FUDMA Journal of Earth and Environmental Sciences (FUDJEES), Vol. 2, No. 2, 2025
Print ISSN: 1595-9686
EISSN: 1595-9708

AIR QUALITY ASSESSMENT IN SELECTED DUMP SITES IN MAKURDI, BENUE STATE, NIGERIA

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https://doi.org/10/3303/jees.2025.0202/013

ABSTRACT

This study investigates air quality at dump sites in Makurdi, focusing on the pollutants: nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). It compares the levels of these pollutants to national air quality standards and the guidelines set by the World Health Organisation (WHO). The study analyses variation in pollutant concentrations across locations, including Modern Market, North Bank, Wadata, and Wurukum, and compares dump and control sites as well as morning and evening periods. Findings indicate that NO_2 concentrations are higher at dump sites than at control sites, suggesting that waste disposal activities contribute to NO_2 emissions. Evening NO_2 levels with (0.073 ± 0.047) are higher than morning levels with (0.066 ± 0.052), due to increased waste-burning or vehicle activities during peak hours. SO_2 levels also show elevated concentrations at dump sites in the morning, with Modern Market exhibiting the highest SO_2 levels with (0.122 ± 0.169), likely due to early waste-burning practices. In contrast, control sites show lower SO_2 levels with (0.013 ± 0.034), underscoring the influence of waste management practices on localised SO_2 pollution. CO concentrations are higher at dump sites, with morning measurements in Wurukum (3.05 ± 0.79) and Wadata (2.983 ± 0.983) reaching peak levels, attributed to incomplete combustion processes standard in waste incineration. Evening CO levels are lower yet remain elevated compared to control sites, which show minimal CO presence. The observed pollutant patterns highlight the need for improved waste management practices and regulatory interventions to mitigate air quality degradation and protect public health.

Keywords: Air Pollution; Dump Site, Air quality, Gasman Monitor, Health Effects

INTRODUCTION

Air pollution is one of the most pressing environmental challenges in urban centres of developing countries, driven by rapid population growth, unplanned urban expansion, and inadequate waste management systems. In Nigeria, open dumping and open burning of municipal solid waste (MSW) remain standard disposal practices, particularly in medium-sized cities such as Makurdi. These practices contribute significantly to ambient air pollution through the release of harmful gaseous pollutants, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO), which pose serious risks to human health and environmental quality (Akan et al., 2017; Musa et al., 2021).

Dump sites act as primary point sources of air pollution due to continuous decomposition of organic waste, spontaneous fires, and deliberate burning of refuse. The combustion of mixed waste materials such as plastics, rubber, organic matter, and textiles releases toxic gases that may accumulate in the atmosphere, especially under poor dispersion conditions. Prolonged exposure to these pollutants has been linked to respiratory and cardiovascular diseases, eye irritation, and increased mortality, particularly among populations living close to dump sites (Ajao et al., 2018; WHO, 2021).

The World Health Organisation (WHO) provides global guidelines for ambient air quality to safeguard public health. The updated WHO Global Air Quality Guidelines (2021) emphasise that there is no safe threshold for many air pollutants and recommend stricter limits for key pollutants such as NO_2, SO_2, and CO. These guidelines highlight the importance of regular air quality monitoring, especially in pollution-prone environments such as waste dump sites (WHO, 2021).

In Nigeria, ambient air quality is regulated by the National Environmental (Air Quality Control) Regulations enforced by the National Environmental Standards and Regulations Enforcement Agency (NESREA). Despite these regulations, enforcement remains weak, and routine monitoring is limited, particularly in peri-urban and informal waste disposal areas. Consequently, residents living near dump sites are often exposed to elevated pollutant concentrations without adequate assessment or mitigation (NESREA, 2018; Ede & Edokpa, 2017). Empirical studies conducted across Nigerian cities since 2017 have consistently reported higher concentrations of NO_2, SO_2, and CO at dump sites compared to control locations, mainly due to open waste burning and decomposition processes (Akan et al., 2017; Ajao et al., 2018; Ede & Edokpa, 2017). In Makurdi, rapid urbanisation and increasing waste generation have placed considerable pressure on waste management infrastructure, resulting in poorly managed dump sites that are frequently subjected to open burning. Although some studies have examined solid waste-related environmental issues in the city, comprehensive and recent assessments of ambient air quality at selected dump sites remain limited (Musa et al., 2021).

