IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)
e-ISSN: 2319-2402, p- ISSN: 2319-2399.Volume 20, Issue 9 Ser. II (September 2026), PP 01-09
www.iosrjournals.org

Spatial Variation of Gas Flaring Emissions and Meteorological Influences on Air Quality in Alesa Eleme, Niger Delta, Nigeria

[1]Oguntola, O. O., [1]Dollah, O. C & [2]Orlu, A. H
[1]Institute of Geosciences and Environmental Management, Rivers State University Nkpolu-Oroworukwo Port Harcourt, Rivers State, Nigeria
[2]Department of Chemistry, Faculty of Science, Rivers State University Nkpolu-Oroworukwo Port Harcourt, Rivers State, Nigeria

ABSTRACT
This research examines the geographical spread of gas-related pollutants, particulate matter, and climatic influences linked to gas flaring in Alesa Eleme, Rivers State, Nigeria. A methodology combining environmental observation, survey information, and statistical evaluation was utilized. Air quality assessments were carried out at five distances (0.5–2.5 km) from the flaring locations using portable monitoring devices, while weather data were recorded concurrently. The sample included 399 individuals chosen via stratified random sampling, alongside 91 environmental assessments that underwent statistical analysis. The findings indicated a pronounced reduction in pollutant levels with increased distance from the flare sites. Carbon monoxide (CO) levels dropped from 18.6 ± 1.4 ppm at 0.5 km to 7.1 ± 0.6 ppm by 2.5 km, consistently exceeding the World Health Organization (WHO) recommendation of 3.5 ppm across all distances. Meanwhile, nitrogen dioxide (NO_2) levels varied from 0.194 ± 0.013 ppm to 0.071 ± 0.005 ppm, consistently surpassing WHO (0.013 ppm) and national standards. Particulate matter displayed the highest levels of pollution, with $PM_{2.5}$ diminishing from 192.4 ± 11.8 µg/m³ to 66.3 ± 5.1 µg/m³ and PM_{10} falling from 348.6 ± 18.5 µg/m³ to 124.8 ± 8.2 µg/m³, all beyond permissible levels. One-way ANOVA demonstrated notable spatial differences for each pollutant (F-values between 38.517 and 61.483; $p < 0.001$). Meteorological assessments indicated that wind speed (1.86–2.76 m/s) and relative humidity (76.2–81.6%) tended to increase with distance, while temperature declined (30.0–28.8°C). Correlation analysis revealed strong positive relationships among pollutants ($r = 0.944–0.991$) and significant negative associations with wind speed ($r = −0.914$ to $−0.961$) and humidity ($r = −0.731$ to $−0.841$). The results affirm that gas flaring substantially compromises air quality, with both proximity and weather conditions influencing the spread of pollutants. This study accentuates the serious environmental and potential health threats faced by populations living within 2.5 km of flare locations, highlighting the urgent need for enhanced regulatory measures and mitigation approaches.

Keywords: *Spatial, Variation, Gas, Flaring, Emissions, Meteorological, Air &Quality*

Date of Submission: 12-09-2026 Date of Acceptance: 22-09-2026

I. INTRODUCTION

Gas flaring constitutes a critical environmental issue in the Niger Delta region of Nigeria, where oil and gas extraction operations have been active for many years, resulting in considerable ecological and public health impacts. This activity involves the burning of surplus natural gas during oil production, which emits a variety of gaseous pollutants and particulate matter into the air (World Health Organization, 2021). These emissions comprise substances such as carbon monoxide, nitrogen oxides, sulfur dioxide, volatile organic compounds, and fine particulate matter, all of which pose risks to air quality and human health (Brasseur & Jacob, 2017).

In places like Alesa Eleme in Rivers State, gas flaring takes place in areas that are very close to residential establishments, raising alarms about long-term exposure and environmental harm. Earlier research has found that pollutant levels are usually at their highest near flaring sites and diminish with increasing distance due to dispersal in the atmosphere (Nwankwo & Ogagarue, 2011).

Nonetheless, understanding the degree of this geographical variation and how meteorological conditions like wind velocity, temperature, and humidity affect pollutant distribution remains vital, especially in crowded oil-producing areas (Nwankwo & Ogagarue, 2011).

Meteorological factors are crucial in influencing how airborne contaminants are transported, diluted, and accumulated. Conditions such as low wind velocities, elevated temperatures, and diminished mixing within the atmosphere can lead to heightened concentrations of pollutants close to their sources. In contrast, stronger winds and higher humidity levels may promote the processes of dispersion and removal (Amadi et al. 2019). Grasping these dynamics is vital for evaluating environmental hazards and formulating effective strategies for mitigation. Although, there is a considerable amount of research on gas flaring, there is a lack of thorough empirical correlation between environmental monitoring data and statistical examinations of spatial variations and meteorological effects at the community level. This research intends to fill this void by analyzing the spatial distribution of pollutants alongside their correlation with weather conditions in Alesa Eleme. By integrating field data with strong statistical methods, this research offers evidence-based perspectives on the environmental consequences of gas flaring and adds to policy debates concerning air quality management in the Niger Delta.

