported by Odubanjo *et al.* [19]. Remarkably, these results for (PM_{2.5} and PM₁₀) are in agreement with the reports of Abulude *et al.* [22] and Ndubueze *et al.* [15].

Table 6: Results of Concentration of Particulates Measured at Markets During the Rainy Season

Study Location (mg/m ³)	Particulates and Concentrations Measured in the Rainy Season					
	Dust Particles		Metallic particle		Other Suspend Solids	
	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀
Market M _A	0.023±0.10	0.047±0.11	0.010±0.03	0.031±0.02	0.013±0.01	0.021±0.01
Market M _B	0.024±0.40	0.048±0.10	0.011±0.02	0.020±0.01	0.014±0.00	0.026±0.02
Market M _C	0.027±0.10	0.049±0.30	0.015±0.01	0.036±0.00	0.007±0.02	0.019±0.00
Market M _D	0.021±0.18	0.045±1.25	0.010±0.00	0.021±0.03	0.011±0.01	0.022±0.01

Results presented in Means ± Standard Deviation; Market M_A=Tiv Market; M_B=Main Market; M_C=Rice Mill Market and M_D=Market by Enugu Roundabout; Results differences were significant at p<0.05

At this point, the results in Tables 5 and 6 showed a comparison with the spatial dynamics of seasonal variation of particulate matters of markets in Otukpo Metropolis in the dry and rainy seasons. From the results, it has been recognized that the dry season has higher particulate matter in the atmospheric air within marketplaces in Otukpo Metropolis compared to the rainy season. This observation seems to be the commonest trend towards particulate distribution in the atmosphere of Otukpo Metropolis, particularly in hotspots with high combustion activities like parks, busy roads, markets with various machine activities, grinding, blending, and soldering. As noted before, from parks/busy roads, the dry season period considered in this study (October to March) generally records higher concentrations of particulate matter (PM₁₀ and PM_{2.5}) than the rainy season. Again, the original interpretation of this trend is primarily due to the increase in Harmattan dust, increase in biomass burning activities (including bush burning) from farming activities, wood-based industrial activities, poor atmospheric dispersion under stable, dry conditions [9], and increased road construction activities. A similar conclusion has been reached in this regard by Nwachukwu and Ugwuanyi [11].

Meanwhile, the results of particulate matter (PM_{2.5} and PM₁₀) obtained in the rainy season of this study (Table 6) showed that the concentration of dust particles is higher than that of metallic and other suspended solids. In addition, the results are lower than the recommended standard permissible limit of 35-40 µg/m³ by FMEnv, 15 µg/m³ by WHO, and 35 µg/m³ by NAAQS for PM_{2.5}, and 50-150 µg/m³ by FMEnv, 45 µg/m³ by WHO, and 150 µg/m³ by NAAQS for PM₁₀. Importantly, the results are lower than those reported by [16], but are consistent with those reported by [9,15,19] and [22].

Table 7: Results of Concentration of Particulates Measured at Residential Areas During the Dry Season

Study Location (mg/m ³)	Results of Concentrations of Particulates Measured in Parks in the Dry Season					
	Dust Particles		Metallic particle		Other Suspend Solids	
	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀	PM _{2.5}	PM ₁₀
GRA	0.022±0.30	0.026±0.20	0.019±0.00	0.022±0.01	0.014±0.01	0.020±0.01
Effa Quarters	0.024±0.25	0.028±0.40	0.017±0.05	0.020±0.02	0.015±0.01	0.017±0.04
St Francis	0.025±0.18	0.027±0.50	0.020±0.02	0.021±0.04	0.011±0.00	0.018±0.01
Otada Village	0.008±0.11	0.006±0.18	0.005±0.02	0.006±0.01	0.006±0.03	0.005±0.00

Results presented in Means ± Standard Deviation; Otada Village = the control site; Results differences were significant at $p < 0.05$

The results of the mean concentration of particulate matters (fine particulate matter-PM_{2.5}) and (inhalable coarse particulate matter-PM₁₀) for residential areas obtained during the six months' dry season period of this investigation in Table 7, showed that the residential areas, while generally have lower particulate matters than parks/garages, roads traffic hotspots, and markets still recorded high levels of fine particulate matters between the range of 0.010-0.025 mg/m³ (or 10-25 µg/m³) for PM_{2.5} and 0.008-0.028 mg/m³ (8.0-28 µg/m³) for PM₁₀, and the particulate matters may probably be produced from household activities, including the burning of solid biomass (wood) for cooking and the open burning of refuse/domestic wastes in agreement with the report of [12]. In addition, the atmospheric air particulate matters of the low-density and high-density areas (i.e., low and high populated) residential areas) may equally be attributed to air movement and breezes, where particulate matters may be moved or circulated from points of generation to other locations including the residential areas. Meanwhile, it should also be noted that in all residential areas (the low-density zones, such as St. Francis residential areas) and high-density zones (GRA and Effa Quarters). However, there are low vehicular activities, domestic cooking, power generation, and household waste burning are still very common.