Therefore, this study assesses ambient air quality at selected dump sites in Makurdi by measuring NO_2, SO_2, and CO concentrations to evaluate compliance with WHO and national air quality standards and identify potential environmental and public health risks. The findings will provide baseline data to support improved waste management practices, policy formulation, and ecological health planning in Makurdi and similar urban centres in Nigeria.

MATERIALS AND METHODS

Study Area

The study was conducted in Makurdi Town, which serves as both the administrative centre of Makurdi Local Government Area (LGA) and the capital of Benue State. Geographically, Makurdi lies between longitudes 8°35′E and 8°41′E, and latitudes 7°45′N and 9°52′N. The River Benue bisects the town into North and South Bank regions, connected by two major bridges. Located in a valley within north-central Nigeria, Makurdi sits approximately 100 meters above sea level (Meka Troniks E, 2009).

As of 2024, the estimated population of Makurdi is around 472,000, reflecting a 3.96% increase from the previous year. Like many urban centres in developing nations, the city is experiencing fast-paced growth and expansion. Strategically positioned as a transportation hub, Makurdi connects southeastern and northern Nigeria via rail, road, and inland waterways. The primary economic activities among indigenous residents include industrial activities, transportation, abattoir operations, farming and fishing, while civil service and trading are more common among non-indigenous settlers.

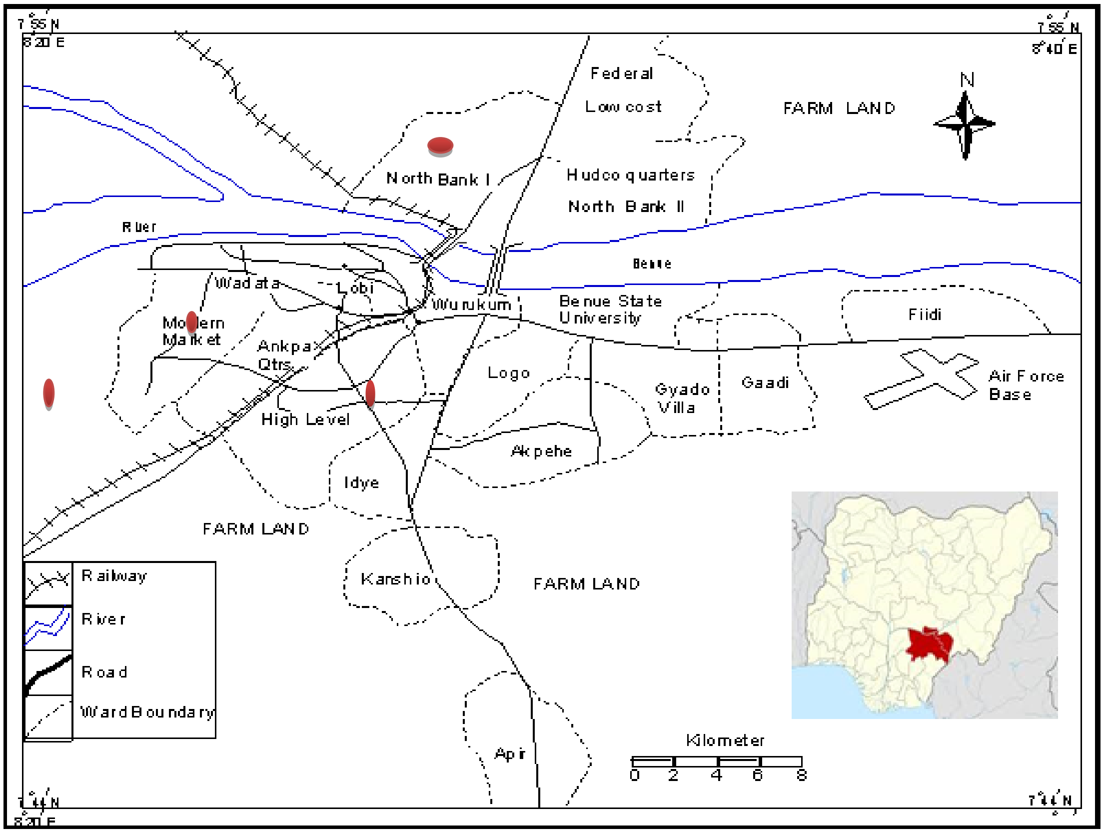

Figure 1: Map of Makurdi town showing the study areas
Source: Benue State Ministry for Lands and Survey (2011)

Materials

Hanhart Stopwatch model Mt 361, Crowcon Gasman to detector for carbon dioxide model number 19278 H, Crowcon Gasman to detector for nitrogen dioxide model number 19844 H, and Crowcon Gasman to detector for sulphur dioxide model number 19658 H.