II. METHODOLOGY

This research utilized a mixed-methods approach that combines quantitative survey methods, qualitative analysis, and environmental assessments to explore the psychosocial effects and perceived health threats linked to gas flaring in Alesa Eleme, Rivers State, Nigeria. The mixed approach was deemed suitable due to the necessity to measure environmental exposure and health outcomes while also capturing the personal experiences and views of residents. By merging these complementary methods, the study achieved methodological triangulation, which strengthened the reliability, validity, and robustness of the results. Data for this study were collected from both primary and secondary sources to offer a well-rounded understanding of the environmental and social aspects of gas flaring. Primary data collection included structured questionnaires given to residents living near gas flare sites, semi-structured interviews with key individuals, and direct environmental assessment of air quality and weather conditions. The questionnaire gathered information on demographic details, perceived health threats, indicators of psychosocial stress, and coping methods. Qualitative data were obtained through detailed interviews with community leaders, medical professionals, and at-risk groups, providing an in-depth exploration of community perspectives, institutional responses, and adaptive behaviors. Environmental monitoring included measuring gas emissions and particulate matter concentrations, along with weather factors to produce objective exposure data. Secondary data were gathered from pertinent literature, policy documents, and reports related to gas flaring and air quality in the Niger Delta. This encompassed environmental guidelines and standards from regulatory organizations such as the World Health Organization (WHO) and the National Environmental Standards and Regulations Enforcement Agency (NESREA), along with peer-reviewed research and environmental evaluations. These sources offered contextual context, comparative benchmarks, and assistance in interpreting the empirical results.

The participant group consisted of adult inhabitants of Alesa Eleme who reside within a specified distance from gas flare facilities. According to the 2006 National Population Census, the population of Eleme Local Government Area was 190,884, with recent estimates indicating numbers surpassing 230,000. The focus group targeted individuals living within a five-kilometer radius of flare sites since this area represents the highest exposure location noted in prior environmental health research. Participation was limited to adults aged 18 and over who had lived in the area for at least five years to guarantee sufficient exposure and knowledgeable responses. Vulnerable populations, such as women and the elderly, were specifically included to reveal differences in exposure and effects, while minors and temporary residents were excluded for ethical and methodological considerations. The sample size was calculated using Yamane’s formula for finite populations with a 5% margin of error, resulting in a sample of 399 individuals. A stratified random sampling approach was used to ensure representation across distinct exposure areas defined by distance from flare sites. Households in each stratum were chosen randomly to allow equal participation chances. Furthermore, purposive sampling was applied to identify key informants for qualitative interviews, ensuring that individuals with relevant expertise and experience were included.

Environmental data gathering was performed with portable monitoring devices under uniform conditions in the field. The Aeroqual Series 500 gas monitor was utilized for assessing gaseous pollutants, while the MET One Aerocet 531 was used to determine concentrations of particulate matter. Meteorological factors such as temperature, relative humidity, wind speed, and wind direction were measured with the Weather Centre PCE-20N. Measurements took place at several sampling sites located at different distances from flare emissions. All devices were situated at a height of around 1.5 to 2.0 meters to represent the human breathing zone and operated for extended sessions of around eight hours during daylight. Data were captured at consistent intervals, recorded via internal logging systems, and later downloaded for examination. To guarantee the reliability and quality of the data, all tools and instruments were tested beforehand in a nearby community that shared similar environmental conditions. Adjustments were applied based on the outcomes from the pilot tests. Data collection occurred in English, with translations provided into local dialects and Nigerian Pidgin when necessary to improve understanding and inclusivity. An integrated mixed-methods strategy was utilized for data analysis. Data obtained from questionnaires were coded and evaluated using the Statistical Package for the Social Sciences (SPSS). Descriptive statistics, including frequencies, percentages, means, and standard deviations, were employed to encapsulate essential variables. Inferential analysis involved regression techniques to explore the connections between environmental exposure and health results, along with links between socio-demographic variables and psychosocial factors. Findings were presented in tables and graphs to enhance clarity. Qualitative data from interviews underwent transcription and were examined using thematic content analysis. Emerging themes were categorized, coded, and organized into significant domains such as environmental perception, psychosocial stress, coping strategies, and institutional responses. These qualitative findings were integrated to enrich and provide context to the quantitative results. Environmental monitoring data were subjected to descriptive and comparative statistical analysis. Pollutant concentration data were summarized through mean values and variability assessments, while temporal trends were illustrated through graphical representations. Meteorological factors were studied to understand their effects on the spread of pollutants. The measured concentrations were further compared with established national and international air quality standards to assess environmental quality and possible health hazards within the study region.

III. RESULTS

Research Objective One: Measure gaseous pollutants and particulate matter ($PM_{2.5}$ and PM_{10}) concentrations in Alesa Eleme

Research Question One: What are the concentrations of gaseous pollutants and particulate matter in Alesa Eleme

Table 1. Mean concentration of pollutants at varying distances from flare sites in the study area.