In the meantime, the results of the suburban area of Otukpo (Otada village) chosen as the control site of this study (which is an area with minimal vehicular or industrial and other generating machines' emissions), showed that the concentration of particulate matters are relatively lower than that of all other residential areas and also much lower than those of the parks and markets results obtained in this study. While the control site recorded PM_{2.5} in the range of 0.005-0.008 mg/m³ for dust, metallic and other suspended solid particles, the PM₁₀ was in the range of 0.005-0.006 mg/m³, indicating that the air quality of the control site is good as the results of its particulate matters are within the recommended range of 0-50 µg/m³ by AQI, 00.0-15.4 µg/m³ of PM_{2.5}, and 0.0-54 µg/m³ for PM₁₀, by US-EPA for good quality of air. Furthermore, the results of

particulate matter obtained for other low-populated and high-populated residential areas are higher than $3.45 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and $4.55 \mu\text{g}/\text{m}^3$ for PM_{10} reported by Onoja *et al.* [16], for the residential zone of Otukpo. However, the results of dry and rainy seasons for Otukpo low-density and high-density residential areas are lower than those reported by Odubanjo *et al.* [19], Abulude *et al.* [22], and Ndubueze *et al.* [15].

Table 8: Results of Concentration of Particulates Measured at Residential Areas During the Rainy Season

Study Location	Results of Concentrations of Particulates Measured in Parks in the Dry Season					
	Dust Particles		Metallic particle		Other Suspend Solids	
	$\text{PM}_{2.5}$	PM_{10}	$\text{PM}_{2.5}$	PM_{10}	$\text{PM}_{2.5}$	PM_{10}
GRA	0.0102±0.20	0.004±0.12	0.001±0.01	0.003±0.03	0.001±0.01	0.002±0.00
Effa Quarters	0.0105±0.15	0.003±0.10	0.001±0.01	0.002±0.16	0.001±0.00	0.002±0.01
St Francis	0.014±0.35	0.010±0.20	0.003±0.00	0.004±0.01	0.002±0.01	0.001±0.01
Otada Village	0.0010±0.10	0.001±0.15	0.000±0.00	0.001±0.01	0.001±0.00	0.002±0.00

Results presented in Means ± Standard Deviation; Otada Village = the control site; Results differences were significant at $p < 0.05$

Moreover, the results in Tables 7 and 8 showed a comparison with the spatial dynamics of seasonal variation of particulate matter in low-density, high-density, and suburban residential areas in Otukpo Metropolis in the dry and rainy seasons. It is necessary to understand that the results have revealed that the dry season still has higher particulate matter ($\text{PM}_{2.5}$ and PM_{10}) than the rainy season. Overall, the results of particulate matter of residential areas obtained in the rainy season in Table 8 are higher than those reported by [16], but are lower than those reported by [19,22], and [15]. Additionally, the results are lower than the recommended permissible limit of $40 \mu\text{g}/\text{m}^3$ by FMEnv, $10 \mu\text{g}/\text{m}^3$ by WHO, $35 \mu\text{g}/\text{m}^3$ by NAAQS for $\text{PM}_{2.5}$, and $150 \mu\text{g}/\text{m}^3$ by FMEnv and NAAQS, and $45 \mu\text{g}/\text{m}^3$ by WHO for PM_{10} . Essentially, and in general, it has been noted that consistently the dry season has recorded higher $\text{PM}_{2.5}$ and PM_{10} concentrations in Otukpo Metropolis, although the results of particulate matters especially dusts obtained in the current study in different study locations such as parks/busy roads, markets, low-populated and dense-populated residential areas are significantly higher than the previously reported results by Onoja *et al.* [16], however, they are within the National and International recommended acceptable permissible limits, while the results of the suburban residential area chosen as control has been used to compare with that of other study locations.