Experimental Design

The experimental design consisted of sampling at two distinct sites in four locations at two periods of the day (morning and evening), respectively, yielding a 2x4x2 design.

Data Collection

Four locations and one sample site from each were selected within the metropolis for the study. The locations and their sites were: North Bank Dump Site, Wurukum Dump Site, Wadata Market Dump Site, and Modern Market Dump Site. Farm sites, one for each of the four locations, were used as control sites, where no vehicular movements or commercial activities occurred. Samples were taken at 7.00 - 8.00 am for the dump site and at 8.00-9.00 am for the control site in the morning, and at 4.00-5.00 pm for the control sites and at 5.00-6.00 pm for the dump site in the evening. For each pollutant at each site, samples were collected at 5-minute intervals for 1 hour, for a total of 2 hours at each location. The mean of the morning and evening values was then determined as the pollutant value observed for that day. The samples were taken for five days at each location over a period of twenty days from 10th February 2025 to 1st March 2025.

Procedure

The instrument was switched on to the test position. The light-emitting diode (LED) emitted red light continuously, and an audible alarm was heard. The instrument was then switched to the gas position, and a green light was observed on the LED. The liquid crystal diode (LCD) displayed a zero reading. The Hanhart Stopwatch model Mt 361 was then switched on, and the readings were taken at intervals of 5 minutes for a period of one hour for each site to ensure a steady concentration of the gas (Gasman Operation Manual)

Data Analysis

Data analysis was conducted in RStudio. Analysis of Variance (ANOVA) was used to compare the mean pollutant concentration across the various locations. Statistical significance was established at $p<0.05$ and Tukey's HSD was used to separate the means.

RESULTS

The Average Daily Concentration of Pollutants across Locations

The mean concentrations of three air pollutants (NO_2, SO_2, and CO) measured at four different locations: Modern Market, North Bank, Wadata, and Wurukum are shown in Table 1. Mean NO_2 concentrations ranged from 0.062 to 0.066 ppm. The NO_2 levels are consistent with Modern Market (0.064 ± 0.056 ppm), North Bank (0.062 ± 0.054 ppm), Wadata (0.066 ± 0.053 ppm), and Wurukum (0.066 ± 0.07 ppm). There were no statistically significant differences ($p>0.5$). This suggests that NO_2 pollution is evenly distributed among these sites.

Mean SO_2 concentrations vary significantly ($p<0.001$) between locations, with Modern Market showing the highest concentration (0.07 ppm**)**, Wurukum **(**0.066 ± 0.057ppm), North Bank (0.059 ± 0.058ppm) and Wadata the lowest (0.056 ppm).

CO concentrations show a wide range across the locations, with North Bank and Wurukum having higher concentrations (5.19 ppm and 5.115 ppm, respectively) than Modern Market (5.19 ± 4.911 ppm) and Wadata (3.831 ± 3.028 ppm). These indicate that North Bank and Wurukum have significantly higher CO levels than Modern Market and Wadata**.**

Table 1: Mean Pollutant Concentrations between Locations

Location	NO_2	SO_2	CO
Modern Market	0.064 ± 0.056	0.07 ± 0.084^{a}	3.673 ± 2.958^{b}
North Bank	0.062 ± 0.054	0.059 ± 0.058^{bc}	5.19 ± 4.911^{a}
Wadata	0.066 ± 0.053	0.056 ± 0.058c	3.831 ± 3.028^{b}
Wurukum	0.066 ± 0.07	0.066 ± 0.057^{ab}	5.115 ± 4.45^{a}
p-value	> 0.05	< 0.001	< 0.001

Columns with different alphabets are significantly different.