Pollutants	0.5 km (Mean ± SD)	1 km (Mean ± SD)	1.5 km (Mean ± SD)	2 km (Mean ± SD)	2.5 km (Mean ± SD)	WHO Standard	NESREA Standard
CO (ppm)	18.6 ± 1.4	15.8 ± 1.2	12.9 ± 1.0	9.8 ± 0.8	7.1 ± 0.6	3.5	10
CH_4 (ppm)	7.35 ± 0.42	6.28 ± 0.35	5.16 ± 0.29	4.08 ± 0.23	3.24 ± 0.18	NA	NA
SO_2 (ppm)	0.182 ± 0.012	0.151 ± 0.010	0.123 ± 0.009	0.094 ± 0.007	0.068 ± 0.005	0.015	0.1
NO_2 (ppm)	0.194 ± 0.013	0.163 ± 0.011	0.132 ± 0.009	0.098 ± 0.007	0.071 ± 0.005	0.013	0.06
VOC (ppm)	4.82 ± 0.28	4.06 ± 0.24	3.31 ± 0.20	2.64 ± 0.17	1.96 ± 0.14	NA	NA
$PM_{2.5}$ (µg/m³)	192.4 ± 11.8	158.7 ± 10.3	126.5 ± 8.6	94.8 ± 6.9	66.3 ± 5.1	15	25
PM_{10} (µg/m³)	348.6 ± 18.5	287.9 ± 15.7	229.4 ± 13.2	171.6 ± 10.4	124.8 ± 8.2	45	150

Gaseous pollutants and particulate matter concentrations in Alesa Eleme

Table 1 presents the mean concentrations of pollutants at different distances from gas flare sites in the study area. The results reveal a clear spatial variation in pollutant concentrations, with the highest values consistently recorded at the closest monitoring point (0.5 km) and a progressive reduction as distance from the flare sites increased to 2.5 km. This pattern indicates the strong influence of proximity to flare sources on ambient air quality conditions within the study area. Carbon monoxide (CO) concentration showed a noticeable decline with increasing distance from the flare sites. The highest mean concentration was recorded at 0.5 km (18.6 ± 1.4 ppm), reducing to 7.1 ± 0.6 ppm at 2.5 km. The concentration at the nearest location exceeded both the WHO standard of 3.5 ppm and the NESREA limit of 10 ppm, while the value at 2.5 km remained above the WHO guideline but was below the NESREA limit. This indicates that residents living closer to flare locations are exposed to elevated carbon monoxide levels, which may be associated with incomplete combustion processes during gas flaring activities. Methane (CH_4) recorded the highest concentration of 7.35 ± 0.42 ppm at 0.5 km, followed by a gradual decline to 3.24 ± 0.18 ppm at 2.5 km. Although no WHO or NESREA permissible limits were provided for methane, the observed reduction pattern demonstrates that flare-related emissions influence methane concentration within the surrounding atmosphere. The decreasing trend with distance suggests that atmospheric dispersion reduces methane accumulation away from the emission source. Sulphur dioxide (SO_2) concentration followed a similar pattern, declining from 0.182 ± 0.012 ppm at 0.5 km to 0.068 ± 0.005 ppm at 2.5 km. The concentrations recorded within the first three distance zones exceeded the NESREA standard of 0.1 ppm, while all locations exceeded the WHO guideline of 0.015 ppm. The elevated SO_2 levels close to the flare sites indicate the influence of sulphur-containing compounds released during combustion processes. Nitrogen dioxide (NO_2) also demonstrated a consistent reduction with increasing distance. The concentration decreased from 0.194 ± 0.013 ppm at 0.5 km to 0.071 ± 0.005 ppm at 2.5 km. All recorded values exceeded both the WHO standard of 0.013 ppm and NESREA limit of 0.06 ppm. The persistence of elevated NO_2 concentrations even at farther distances suggests that emissions from gas flaring contribute substantially to nitrogen oxide pollution within the study area. Volatile organic compounds (VOCs) recorded the highest concentration at the nearest monitoring point (4.82 ± 0.28 ppm), declining gradually to 1.96 ± 0.14 ppm at 2.5 km. Although regulatory limits were not provided for VOCs in the table, the observed spatial distribution indicates that flare activities represent an important emission source. Higher VOC concentrations around flare locations may reflect the release of unburnt hydrocarbons and incomplete combustion products.

Particulate matter concentrations showed the most pronounced variation across the distance categories. $PM_{2.5}$ reduced from 192.4 ± 11.8 µg/m³ at 0.5 km to 66.3 ± 5.1 µg/m³ at 2.5 km. However, all recorded values remained above the WHO guideline of 15 µg/m³ and NESREA limit of 25 µg/m³. Similarly, PM_{10} concentration declined from 348.6 ± 18.5 µg/m³ at 0.5 km to 124.8 ± 8.2 µg/m³ at 2.5 km. The values exceeded the WHO standard of 45 µg/m³ across all distance categories, while concentrations within the first four zones exceeded the NESREA limit of 150 µg/m³. These findings indicate substantial particulate pollution associated with flare emissions, particularly within communities located close to flare points.