(ii) Gaseous Air Pollutants (Inorganic Gaseous Pollutants)

The results of the gaseous inorganic pollutants obtained in this study for parks/busy roads in Table 9 showed high concentrations of carbon (IV) oxide (CO_2) and carbon (II) oxide (CO) across different parks/busy roads, especially in the dry season. Also, across the parks/busy roads in Otukpo Metropolis, the results in Table 9 further showed that the concentration of ozone (O_3) and ammonia (NH_3) were next, then that of hydrogen sulphide (H_2S), sulphur (IV) oxide (SO_2), and nitrogen (IV) oxide (NO_2). Notably, while Parks D recorded the highest results for CO_2 ($1.14 \text{ mg}/\text{m}^3$), Parks C recorded the highest results for CO ($0.56 \text{ mg}/\text{m}^3$) and O_3 ($0.036 \text{ mg}/\text{m}^3$), as Park A recorded the highest value for NH_3 ($0.015 \text{ mg}/\text{m}^3$). Nevertheless, the results of CO_2 , CO, and NH_3 obtained in the current study are lower than the National and International recommended standard permissible limits of 40,000 ppm (or $72,000 \text{ mg}/\text{m}^3$) and 1000 ppm for CO_2 recommended by W.H.O and FMEnv, $10.00\text{-}20.00 \text{ mg}/\text{m}^3$ (or $10,000 \mu\text{g}/\text{m}^3$) for CO recommended by W.H.O and FMEnv and $0.6 \text{ mg}/\text{m}^3$ in 24 hrs for NH_3 , recommended by FMEnv. Meanwhile, with the results of the spatial dynamics and the seasonal variation of concentrations of the gaseous pollutants in Table 9, there is increasing evidence that the rainy season has lower concentrations of the gaseous inorganic pollutants than the dry season. The traditional explanation and the rationale for this is that most of the gaseous pollutants are readily soluble in water and are easily dissolved in rainwater in a reasonable quantity, thereby reducing their quantities in the atmospheric air in the rainy season.

Table 9: Results of Gaseous Pollutants from Motor Parks/Busy Roads for Dry and Rainy Seasons

Gas	Results of Gaseous Inorganic Pollutants from Each Study Location (mg/m ³)							
	Parks A		Parks B		Parks C		Parks D	
	DS	RS	DS	RS	DS	RS	DS	RS
CO ₂	1.12±5.50	0.56±1.50	1.13±1.10	0.565±0.30	1.132±0.3	0.566±0.00	1.14±0.6	0.570±0.50
CO	0.54±0.10	0.558±0.5	0.55±0.20	0.548±0.10	0.56±0.11	0.544±0.20	0.55±0.20	0.549±0.12
NH ₃	0.015±0.10	0.011±0.01	0.013±0.15	0.010±0.00	0.009±0.01	0.005±0.01	0.014±0.12	0.010±0.00
H ₂ S	0.005±0.01	0.003±0.00	0.004±0.10	0.003±0.11	0.006±0.10	0.004±0.01	0.005±0.10	0.004±0.01
SO ₂	0.004±0.01	0.002±0.15	0.005±0.02	0.002±0.00	0.002±0.10	0.001±0.20	0.002±0.50	0.001±0.15
NO ₂	0.003±0.11	0.001±0.00	0.006±0.10	0.004±0.15	0.002±0.00	0.001±0.14	0.002±0.00	0.001±0.01
O ₃	0.026±0.10	0.022±0.20	0.032±0.12	0.028±0.10	0.036±0.10	0.032±0.20	0.030±0.00	0.026±0.10

Results presented in Means ± Standard Deviation; DS=Dry Season; RS=Rainy Season; Parks A= By Joy FM; Parks B= By Railway; Parks C= By Conoil; Parks D= By Enugu Roundabout; Results differences were significant at $p < 0.05$

On the other hand, although the obtained results in this study are in the range of previous studies' results, a critical comparison of the results of the gaseous inorganic pollutants in Table 9 for parks/busy roads has revealed that the results for CO, and NO₂ were consistent with those reported by Onoja *et al.* [16], the result of CO₂ and SO₂ were higher than that reported by [16], while the result of O₃ was lower than those reported by Onoja *et al.* [16], for busy road and garage. Besides, the results of this study are consistent with those reported by Abulude *et al.* [22], and Ndubueze *et al.* [15], except that CO₂, CO, and NH₃ were not reported by Abulude *et al.* [22], and the values of CO₂, O₃, CO, and NO₂ pollutants reported by Ndubueze *et al.* [15], are somewhat higher than the results obtained in this study.