The Average Daily Concentration of Pollutants in the Study Sites

Table 2 presents the mean concentrations of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) across two different sites: a dump site and a control site.

The mean concentration of NO_2 at the dump site is 0.07, while at the control site, it is 0.014. The higher NO_2 concentration at the dump site suggests elevated emissions, potentially from decomposing waste and vehicular traffic associated with waste disposal. The control site shows much lower NO_2 levels and a significantly cleaner environment.

SO_2 levels are also higher at the dump site, with a mean concentration of 0.073 ± 0.078, compared to 0.012 ± 0.032 at the control site. The elevated SO_2 at the dump site could result from burning waste materials, including sulfur-containing compounds. The significant difference underscores the dump site's potential as a point source for SO_2 pollution.

CO concentrations are notably higher at the dump site, averaging 2.719 ± 0.763, compared to 1.552 ± 0.522 at the control site. The significant difference suggests that waste decomposition, as well as occasional fires or incineration at the dump site, may be increasing CO levels.

Table 2: Mean Pollutant Concentrations between Sites

Site	NO_2	SO_2	CO
Dump site	0.07 ± 0.05^b	0.073 ± 0.078^b	2.719 ± 0.763^c
Control	0.014 ± 0.056^c	0.012 ± 0.032^d	1.552 ± 0.522^d
p-value	< 0.001	< 0.001	< 0.001

Columns with different superscripts are significantly different.

The Average Daily Concentrations of Pollutants within the Period (Morning and Evening)

The concentrations of NO_2, SO_2 and CO are shown in Table 3. The result is the average of the data collected in the morning and evening from the locations monitored during the study.

Mean NO_2 concentrations vary significantly ($p<0.001$) between morning and evening. Morning (0.068 ± 0.063 ppm) has higher NO2 levels than Evening (0.061 ± 0.054 ppm). Superscripts indicate that the NO_2 levels in the morning are significantly higher than in the evening.

Mean SO_2 concentrations vary significantly ($p<0.001$) between morning and evening. Morning (0.071 ± 0.072 ppm) has higher SO2 than Evening (0.055 ± 0.057 ppm). Superscripts show that SO_2 levels in the morning are significantly higher than those in the evening.

Mean CO concentrations vary significantly ($p<0.001$) between morning and evening. Morning (4.618 ± 3.924ppm) has higher CO than Evening (4.287 ± 4.052 ppm). Superscripts indicate that CO levels are significantly higher in the morning than in the evening.

Table 3: Mean Pollutant Concentrations between Periods

Period	NO_2	SO_2	CO
Morning	0.068 ± 0.063^a	0.071 ± 0.072^a	4.618 ± 3.924^a
Evening	0.061 ± 0.054^b	0.055 ± 0.057^b	4.287 ± 4.052^b
p-value	< 0.01	< 0.001	< 0.001

Columns with different alphabets are significantly different.

Pollutant Variation in Concentrations between Locations and Sites

Table 4 presents mean concentrations of NO_2, SO_2, and CO across four locations (Modern Market, North Bank, Wadata, and Wurukum) in Makurdi, comparing dump sites and control sites within each area.

NO_2 concentrations are consistently higher at dump sites compared to control sites across all locations. The highest NO_2 concentration is observed at the Modern Market dump site (0.0775 ± 0.051), which may reflect higher waste activity and potential burning. The significantly lower NO_2 values at control sites (notably Modern Market Control at 0.0083 ± 0.0278) suggest that activities at the dump sites contribute to elevated NO_2 levels, possibly from waste decomposition and vehicular emissions associated with dump operations.

SO_2 concentrations are higher at dump sites than at control sites. The Modern Market dump site records the highest SO_2 level (0.1 ± 0.1257), while control sites show consistently low concentrations (e.g., North Bank Control: 0.0058 ± 0.0235). This pattern indicates that combustion of sulfur-containing materials at dump sites is a significant source of SO_2 emissions.

Carbon monoxide (CO) concentrations are higher at dump sites, with Wadata (2.9 ± 0.9019) and Wurukum (2.8833 ± 0.842) recording the highest values. These levels exceed those at control sites, such as Wadata Control (1.425 ± 0.5448). The elevated CO is likely due to incomplete combustion during frequent waste burning at the dump site.