Overall, the results demonstrate that pollutant concentrations decrease systematically with increasing distance from flare sites. The highest pollution burden occurs within the 0.5 km zone, where most pollutants exceeded both national and international air quality limits. Although concentrations reduced at greater distances, several pollutants remained above permissible thresholds even at 2.5 km, indicating that the influence of gas flaring extends beyond the immediate vicinity of the flare locations. The observed pattern highlights the role of distance as an important factor controlling exposure levels and suggests that communities located closer to flare sites experience greater environmental and potential health risks due to prolonged exposure to elevated pollutant concentrations.

Hypothesis One: There is no significant difference between the concentration of pollutants (CO, CH_4, SO_2, NO_2, and VOC) and particulate matter ($PM_{2.5}$ and PM_{10}) in Alesa Eleme.

Table 2. ANOVA summary testing the hypothesis 'The concentration of pollutants (CO, CH_4, SO_2, NO_2, VOC) and particulate matter ($PM_{2.5}$ and PM_{10}) in Alesa Eleme does not significantly vary.

Pollutants	N	0.5 km	1 km	1.5 km	2 km	2.5 km	df	F	p-Value	Duncan MRT
CO (ppm)	91	18.6	15.8	12.9	9.8	7.1	4, 86	42.684	.000	0.5km > 1km > 1.5km > 2km > 2.5km
CH_4 (ppm)	91	7.35	6.28	5.16	4.08	3.24	4, 86	38.517	.000	0.5km > 1km > 1.5km > 2km > 2.5km
SO_2 (ppm)	91	0.182	0.151	0.123	0.094	0.068	4, 86	45.392	.000	0.5km > 1km > 1.5km > 2km > 2.5km
NO_2 (ppm)	91	0.194	0.163	0.132	0.098	0.071	4, 86	47.865	.000	0.5km > 1km > 1.5km > 2km > 2.5km
VOC (ppm)	91	4.82	4.06	3.31	2.64	1.96	4, 86	51.736	.000	0.5km > 1km > 1.5km > 2km > 2.5km
$PM_{2.5}$ (µg/m³)	91	192.4	158.7	126.5	94.8	66.3	4, 86	56.924	.000	0.5km > 1km > 1.5km > 2km > 2.5km
PM_{10} (µg/m³)	91	348.6	287.9	229.4	171.6	124.8	4, 86	61.483	.000	0.5km > 1km > 1.5km > 2km > 2.5km

Table 2 presents the one-way Analysis of Variance (ANOVA) results used to test the hypothesis that the concentration of pollutants (CO, CH_4, SO_2, NO_2, VOCs) and particulate matter ($PM_{2.5}$ and PM_{10}) in Alesa Eleme does not significantly vary across different distances from gas flare locations. The analysis was conducted to determine whether the observed differences in pollutant concentrations among the five distance categories (0.5 km, 1 km, 1.5 km, 2 km, and 2.5 km) were statistically significant. The ANOVA results show that all assessed pollutants recorded statistically significant variations across the different distance zones, as indicated by p-values of 0.000, which are below the 0.05 significance level. Therefore, the null hypothesis that pollutant concentrations do not significantly vary with distance from flare sites is rejected. This implies that distance from gas flare locations significantly influences the concentration and distribution of pollutants within Alesa Eleme. Carbon monoxide (CO) recorded a significant difference across the distance categories, with an F-value of 42.684 and p = 0.000. The mean concentration declined progressively from 18.6 ppm at 0.5 km to 7.1 ppm at 2.5 km. The Duncan Multiple Range Test (DMRT) separated all distance categories into distinct groups, indicating that each increase in distance produced a significant reduction in CO concentration. This demonstrates that the highest exposure burden occurs among locations closest to the flare sources. Methane (CH_4) also showed significant spatial variation, with an F-value of 38.517 and p = 0.000. Concentrations reduced from 7.35 ppm at 0.5 km to 3.24 ppm at 2.5 km. The DMRT classification followed the order 0.5 km > 1 km > 1.5 km > 2 km > 2.5 km, confirming that methane levels decreased consistently with increasing distance from the emission source. Sulphur dioxide (SO_2) recorded significant differences among the distance categories (F = 45.392, p = 0.000). The concentration decreased from 0.182 ppm at 0.5 km to 0.068 ppm at 2.5 km. The DMRT results showed that each distance zone formed a separate statistical group, indicating a strong influence of proximity to flare sites on SO_2 distribution. Nitrogen dioxide (NO_2) exhibited the highest variation among the gaseous pollutants, with an F-value of 47.865 and p = 0.000. The mean concentration declined from 0.194 ppm at 0.5 km to 0.071 ppm at 2.5 km. The significant difference among all distance categories indicates that emissions from flare activities contribute substantially to nitrogen oxide levels, particularly within areas located close to the source. Volatile organic compounds (VOCs) recorded an F-value of 51.736 with a significance level of 0.000, showing significant differences across the sampling distances. VOC concentration decreased from 4.82 ppm at 0.5 km to 1.96 ppm at 2.5 km. The DMRT ranking showed a clear separation among all distances, suggesting that dispersion and dilution processes strongly influence VOC concentrations away from flare points. The particulate matter fractions demonstrated the greatest level of spatial variation. $PM_{2.5}$ recorded an F-value of 56.924 (p = 0.000), while PM_{10} recorded the highest F-value of 61.483 (p = 0.000) among all measured pollutants. $PM_{2.5}$ declined from 192.4 µg/m³ at 0.5 km to 66.3 µg/m³ at 2.5 km, whereas PM_{10} reduced from 348.6 µg/m³ to 124.8 µg/m³ within the same distance range. The DMRT results indicated significant differences among all distance categories, confirming that particulate matter concentration is strongly influenced by proximity to gas flaring activities. Generally, the Duncan Multiple Range Test showed a consistent pattern for all pollutants, where the 0.5 km zone recorded the highest pollutant concentration, followed by 1 km, 1.5 km, 2 km, and 2.5 km respectively. The clear separation of the distance groups indicates that pollutant concentrations reduce significantly as distance from flare locations increases. The results demonstrate that gas flaring activities are a major determinant of air quality variation in Alesa Eleme. The significant differences observed across distance zones suggest that residents living closer to flare sites experience greater exposure to elevated concentrations of gaseous pollutants and particulate matter. The findings further confirm that distance plays an important role in controlling pollutant dispersion and the intensity of environmental exposure within the study area.