Table 10: Results of Gaseous Pollutants from Markets for Dry and Rainy Seasons

Gas	Results of Gaseous Inorganic Pollutants from Each Study Location							
	Market M _A		Market M _B		Market M _C		Market M _D	
	DS	RS	DS	RS	DS	RS	DS	RS
CO ₂	1.20±0.10	0.60±0.20	1.21±0.10	0.604±0.1	1.24±0.20	0.62±0.30	1.15±0.20	0.575±0.3
CO	0.55±0.20	0.54±0.1	0.56±0.00	0.54±0.20	0.57±0.15	0.55±0.10	0.54±0.14	0.53±0.10
NH ₃	0.012±0.4	0.008±0.0	0.01±0.01	0.005±0.0	0.014±0.1	0.01±0.02	0.01±0.10	0.006±0.0
H ₂ S	0.003±0.1	0.002±0.0	0.002±0.2	0.001±0.1	0.004±0.2	0.003±0.0	0.003±0.1	0.002±0.0
SO ₂	0.014±0.1	0.01±0.02	0.015±0.1	0.01±0.01	0.016±0.1	0.011±0.2	0.012±0.0	0.01±0.02
NO ₂	0.010±0.0	0.007±0.0	0.011±0.6	0.008±0.0	0.012±0.1	0.009±0.4	0.010±0.0	0.006±0.1
O ₃	0.02±0.01	0.018±0.1	0.024±0.2	0.022±0.0	0.016±0.0	0.014±0.1	0.022±0.0	0.02±0.01

Results are presented in Means ± Standard Deviation; Market M_A=Tiv Market; M_B=Main Market; M_C=Rice Mill Market and M_D=Market by Enugu Roundabout; DS = Dry Season; RS= Rainy Season; Results of Each Park was Obtained in Triplicate (n=3); Six Months Each for Dry Seasons and Rainy Seasons; Results differences were significant at $p < 0.05$

The results of inorganic gaseous pollutants in markets in Otukpo Metropolis obtained in the current study in Table 10 showed that CO₂, CO, and NH₃ still have higher concentrations than other pollutants. Overall, Market M_C (Rice Mill Market) recorded the highest concentrations of inorganic gaseous pollutants among other markets in this order (Market M_C > Market M_B > Market M_A > Market M_D), presumably due to heavy rice milling activities going on within the market area. Still, from the results in Table 10, it is crystal clear that the rainy recorded lower concentrations of gaseous pollutants than the dry season and it is reasonable to agree, that substantial quantity of the gaseous pollutants recorded in the dry season may have been dissolved in rain water particularly CO₂, NH₃, SO₂ and NO₂ during the rainy season, thereby leading to a reasonable reduction in the quantity of the gaseous pollutants in the rainy season. However, it is essential to establish that the results obtained for the gaseous pollutants in markets in Otukpo Metropolis are lower than the National and International recommended standard permissible limits including H₂S whose concentration (0.001-0.003 mg/m³) is lower than 0.042 ppm (or 0.0756 mg/m³), recommended as the standard permissible limit by the Nigerian Federal Ministry of Environments (FMEnv).

From the results of gaseous pollutants in Table 10 obtained for markets, there are some clear indications that the results for H₂S, O₃, NO₂, NH₃, SO₂, and NO₂ are lower than (0.10), (0.18-0.21), (0.2-1.5), (0.15-0.35) and (0.151-0.228) mg/m³ respectively reported by [15], while that CO and CO₂ are higher than that reported by Ndubueze *et al.* [15], except two results of CO₂. Furthermore, the results obtained in this study are higher than the previously reported values of 1.5532 µg/m³ for SO₂, 1.50 µg/m³ for NO₂, 545.00 µg/m³ for CO₂, and 30.50 µg/m³ for O₃, reported by Onoja *et al.* [16], but the concentrations of CO recorded for markets in this work are lower than 650 µg/m³ for CO by Onoja *et al.* [16]. Additionally, while the concentrations of all the inorganic gaseous pollutants are in agreement with those reported by [13], and [12], particularly, the concentrations of NO₂ and O₃ reported in our findings are consistent with those reported by Abulude *et al.* [22].

Table 11: Results of Gaseous Pollutants from Residential Areas for Dry and Rainy Seasons

Gas	Results of Gaseous Inorganic Pollutants from Each Study Location (mg/m ³)							
	RA (GRA)		RB (Effa Quarters)		RC (St Francis)		RD (Otada Village)	
	DS	RS	DS	RS	DS	RS	DS	RS
CO ₂	0.61±0.20	0.31±0.10	0.63±0.40	0.32±0.10	0.64±0.3	0.325±0.0	0.31±0.6	0.60±0.50
CO	0.51±0.10	0.50±0.0	0.515±0.20	0.51±0.10	0.52±0.15	0.51±0.10	0.30±0.10	0.29±0.10
NH ₃	0.002±0.0	0.001±0.01	0.002±0.05	0.001±0.0	0.002±0.01	0.001±0.01	0.001±0.0	ND
H ₂ S	0.002±0.01	0.001±0.00	0.004±0.00	0.003±0.01	0.004±0.01	0.003±0.00	0.002±0.10	0.001±0.01
SO ₂	0.002±0.01	0.001±0.01	0.002±0.01	0.001±0.00	0.002±0.01	0.001±0.01	0.001±0.50	ND
NO ₂	0.001±0.0	0.0008±0.0	0.001±0.01	0.0009±0.0	0.001±0.01	0.0009±0.0	0.001±0.0	0.0007±0.0
O ₃	0.015±0.01	0.014±0.01	0.02±0.01	0.018±0.02	0.021±0.02	0.019±0.01	0.01±0.01	0.009±0.00