Table 4: Mean Pollutant Concentrations between Location and Site

Location	Site	NO_2	SO_2	CO
Modern Market	Dump site	0.0775 ± 0.051^{cde}	0.1 ± 0.1257^{ab}	2.4667 ± 0.5932^{f}
Modern Market	Control	0.0083 ± 0.0278^{f}	0.015 ± 0.0359^{f}	1.4667 ± 0.501^{g}
North Bank	Dump site	0.0567 ± 0.0498^{e}	0.0583 ± 0.0495^{de}	2.625 ± 0.5807^{ef}
North Bank	Control	0.0175 ± 0.0382^{f}	0.0058 ± 0.0235^{f}	1.675 ± 0.5212^{g}
Wadata	Dump site	0.0758 ± 0.043^{cde}	0.055 ± 0.05^{e}	2.9 ± 0.9019^{ef}
Wadata	Control	0.0125 ± 0.0332^{f}	0.0192 ± 0.0395^{f}	1.425 ± 0.5448^{g}
Wurukum	Dump site	0.0692 ± 0.0531^{de}	0.08 ± 0.0495^{bcd}	2.8833 ± 0.842^{ef}
Wurukum	Control	0.0192 ± 0.0955^{f}	0.0076 ± 0.0267^{f}	1.6417 ± 0.4815^{g}
p-value		< 0.001	< 0.001	< 0.001

Columns with different superscripts are significantly different.

Pollutant Variation in Concentrations between Location and Period

The data obtained in this research work for gaseous emissions were calculated by Variation in concentration of nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and carbon monoxide (CO) obtained at different locations (Wadata, Modern Market, Wurukum, and North Bank) and for different sampling periods (morning and evening), respectively, are shown in Table 5.

There are significant differences in NO_2 levels between morning and evening across the locations**.** Morning concentrations are generally higher than Evening concentrations for most locations. Modern Market and Wadata show significant differences in NO_2 levels between periods. Modern Market

(0.073 ± 0.058ppm) and Wadata (0.058 ± 0.054ppm) both have higher NO_2 in the morning compared to the evening (0.055 ± 0.052ppm) and (0.073 ± 0.05ppm) respectively, while North Bank and Wurukum also show similar patterns but with less pronounced differences.

For sulphur dioxide (SO_2), its concentrations ranged from the highest (0.083 ± 0.101ppm) in the morning at Modern Market to the lowest concentration (0.063 ± 0.061ppm) in the morning at Wadata. The levels of SO_2 were considerable (0.062 ± 0.055 ppm) in the evening at Wurukum and low (0.05 ± 0.054 ppm) in the evening at Wadata. There are no statistically significant differences in SO_2 levels between morning and evening across all locations.

CO concentrations ranged from moderate (5.325 ± 4.613ppm) in the morning at North Bank, to the lowest concentration (3.883 ± 3.072ppm) in the morning at Wadata and the highest CO concentration (5.054 ± 5.198ppm) in the evening at North Bank and the lowest concentration (3.329 ± 2.958ppm) in the evening at Wadata. There are no statistically significant differences in CO levels between morning and evening across all locations. CO concentrations show variability within locations but no significant overall trend between the two periods. The values were below the Nigerian Air quality standard, which stipulates a range of 09 ppm for a 24-hour range time for CO, 0.06 and 0.11ppm for SO_2 and 0.1 ppm for NO_2.

Table 5: Mean Pollutant Concentrations between Location and Period

Location	Period	NO_2	SO_2	CO
Modern Market	Morning	0.073 ± 0.058^{a}	0.083 ± 0.101	4.017 ± 2.923
Modern Market	Evening	0.055 ± 0.052^{c}	0.057 ± 0.06	3.329 ± 2.958
North Bank	Morning	0.07 ± 0.054^{ab}	0.068 ± 0.057	5.325 ± 4.613
North Bank	Evening	0.054 ± 0.052^{c}	0.05 ± 0.056	5.054 ± 5.198
Wadata	Morning	0.058 ± 0.054^{bc}	0.063 ± 0.061	3.883 ± 3.072
Wadata	Evening	0.073 ± 0.05^{a}	0.05 ± 0.054	3.779 ± 2.989
Wurukum	Morning	0.069 ± 0.08^{ab}	0.069 ± 0.058	5.246 ± 4.554
Wurukum	Evening	0.063 ± 0.059^{abc}	0.062 ± 0.055	4.983 ± 4.35
p-value		< 0.001	> 0.05	> 0.05

Columns with different alphabets are significantly different.