Research Question Two: Assess the the prevailing meteorological conditions in Alesa Eleme, Rivers State

Research Question Two: What are the prevailing meteorological conditions in Alesa Eleme, Rivers State?

Table 3. Prevailing meteorological conditions in the study area

Weather Parameters	0.5 km (Mean ± SD)	1 km (Mean ± SD)	1.5 km (Mean ± SD)	2 km (Mean ± SD)	2.5 km (Mean ± SD)	Mean
Wind speed (m/s)	1.86 ± 0.21	2.08 ± 0.19	2.31 ± 0.18	2.54 ± 0.16	2.76 ± 0.15	2.31 ± 0.18
Wind direction (°)	216 ± 17	218 ± 16	219 ± 15	221 ± 14	222 ± 13	219 ± 15
Temperature (°C)	30.0 ± 0.8	29.7 ± 0.7	29.4 ± 0.7	29.1 ± 0.6	28.8 ± 0.6	29.4 ± 0.7
Relative humidity (%)	76.2 ± 3.4	77.8 ± 3.2	79.1 ± 3.0	80.4 ± 2.8	81.6 ± 2.6	79.0 ± 3.0
Precipitation (mm)	214.8	216.5	215.9	217.4	216.8	216.3
Solar radiation (W/m²)	421.6 ± 23.8	435.2 ± 22.5	448.7 ± 21.3	461.3 ± 20.2	473.5 ± 18.9	448.1 ± 21.3

Prevailing meteorological conditions in the study area

Table 3 presents the prevailing meteorological conditions recorded at varying distances from the gas flare locations in the study area. The measured parameters include wind speed, wind direction, temperature, relative humidity, precipitation, and solar radiation. These meteorological variables provide important information on the atmospheric conditions that influence pollutant dispersion, transport, and accumulation within the study area. The results show that wind speed increased progressively with distance from the flare locations. The lowest mean wind speed was recorded at 0.5 km (1.86 ± 0.21 m/s), while the highest value occurred at 2.5 km (2.76 ± 0.15 m/s), with an overall mean of 2.31 ± 0.18 m/s. The increasing wind speed away from the flare sites suggests improved atmospheric mixing and dispersion capacity at greater distances. Areas closer to the emission sources experienced relatively lower wind movement, which may contribute to the accumulation of pollutants due to reduced air circulation. The gradual increase in wind speed towards farther locations indicates that atmospheric movement plays a role in reducing pollutant concentration as distance increases.

Wind direction remained relatively consistent across the different monitoring locations, ranging from 216° at 0.5 km to 222° at 2.5 km, with an overall mean of 219 ± 15°. The similarity in wind direction across the sampling points indicates a stable prevailing airflow pattern within the study area. This consistency suggests that emitted pollutants are transported along a relatively uniform pathway, meaning that communities located downwind of the flare sources may experience greater exposure depending on their position relative to the prevailing wind movement. Temperature showed a gradual decline with increasing distance from the flare locations. The highest temperature was recorded at 0.5 km (30.0 ± 0.8°C), while the lowest value was observed at 2.5 km (28.8 ± 0.6°C), with an overall mean temperature of 29.4 ± 0.7°C. The slightly elevated temperatures near the flare sites may be associated with heat generated from continuous gas combustion activities. The reduction in temperature away from the flare locations suggests a decreasing influence of thermal emissions from the flare sources.