Results are presented in Means ± Standard Deviation; Market M_A=Tiv Market; M_B=Main Market; M_C=Rice Mill Market and M_D=Market by Enugu Roundabout; DS = Dry Season; RS= Rainy Season; Results of Each Park was Obtained in Triplicate (n=3); Six Months Each for Dry Seasons and Rainy Seasons; Results differences were significant at p<0.05

The results of the gaseous inorganic pollutants obtained in residential areas in Table 11 showed that the suburban residential area (Otada village), which is the control site, recorded the lowest inorganic gaseous pollutants compared to other residential areas. This observation may be attributed to less emission of gaseous pollutants due to reduced vehicular activities and combustion from generating sets. This explanation and the results in Table 11 further suggest that the control site (Otada village) has a better air quality than other residential areas. Meanwhile, the results in Table 11 showed that the dry season recorded the highest gaseous pollutants load compared to the rainy season, and St. Francis and Effa Quarters residential areas recorded higher gaseous inorganic pollutants than the GRA (Government Reserved Areas) residential areas presumably, due human population and other social and economic activities in the areas.

Nevertheless, although the obtained results this study for inorganic gaseous pollutants in the residential areas of Otukpo Metropolis consistent with results reported elsewhere and are in the range of previous studies' results, the values in this research for O₃, NO₂, and CO are lower than those reported by Onoja *et al.* [16], while those of SO₂, and CO₂ are higher than those reported by Onoja *et al.* [16], for Otukpo residential area. Besides, the results of NO₂, SO₂, H₂S, O₃, CO₂ and CO, are in agreement with the results reported by Ndubueze *et al.* [15]. Meanwhile, it is reasonable to expect that the results for CO₂, CO, O₃, SO₂, NO₂, obtained in this study for residential areas are lower than the air pollution permissible limit by National and International regulatory bodies such as the Nigerian Federal Ministry of Environment and World Health Organisation. It seems more correct to say that the air quality in the residential areas particularly in the Otada village and GRA areas, is relatively good compared to other residential areas.

(iii) Gaseous Air Pollutants (Organic Gaseous Pollutants)

The gaseous organic pollutants identified in this study include methanal (HCHO), total volatile organic compounds (TVOC) and methane (CH₄), and the concentration of HCHO, TVOC, and CH₄ ranges obtained in Table 12 is in the range 0.056-0.064 mg/m³ for HCHO, 0.058-0.062 mg/m³ for TVOC and 0.017-0.078 for CH₄ in all the sampled areas, which are equally lower the permissible limits set by regulatory bodies.

Table 12: Results of Organic Gaseous Pollutants from Parks/Busy Roads, Commercial Market Paces and Residential Areas in Otukpo Metropolis

Gaseous Organic Pollutants	Results of Gaseous Organic Pollutants form Each Study Location (mg/m ³)					
	Parks/Busy Roads (Mean Value for Parks)		Markets (Mean Value for Markets)		Residential Areas (Mean Value for RAs)	
	DS	RS	DS	RS	DS	RS
HCHO	0.064±0.02	0.062±0.01	0.061±0.01	0.059±0.01	0.058±0.04	0.056±0.00
TVOC	0.06±0.00	0.058±0.03	0.062±0.02	0.061±0.03	0.062±0.02	0.060±0.01
CH ₄	0.078±0.00	0.076±0.02	0.077±0.01	0.076±0.01	0.018±0.01	0.017±0.03

Results are presented in Means ± Standard Deviation; DS = Dry Season; RS= Rainy Season; Results of Each Park was Obtained in Triplicate (n=3); Six Months Each for Dry Seasons and Rainy Seasons; RAs=Residential areas; CH₄=Methane; Results differences were significant at p<0.05