Mean Pollutant Concentrations between Site and Period

Table 6 compares mean pollutant concentrations (NO_2, SO_2, and CO) at dump and control sites in Makurdi, measured during the morning and evening periods.

Nitrogen Dioxide (NO_2) levels are higher at the dump site during both the morning (0.066 ± 0.052) and evening (0.073 ± 0.047) periods, with evening concentrations slightly exceeding those in the morning. The significantly lower NO_2 values at the control site (0.02 ± 0.073 in the morning and 0.009 ± 0.029 in the evening) suggest that NO_2 emissions are primarily associated with activities at the dump site. This may be due to heightened waste decomposition and emissions from waste-related vehicular traffic at the dump site.

Sulfur Dioxide (SO_2) concentrations are also higher at the dump site, particularly in the morning (0.085 ± 0.097) compared to the evening (0.062 ± 0.051). The morning increase could be influenced by early waste-burning activities, which release sulfur compounds. In contrast, SO_2 levels at the control site remain low throughout the day (0.01 ± 0.031 in the morning and 0.014 ± 0.034 in the evening), indicating minimal sulfur pollution sources in these areas.

Carbon Monoxide (CO) levels are consistently elevated at the dump site, with morning values at 2.838 ± 0.762 and slightly lower evening values at 2.6 ± 0.748. This pattern likely reflects peak waste combustion and vehicular emissions in the morning, which then reduce by the evening. At the control site, CO concentrations are significantly lower in both periods (1.688 ± 0.499 in the morning and 1.417 ± 0.511 in the evening), pointing to the absence of combustion-related pollution sources found at the dump site.

Table 6: Mean Pollutant Concentrations between Site and Period

Site	Period	NO_2	SO_2	CO
Dump site	Morning	0.066 ± 0.052c	0.085 ± 0.097b	2.838 ± 0.762c
Dump site	Evening	0.073 ± 0.047bc	0.062 ± 0.051c	2.6 ± 0.748c
Control	Morning	0.02 ± 0.073d	0.01 ± 0.031e	1.688 ± 0.499d
Control	Evening	0.009 ± 0.029d	0.014 ± 0.034e	1.417 ± 0.511d
p-value		< 0.001	< 0.001	< 0.05

Columns with different superscripts are significantly different.

Pollutant Variation in Concentrations between Location, Site and Period

Table 7 details the mean concentrations of (NO_2), (SO_2), and (CO) across different locations (Modern Market, North Bank, Wadata, and Wurukum), distinguishing between dump and control sites and morning and evening periods.

Nitrogen dioxide (NO_2) concentrations are generally higher at dump sites than at control sites, indicating significant contributions from waste-related activities. At dump sites, NO_2 levels show a slight diurnal variation, with evening values often exceeding those in the morning. For example, Wadata records a higher evening concentration (0.095 ± 0.022) compared to morning (0.057 ± 0.05), likely due to increased waste burning and vehicular activity later in the day.

Sulfur dioxide (SO_2) concentrations are highest at the Modern Market dump site in the morning (0.122 ± 0.169), likely due to early waste-burning activities. Evening SO_2 levels at dump sites such as North Bank and Wadata are comparatively lower (about 0.052–0.072). Control sites record very low SO_2 concentrations (e.g., Wurukum morning: 0.002 ± 0.013), highlighting the influence of waste management activities on SO_2 levels.

Carbon monoxide (CO) levels are markedly higher at dump sites, particularly in the morning at Wurukum (3.05 ± 0.79) and Wadata (2.983 ± 0.983), likely due to incomplete combustion from waste burning. Although evening CO concentrations are slightly lower (Wadata evening: 2.817 ± 0.813), they remain higher than at control sites. Control locations record much lower CO levels (e.g., Modern Market control evening: 1.317 ± 0.469), reflecting minimal combustion activities.