Relative humidity exhibited an opposite trend to temperature, increasing gradually with distance. The lowest humidity value was recorded at 0.5 km (76.2 ± 3.4%), while the highest was observed at 2.5 km (81.6 ± 2.6%), with a mean value of 79.0 ± 3.0%. The lower humidity levels near flare locations may be linked to increased thermal energy released from combustion processes, which can enhance evaporation and reduce moisture content in the immediate atmosphere. Higher humidity at greater distances indicates a more stable and moisture-rich atmospheric condition away from direct flare influence. Precipitation values remained relatively uniform across the different distance categories, ranging from 214.8 mm at 0.5 km to 217.4 mm at 2 km, with an overall mean of 216.3 mm. The minimal variation suggests that rainfall distribution was relatively consistent throughout the study area during the monitoring period. Precipitation can influence pollutant concentration by removing airborne particles and gases through wet deposition; however, the similarity in rainfall values indicates that differences in pollutant levels across distances were more strongly associated with emission proximity and atmospheric dispersion rather than rainfall variability. Solar radiation increased progressively with distance from the flare locations. The lowest value was recorded at 0.5 km (421.6 ± 23.8 W/m²), while the highest occurred at 2.5 km (473.5 ± 18.9 W/m²), with an overall mean of 448.1 ± 21.3 W/m². The lower solar radiation close to the flare sites may be influenced by increased atmospheric pollutants, particularly particulate matter, which can reduce incoming solar energy through scattering and absorption. The increase in solar radiation at greater distances suggests clearer atmospheric conditions away from the direct influence of flare emissions. Overall, the meteorological conditions indicate that atmospheric factors influenced pollutant behaviour within the study area. The combination of lower wind speed, higher temperature, lower humidity, and reduced solar radiation near the flare sites created conditions that may favour pollutant accumulation. Conversely, increased wind speed and improved atmospheric conditions at greater distances supported pollutant dispersion and dilution. The observed meteorological pattern corresponds with the spatial reduction of pollutant concentrations recorded across the distance zones, demonstrating the combined influence of emission proximity and atmospheric conditions on air quality variations in the study area.

Hypothesis One: There is no significant relationships between the meteorological parameters and pollutants concentrations in the study area

Table 4. PPMC summaries testing the relationships between the meteorological parameters and pollutants concentrations in the study area

Variables	CO	CH_4	SO_2	NO_2	VOCs	$PM_{2.5}$	PM_{10}	Wind Speed	Temperature	Relative Humidity	Precipitation	Solar Radiation
CO	1	.982**	.965**	.974**	.979**	.951**	.962**	-.941**	.861**	-.791**	-.763**	-.821**
Sig. (2-tailed)		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N	91	91	91	91	91	91	91	91	91	91	91	91
CH_4	.982**	1	.954**	.963**	.971**	.944**	.953**	-.923**	.834**	-.772**	-.741**	-.801**
Sig. (2-tailed)	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N	91	91	91	91	91	91	91	91	91	91	91	91
SO_2	.965**	.954**	1	.981**	.956**	.972**	.984**	-.933**	.852**	-.812**	-.779**	-.831**
Sig. (2-tailed)	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N	91	91	91	91	91	91	91	91	91	91	91	91
NO_2	.974**	.963**	.981**	1	.969**	.961**	.975**	-.952**	.871**	-.823**	-.801**	-.841**
Sig. (2-tailed)	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N	91	91	91	91	91	91	91	91	91	91	91	91
VOCs	.979**	.971**	.956**	.969**	1	.946**	.957**	-.914**	.823**	-.763**	-.731**	-.781**
Sig. (2-tailed)	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000
N	91	91	91	91	91	91	91	91	91	91	91	91
$PM_{2.5}$	.951**	.944**	.972**	.961**	.946**	1	.991**	-.961**	.883**	-.841**	-.823**	-.861**
Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000
N	91	91	91	91	91	91	91	91	91	91	91	91
PM_{10}	.962**	.953**	.984**	.975**	.957**	.991**	1	-.952**	.872**	-.832**	-.811**	-.851**

Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000
N	91	91	91	91	91	91	91	91	91	91	91	91
Wind Speed	-.941**	-.923**	-.933**	-.952**	-.914**	-.961**	-.952**	1	-.781**	.721**	.684**	.741**
Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000
N	91	91	91	91	91	91	91	91	91	91	91	91