The results of organic gaseous pollutants from each study location in Table 12 showed that methane gas has the highest concentration in all the study locations (CH₄>HCHO>TVOC) except in the control site, the suburban area (Otada village), where it has the lowest concentration (TVOC>HCHO>CH₄). To account for this, the preceding rationale also can be used to explain this observation, where locations with intense human population, heavy vehicular and commercial activity like Otukpo main market, busy parks and traffic hotspots and residential areas with high-density and where domestic cooking, power generation, and household waste burning are common contributors to the gaseous inorganic pollutants in the atmospheric air of Otukpo metropolis. Importantly, the concentrations of TVOC, HCHO, and CH₄ obtained in the current study are generally lower than 0.3 mg/m³ recommended permissible limits for TVOC, 0.10 mg/m³ for HCHO recommended by WHO and FME_{nv}, and 5000 ppm (3280 mg/m³), the IDLH Value of CH₄. Meanwhile the results of the current study are not in agreement with the report of Sombo *et al.* [9], which reported that the total volatile organic compounds (TVOC) and formaldehyde (HCHO) was found to exceed permissible limits in several local government areas including Otukpo, indicating a risk of serious health complications.

On the other hand, although the obtained results for TVOC, HCHO, and CH₄ are in the range of previously reported results, it should, however, be recognized that the results obtained in this work are slightly higher than 0.5686 mg/m³ for TVOC, and 0.6024 mg/m³ for HCHO, for the market reported by Onoja *et al.* [16]. However, the results of TVOC and HCHO in this work are lower than 0.0645 mg/m³ for TVOC and 0.0874 mg/m³ for HCHO for the residential zone, 0.0987 mg/m³ for TVOC and 0.0895 mg/m³ for HCHO for the garage, and 0.0532 mg/m³ for TVOC and 0.0865 mg/m³ for HCHO for the busy road reported by Onoja *et al.* (2025). In addition, the results of TVOC, HCHO, and CH₄ are consistent with those reported by Ndubueze *et al.* [15], although the values of CH₄ reported by Ndubueze *et al.* [15], are much higher than the results acquired in this work. Essentially, it can be argued that the high concentration of CH₄ reported by Ndubueze *et al.* [15], may largely be as a result of the fact that the study sites of the investigation were dumpsites.

(iv) Concentration of Different Metallic Particulates

The results of the mean concentration of different heavy metal particulates in Table 13 showed that the dust samples obtained from each study location contained higher concentrations of Fe, Zn, and Cu than other metallic elements. The results of spatial seasonal variation of concentration of heavy metals in Table 13 equally showed that the dry season recorded slightly higher concentration of heavy metals compared to the rainy season. More commonly, these observations are often used to assess the level of heavy metal contamination of the atmospheric air in a certain location. From all the sampled locations, the results obtained in this study showed the concentration of the heavy metals in this order (Fe>Zn>Cu>Co>Cr>Mn>Pb>Cd> As>Hg). Nonetheless, the residential areas recorded the lowest concentration of heavy metals while parks/busy roads recorded the highest and then the markets. Additionally, the results in Table 13 further established that the atmospheric air of Otukpo Metropolis is not polluted by heavy metal contaminants and the results are in agreement with those obtained elsewhere as reported by in literature by Liu *et al.* [23], and Goswami and Neog [2024].

Table 13: Results of Concentrations of Metallic Particulates from Each Study Location

Metal	Results of Concentrations of Metallic Particulates in Dry and Rainy Seasons					
	Motor Parks/Roads		Markets		Residential Areas	
	DR	RS	DS	RS	DS	RS
Cr	0.002±0.01	0.0020±0.00	0.0021±0.01	0.0020±0.00	0.0011±0.01	0.0012±0.02
Mn	0.0019±0.0	0.0014±0.02	0.0021±0.00	0.0019±0.02	0.0017±0.00	0.0014±0.00
Fe	0.026±0.01	0.015±0.01	0.029±0.040	0.014±0.01	0.022±0.020	0.016±0.010
Co	0.0021±0.02	0.0018±0.03	0.0024±0.02	0.0022±0.00	0.0020±0.01	0.0015±0.01
Ni	0.0015±0.01	0.0012±0.01	0.0017±0.01	0.0015±0.02	0.0013±0.00	0.0008±0.0.0
Cu	0.022±0.05	0.0086±0.00	0.025±0.030	0.010±0.03	0.017±0.01	0.013±0.012
Zn	0.024±0.01	0.022±0.01	0.026±0.020	0.012±0.01	0.019±0.00	0.015±0.015
Cd	0.001±0.00	0.0006±0.02	0.0008±0.01	0.0007±0.00	0.0006±0.00	0.0002±0.00
Pb	0.0009±0.00	0.0004±0.01	0.0006±0.02	0.0005±0.02	0.0003±0.01	ND
Hg	0.0001±0.00	ND	0.0001±0.01	ND	ND	ND
As	0.0001±0.01	0.0001±0.01	0.0001±0.01	0.0001±0.00	ND	ND
	≈0.082	0.041	≈0.091	≈ 0.046	≈ 0.066	≈ 0.050