FUDMA Journal of Earth and Environmental Sciences (FUDJEES), Vol. 2, No. 2, 2025
Print ISSN: 1595-9686
EISSN: 1595-9708

Table 7: Mean Pollutant Concentrations between Locations, Sites, and Periods

Location	Site	Period	NO_2	SO_2	CO
Modern Market	Dump site	Morning	$0.077 \pm 0.059^{bcdefgh}$	0.122 ± 0.169^{a}	2.65 ± 0.606^{efghijk}
Modern Market	Dump site	Evening	$0.078 \pm 0.042^{bcdefgh}$	$0.078 \pm 0.049^{bcdefgh}$	$2.283 \pm 0.524^{fghijkl}$
Modern Market	Control	Morning	0.013 ± 0.034^{mn}	0.013 ± 0.034^{lm}	1.617 ± 0.49^{jkl}
Modern Market	Control	Evening	0.003 ± 0.018^{n}	0.017 ± 0.038^{klm}	1.317 ± 0.469^{l}
North Bank	Dump site	Morning	0.063 ± 0.049^{efghij}	0.07 ± 0.046^{cdefghi}	2.667 ± 0.51^{efghijk}
North Bank	Dump site	Evening	0.05 ± 0.05^{ghijk}	0.047 ± 0.05^{ghijkl}	$2.583 \pm 0.646^{efghijk}$
North Bank	Control	Morning	0.015 ± 0.036^{lmn}	0.002 ± 0.013^{m}	1.833 ± 0.457^{hijkl}
North Bank	Control	Evening	0.02 ± 0.04^{klmn}	0.01 ± 0.03^{lm}	1.517 ± 0.537^{kl}
Wadata	Dump site	Morning	0.057 ± 0.05^{fghij}	0.058 ± 0.05^{efghij}	2.983 ± 0.983^{defgh}
Wadata	Dump site	Evening	0.095 ± 0.022^{abcde}	0.052 ± 0.05^{fghijk}	2.817 ± 0.813^{efghi}
Wadata	Control	Morning	0.017 ± 0.038^{lmn}	0.025 ± 0.044^{jklm}	1.567 ± 0.564^{jkl}
Wadata	Control	Evening	0.008 ± 0.028^{mn}	0.013 ± 0.034^{lm}	1.283 ± 0.49^{l}
Wurukum	Dump site	Morning	0.068 ± 0.05^{defghi}	0.088 ± 0.049^{abcdef}	3.05 ± 0.79^{defg}
Wurukum	Dump site	Evening	0.07 ± 0.056^{cdefghi}	$0.072 \pm 0.049^{cdefghi}$	2.717 ± 0.865^{efghij}
Wurukum	Control	Morning	0.033 ± 0.132^{jklmn}	0.002 ± 0.013^{m}	1.733 ± 0.446^{ijkl}
Wurukum	Control	Evening	0.005 ± 0.022^{n}	0.014 ± 0.035^{lm}	1.55 ± 0.502^{jkl}
p-value			< 0.001	< 0.001	< 0.001

Columns with different superscripts are significantly different.

DISCUSSION

This study demonstrates that waste disposal activities, particularly open waste burning and emissions from waste transport vehicles, significantly influence ambient air quality around dump sites in Makurdi. The consistently higher concentrations of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) recorded at dump sites compared to control locations clearly indicate the impact of anthropogenic activities associated with waste management.

Nitrogen dioxide (NO_2) concentrations exhibited distinct spatial and temporal variations across the study locations. As shown in Table 7, mean NO_2 levels were consistently higher at dump sites than at control sites during both morning and evening periods. The highest mean NO_2 concentration was recorded at the Wadata dump site in the evening (0.095 ± 0.022), while the lowest value occurred at the Modern Market control site in the evening (0.003 ± 0.018). These elevated concentrations are primarily attributed to open burning of municipal solid waste, vehicular emissions, and combustion of mixed waste materials, which are standard practices at dump sites in Makurdi. Similar findings have been reported by Ogundele et al. (2018) and Akan et al. (2019), who identified waste combustion and traffic-related activities as significant sources of nitrogen oxides in urban dump environments.

The slightly higher NO_2 concentrations observed during evening periods at some dump sites, particularly Wadata and Modern Market, may be linked to increased waste-burning activities and reduced atmospheric dispersion during late hours. This pattern is consistent with reports from other Nigerian urban studies, which documented higher evening pollutant concentrations associated with peak human and waste-related activities (Akinbile & Yusoff, 2021; Terwase et al., 2022).