Table 4 presents the Pearson Product Moment Correlation (PPMC) analysis conducted to determine the relationships between meteorological parameters and pollutant concentrations in the study area. The analysis involved 91 observations and examined the strength and direction of relationships between measured pollutants (CO, CH_4, SO_2, NO_2, VOCs, $PM_{2.5}$, and PM_{10}) and prevailing weather conditions including wind speed, temperature, relative humidity, precipitation, and solar radiation. The correlation coefficients (r) range from -1 to +1, where positive values indicate that variables increase together, while negative values indicate an inverse relationship. The results reveal strong and statistically significant relationships among all measured pollutants. Carbon monoxide (CO) demonstrated very strong positive correlations with other pollutants, including CH_4 (r = 0.982, p = 0.000), SO_2 (r = 0.965, p = 0.000), NO_2 (r = 0.974, p = 0.000), VOCs (r = 0.979, p = 0.000), $PM_{2.5}$ (r = 0.951, p = 0.000), and PM_{10} (r = 0.962, p = 0.000). These strong associations indicate that the pollutants likely originate from similar emission sources, particularly gas flaring activities, where combustion processes release multiple pollutants simultaneously. The significant positive relationships suggest that increases in one pollutant are accompanied by corresponding increases in other pollutants. Methane (CH_4) also recorded strong positive correlations with all assessed pollutants. It correlated strongly with SO_2 (r = 0.954, p = 0.000), NO_2 (r = 0.963, p = 0.000), VOCs (r = 0.971, p = 0.000), $PM_{2.5}$ (r = 0.944, p = 0.000), and PM_{10} (r = 0.953, p = 0.000). This pattern indicates that methane concentration changes correspond closely with variations in gaseous and particulate pollutants within the study area. The relationship suggests that areas experiencing elevated flare emissions also experience increased levels of multiple contaminants. Sulphur dioxide (SO_2) showed particularly strong relationships with particulate matter, recording correlations of r = 0.972 with $PM_{2.5}$ and r = 0.984 with PM_{10}, both significant at p = 0.000. The strong association between SO_2 and particulate matter indicates that combustion emissions contribute simultaneously to gaseous pollution and airborne particles. Similarly, NO_2 exhibited strong positive relationships with $PM_{2.5}$ (r = 0.961) and PM_{10} (r = 0.975), confirming that nitrogen oxide emissions increase alongside particulate pollution. The relationship between particulate matter fractions was the strongest among all pollutant combinations. $PM_{2.5}$ and PM_{10} recorded a correlation coefficient of r = 0.991 (p = 0.000), indicating an almost perfect positive relationship. This suggests that both particulate fractions were influenced by similar emission processes and atmospheric conditions. The strong relationship also indicates that changes affecting fine particles were accompanied by corresponding changes in coarse particulate matter concentrations. The correlation between meteorological parameters and pollutants revealed important patterns regarding pollutant dispersion. Wind speed showed strong negative relationships with all pollutants. The correlation coefficients ranged from r = -0.914 for VOCs to r = -0.961 for $PM_{2.5}$, all significant at p = 0.000. This indicates that increasing wind speed was associated with reduced pollutant concentrations. The inverse relationship suggests that stronger air movement enhances pollutant dispersion and dilution, thereby lowering pollutant accumulation near emission sources. Temperature recorded positive relationships with pollutant concentrations. CO showed a strong positive correlation with temperature (r = 0.861, p = 0.000), while other pollutants also showed significant positive relationships, including CH_4 (r = 0.834), SO_2 (r = 0.852), NO_2 (r = 0.871), VOCs (r = 0.823), $PM_{2.5}$ (r = 0.883), and PM_{10} (r = 0.872). This suggests that higher temperatures were associated with increased pollutant levels. The relationship may be linked to enhanced atmospheric reactions, increased emission rates, and thermal influences from flare activities. Relative humidity showed significant negative correlations with all pollutants. The relationship ranged from r = -0.763 with CO to r = -0.841 with $PM_{2.5}$. This indicates that increasing humidity levels were associated with reduced pollutant concentrations. Higher atmospheric moisture may contribute to pollutant removal through particle settling and absorption processes, resulting in lower observed concentrations. Precipitation also exhibited significant negative relationships with pollutant concentrations. Correlation coefficients ranged from r = -0.731 for VOCs to r = -0.823 for $PM_{2.5}$. The inverse relationship indicates that rainfall contributes to the reduction of airborne pollutants through atmospheric cleansing processes. Areas and periods with higher precipitation recorded lower pollutant concentrations due to the removal of suspended particles and soluble gases. Solar radiation demonstrated negative relationships with pollutants, with correlation values ranging from r = -0.781 for VOCs to r = -0.861 for $PM_{2.5}$. This indicates that increased solar radiation was associated with reduced pollutant concentrations. The relationship may be associated with improved atmospheric mixing and photochemical processes that influence pollutant transformation and removal. The PPMC results demonstrate that meteorological conditions significantly influence pollutant concentrations in the study area. The strong positive relationships among pollutants indicate a common emission source associated with gas flaring activities, while the negative relationship between wind speed, humidity, precipitation, solar radiation, and pollutant concentrations demonstrates the importance of atmospheric conditions in controlling pollutant dispersion. The findings suggest that periods characterized by low wind speed, reduced rainfall, lower humidity, and intense flare activity are more likely to experience higher pollutant accumulation within the surrounding environment.

IV. DISCUSSION OF RESULTS

Concentrations of Gaseous Pollutants and Particulate Matter in Alesa Eleme

The results from this research demonstrated a distinct variation in pollutant levels, where significantly higher concentrations of all examined gaseous pollutants (CO, CH_4, SO_2, NO_2, VOCs) along with particulate matter ($PM_{2.5}$ and PM_{10}) were found at 0.5 km from gas flare sources as opposed to those at 2.5 km. This suggests a notable proximity effect, showing that emissions from gas flaring have a direct impact on the quality of the ambient air. The level of carbon monoxide at the closest site (18.6 ppm) was substantially above the WHO recommended limit (3.5 ppm), indicating a severe risk of exposure. This observation is consistent with past research conducted in the Niger Delta, which noted increased CO concentrations in gas-flaring areas due to incomplete combustion processes (Ajugwo, 2013; Ekpoh & Obia, 2010). Likewise, the reduction in concentration with increasing distance corroborates the dispersion trends noted in atmospheric pollution research, where pollutants are shown to decrease exponentially as they move away from emission sources due to dilution and mixing in the atmosphere (Seinfeld & Pandis, 2016). Methane levels also exhibited a reduction with distance. While there are no WHO guidelines for methane exposure in ambient air, the heightened levels near flare sites are in line with findings from Ite and Ibok (2013), who observed significant hydrocarbon enrichment in areas affected by gas flaring in the Niger Delta. Levels of sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) surpassed the limits set by WHO and NESREA in most sampling locations, indicating a significant amount of emissions resulting from combustion processes. These results align with the research conducted by Gobo et al. (2009), which reported elevated SO_2 and NO_2 concentrations in areas surrounding gas flares in Rivers State, attributing this to the combustion of high-sulphur crude oil and ongoing flaring activities.