ND = Not detected

Comparatively, the results in Table 13 also in addition showed that the highest mean concentration of metallic particulates in car parks/busy roads obtained in this study for Fe is 0.026 mg/100 g, 0.029 mg/100 g in markets and 0.022 mg/100 g in residential areas. In general, the results of heavy metal concentrations in the atmospheric air obtained in the present work are lower than permissible limits recommended by both WHO [25], and Nigerian standards for air quality (NSAQ), [26].

(v) Spatial Variation and Pollutants’ Sources Identification

The comparative spatial dynamics analysis results of this study demonstrate that pollution levels are heavily dependent on the proximity to primary emission sources. Parks/busy roads, especially at traffic hotspots and markets, recorded the highest concentrations of particulate matter (PM), CO₂, and CO, and the increased concentrations were systematically observed at traffic-related locations, and heavy machinery activities locations such as busy roads, motor parks, and markets, particularly in the dry season. This could be attributed partly to emissions from poorly maintained vehicles, the use of low-quality fuel, and traffic congestion leading to prolonged idling and incomplete combustion, and also from the burning of solid biomass (wood) for cooking, Harmattan dust, Whirlwind, and the open burning of refuse/domestic wastes [12,13]. The spatial distribution confirms that vehicular exhaust, burning of solid biomass (wood) for cooking, and the open burning of refuse/domestic wastes might be the dominant anthropogenic sources, while Harmattan dust and Whirlwind might be the natural sources of air pollution in the Otukpo metropolis. Motor parks/busy roads were chosen because they are traffic-related sites and areas characterized by high vehicular density and traffic congestion, while markets are often busied with heavy machine activities.

At this point, it is clear that the predominant sources of pollutants in the ambient air of Otukpo Metropolis are due to industrial machines’ emissions, incomplete combustion of fuels in vehicles and biomass burning, indoor sources from building materials, furniture, and other household products, oxidation of VOCs, Cigarette smoking, and decomposition of organic matter [16]. The high concentration of CO and CO₂, particularly in parks/busy roads, is attributed to emissions from poorly maintained vehicles, the use of low-quality fuel, and traffic congestion leading to prolonged idling and incomplete combustion, and generators [12,13]. The ANOVA analysis confirmed the statistically significant spatial differences in pollutant concentrations, often more pronounced than seasonal differences, highlighting that land use and proximity to emission sources are the most critical determinants of local air quality [9].

(vi) Seasonal Dynamics and Variations

In line with the West Africa regional atmospheric patterns a distinct seasonal trend was observed, and was consistent throughout the study period. The rainy season recorded relatively lower PM levels due to wet deposition (rain washout), but some gaseous pollutants like CO, and H₂S that are not very soluble in water were still showed slightly high values depending on local and traffic flow in agreement the reports of Sombo *et al.* [9] and Ameh *et al.* [13].

(vii) Health Implications and Policy

Health Risks

Air pollution has serious consequences on both living things (humans, animals, and plants) and non-living things (monuments, vehicular components, and buildings) and everything is vulnerable to the harmful effects of particulate matter [22]. In these scientific sense and health regards, the persistently high concentrations of PM_{2.5} and PM₁₀ in Otukpo atmospheric ambient air may translate to an elevated public health risk in Otukpo Metropolis. These fine particles are capable of penetrating deep into the lungs and bloodstream, exacerbating or causing numerous health issues as was mentioned elsewhere in [12]. Even before now, epidemiological data from Benue State has linked unsafe air quality to the prevalence of respiratory tract infections (URTI), pneumonia, chronic bronchitis, and allergic asthma [11,14]. The high Air Quality Index (AQI) values, often placing Otukpo in the "Unhealthy" category, indicate that sensitive groups (children, elderly, and those with pre-existing respiratory conditions) are at immediate risk from outdoor exposure [26].

Health Policies

To salvage or ameliorate the deteriorating air quality of Otukpo Metropolis, the Federal government of Nigeria, Benue State government and the Otukpo local government area authority should put certain health policies in place with the aim to reduce the concentration of air pollutants in the atmospheric air of Otukpo metropolis. Such policies may include; abolition of old farming practices like bush burning and dry season bush burning for rodents' hunting. In addition, routine quarterly air quality assessment policy should be introduced in all major Metropolitan cities and semi-urban towns in Nigeria and the enforcement of regulations such as the clean air act which may have a high impact on vehicular and industrial machines activities.