Sulfur dioxide (SO_2) concentrations also showed marked differences between dump sites and control locations. Dump sites generally recorded higher SO_2 levels, with the highest mean concentration observed at the Modern Market dump site in the morning (0.122 ± 0.169), followed by the Wurukum dump site in the morning (0.088 ± 0.049). In contrast, control sites recorded very low SO_2 concentrations, with values as low as 0.002 ± 0.013 at North Bank and Wurukum during the morning period. These elevated SO_2 levels are primarily associated with the combustion of sulfur-containing materials such as plastics, rubber, textiles, and other domestic wastes. Previous studies have similarly identified open waste burning as a major contributor to sulfur oxide emissions in developing urban centres where waste segregation is limited (Abul, 2018; Efe & Efe, 2020).

Morning peaks in SO_2 concentrations may be linked to early-day waste-burning activities and limited atmospheric mixing. Comparable patterns have been documented around dump sites in Lagos, Ibadan, and Port Harcourt (Nwankwoala & Jumbo, 2020; Akanbi et al., 2022). The statistically significant variation in SO_2 concentrations ($p < 0.001$) further confirms the strong influence of dump site activities on ambient air quality. Although several values were within national air quality limits, continuous exposure to elevated SO_2 levels may pose respiratory health risks, particularly among sensitive groups (USEPA, 2020; WHO, 2021).

Carbon monoxide (CO) concentrations were consistently higher at dump sites than at control locations throughout the sampling periods. The highest mean CO concentration was recorded at the Wurukum dump site in the morning (3.05 ± 0.79), followed by the Wadata dump site in the morning

(2.983 ± 0.983). In contrast, control sites recorded lower CO concentrations, with the lowest value observed at the Wadata control site in the evening (1.283 ± 0.49). These elevated CO levels reflect the effects of incomplete combustion of organic and synthetic waste materials during open burning, as well as emissions from trucks and generators operating around dump sites. Similar trends have been reported in other Nigerian cities, where waste-burning zones recorded significantly higher CO levels than background locations (Ogbonna et al., 2019; Adebayo & Olatunji, 2023).

Morning CO concentrations were generally higher than evening values at most dump sites, likely due to intensified waste-burning and vehicular activities during early hours. The statistically significant p-value (< 0.001) indicates that observed variations in CO concentrations across locations and periods are not due to chance. Although most measured CO levels were within short-term exposure limits, prolonged exposure may result in adverse health effects, including headaches, dizziness, impaired oxygen transport, and cardiovascular complications (WHO, 2021). These findings highlight the potential environmental and public health implications for residents, traders, and waste workers living and operating near dump sites in Makurdi.

CONCLUSION AND RECOMMENDATIONS

This study has demonstrated that waste-related activities at dumpsites in Makurdi significantly contribute to elevated concentrations of key air pollutants, namely nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). The trends observed higher NO_2 levels during the evening. The increased SO_2 and CO concentrations in the morning suggest that both waste combustion and vehicular movement around the dumpsites are significant sources of air contamination.

Measured pollutant levels frequently exceeded recommended limits, indicating potential health hazards for nearby residents (Abam & Unachukwu, 2020; Musa *et al.,* 2021). These findings call for targeted interventions, including the prohibition of open waste burning, stricter control of vehicle emissions near waste facilities, and the promotion of sustainable waste management practices. Adopting these strategies would support compliance with WHO air quality guidelines and help reduce the environmental and health risks associated with dumpsite emissions (Rim-Rukeh, 2020; Onoja *et al*., 2021).

In conclusion, open dumping should be replaced with engineered sanitary landfills and proper waste segregation to reduce air pollutant emissions from dump sites. Environmental authorities should strictly enforce laws against open burning of waste, which is a significant source of NO_2, SO_2, and CO emissions. Routine monitoring of ambient air quality around dump sites should be conducted to ensure compliance with the WHO Ambient Air Quality Guidelines and the National Ambient Air Quality Standards (NAAQS). Adequate buffer distances should be maintained between dump sites and residential or sensitive areas to minimise human exposure to harmful air pollutants. Public education on proper waste disposal, alongside promotion of recycling and composting, should be intensified to reduce waste volume and air pollution.

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