Suggestions and Recommended Policy Interventions

The spatial distribution of pollutants necessitates geographically targeted policy responses and such responses are suggested as follows:

- 1. Traffic Emission Control:** The Federal government of Nigeria, Benue State government and Otukpo local government area authority should as a matter of urgency implement a mandatory emissions testing for all vehicles operating within the Otukpo metropolis. Enforce traffic flow regulations to reduce congestion in the identified hotspots (e.g., main market and major roundabouts) where concentrations of CO and PM levels have reached peak.
- 2. Regulation on Burning of Domestic Wastes:** Governments at all levels should introduce public awareness and sensitization campaigns and regulatory frameworks to discourage the open burning of refuse and solid biomass in residential areas. Closed incinerators should be provided at strategic locations for burning of domestic solid wastes. Additionally, governments at all levels should promote the use of cleaner cooking fuels (e.g., LPG, electric cookstoves) in line with the suggestion in [14].
- 3. Local Monitoring Network:** The Benue State government in particular and Federal government of Nigeria in general should establish a permanent, spatially distributed network of air quality monitoring stations to track real-time pollution levels. This data is essential for forecasting poor air quality events and validating the efficacy of intervention measures supporting the earlier suggestion in [9].
- 4. Urban Cities Renewal and Construction Work:** Infrastructural development like construction of major roads in urban cities like the current construction of Makurdi-Otukpo-Enugu road should be carried out in the rainy season to reduce the volume of dusts release into the atmospheric air.

4. CONCLUSION

As the Air Quality Index for risk assessment in most study locations showed that the particulate ratios of PM₁₀ are being slightly higher than PM_{2.5}, and the ratios of PM_{2.5} being slightly higher than PM₁₀ in other study locations particularly in the rainy season, we have inferred that the air quality of Otukpo Metropolis in most study areas is good, while other locations are moderately good. However, although the concentration of most of the air pollutants found in the ambient atmospheric air of Otukpo Metropolis are either lower or within the National and International recommended permissible limits (SO₂, CO, H₂S, NH₃, and NO₂), the general conclusion is that this study confirms that the Otukpo Metropolis faces significant air quality challenges, particularly concerning fine particulate matter, carbon (IV) oxide, carbon (II) oxide and gaseous organic pollutants which routinely surpass International and National health recommended permissible standards. The clear spatial correlation of high pollution with traffic-related and residential/burning sources emphasizes the necessity of targeted, source-specific mitigation strategies. Addressing the air quality crisis in Otukpo requires a wholistic approach, integrating vehicular emissions control, urban planning to manage traffic, and regulation of domestic combustion activities to safeguard public health in line with global sustainability goals and development.

In addition, as the permissible threshold level of PM (PM_{2.5} and PM₁₀) has continued to receive a downward adjustment by WHO in the year 2021 from 10 µg/m³ to 5 µg/m³ for PM_{2.5} and from 20 µg/m³ to 15 µg/m³ for PM₁₀ as a result of its intense effects on human health globally (WHO, 2021), there are some indications that if urgent steps in terms of pollution control and routine air quality assessment policies, are not urgently put in place to check emission of pollutants into Otukpo Metropolis atmospheric air, certain air pollutants in the Otukpo Metropolis ambient air will soon double or triple their concentrations to exceed National and International recommended permissible limits, especially the particulate matter (PM_{2.5} and PM₁₀). At this point, it can safely be stated that, the sustained efforts through research into the quality of air of urban cities in Nigeria and other global communities would help to solve a lot more of the societal problems, improve visibility of scientific impact and position Nigeria and other international nations among the global knowledge hubs in the area of air quality assessments and evaluations.

Authors' Contribution

Mutah Wadai conceptualized, composed, and developed the topic, supervised the writing of the paper's manuscript, and also provided the statistical tools used in the data analysis. On his part, Idongesit Nnamonso Akpan wrote and developed the entire manuscript, typeset, edited, as well as the production of the final draft of the paper's manuscript, while Ebibi Elijah Onwoke and Apeh, Augustine Joshua, participated in carrying out field instrumental data collections and also helped in data analysis and interpretations.

Availability of Data and Materials

All the data obtained in the course of findings of this study are readily available and can be accessed from the corresponding author upon judicious and reasonable request.

Funding

This study was not sponsored by the government, organisation, foreign support, or any internal or external institutional-based or NGO's sponsors.

Conflict of Interest

In the course of this study, there was no conflict of personal interest.

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