Concentrations of particulate matter ($PM_{2.5}$ and PM_{10}) were alarmingly high at all distances sampled, with figures considerably exceeding WHO standards. This is consistent with the work of Amadi et al. (2019), who found severe levels of particulate pollution in Eleme attributed to petrochemical and gas processing operations. Elevated particulate matter poses serious health risks, especially since $PM_{2.5}$ is closely linked to both respiratory and cardiovascular health issues (WHO, 2021). The evidence supports the conclusion that gas flaring serves as a major contributor to air pollution in Alesa Eleme, which is consistent with regional environmental evaluations conducted in the Niger Delta (Nduka & Orisakwe, 2011).

Effect of Distance on Pollutant Concentration (Spatial Variation and ANOVA Results)

The results from the ANOVA indicated notable differences in the levels of pollutants ($p < 0.05$) across various distance categories, validating that the closeness to flare sites has a significant impact on air quality. The most pronounced variation occurred in particulate matter (PM_{10} and $PM_{2.5}$), signifying that solid emissions are very responsive to both distance and dispersion factors. This observation aligns with atmospheric dispersion principles as well as the empirical findings of Seinfeld and Pandis (2016), which highlight the quick settling of heavier particulate matter close to emission points. The considerable decrease in pollutant levels with increased distance corresponds with the results reported by Nwachukwu et al. (2012), who identified comparable spatial patterns in pollutant concentrations within gas-flaring areas in Bayelsa State. Their research also verified that populations situated within a 1 km radius of flare sites face the most intense exposure levels. The Duncan Multiple Range Test additionally confirmed a sequential decline in pollutants (0.5 km > 1 km > 1.5 km > 2 km > 2.5 km), indicating a consistent pathway of atmospheric dilution. This is in support of the plume dispersion models often utilized in the field of environmental pollution research (Turner, 1994). This suggests that individuals living within a kilometer of flare sites encounter markedly higher levels of pollution, reinforcing previous studies indicating that gas flaring establishes concentrated zones of environmental health risks (Ekpoh & Obia, 2010).

Prevailing Meteorological Conditions in Alesa Eleme

The analysis of meteorological factors indicated that wind speed, temperature, humidity, solar radiation, and precipitation significantly affect how pollutants disperse. An increase in wind speed was noted as the distance from flare sites grew, implying less turbulence and obstructions near sources of emissions. Reduced wind speed close to flare sites likely encourages the buildup of pollutants. This finding corresponds with atmospheric research by Jacob (1999), which underlines the significance of wind speed in promoting the dilution of pollutants. Increased temperatures were detected nearer to flare locations, indicating localized heating effects resulting from ongoing gas combustion. This aligns with the observations of Gobo et al. (2009), who noted microclimatic warming in areas affected by gas flaring in the Niger Delta. Relative humidity was observed to rise with distance, which hints at drier conditions near flare sites due to heat effects. Similar findings were documented by Nwankwo and Ogagarue (2011), who described changes in microclimatic conditions within oil-producing regions. The distance-related increase in solar radiation suggests that particulate emissions close to flare sites could impair atmospheric clarity by scattering and absorbing sunlight. This is in line with WHO (2021) findings on how $PM_{2.5}$ affects solar radiation decrease. The meteorological factors identified in this investigation affirm that gas flaring disrupts local atmospheric stability, consequently affecting the dynamics of pollutant dispersion.

Relationship between Meteorological Parameters and Pollutant Concentrations

The Pearson correlation investigation indicated significant and robust connections between weather variables and the levels of pollutants. Wind speed demonstrated strong negative associations with all types of pollutants, suggesting that higher wind speeds facilitate the spread of pollutants and prevent their accumulation. This observation is in line with the findings of Seinfeld and Pandis (2016), who recognized wind speed as a critical factor for the efficiency of pollutant dispersion. Warmer temperatures exhibited positive associations with pollutants, indicating that elevated temperatures might increase emission levels and promote chemical reactions in the atmosphere. This conclusion is supported by Jacob (1999), who highlighted the role of temperature in photochemical processes within polluted air. Relative humidity and rainfall displayed negative associations with pollutants, reinforcing their importance in removing pollutants through wet deposition and scavenging. This supports the conclusions of Brasseur and Jacob (2017), who highlighted the importance of rain as a vital mechanism for atmospheric purification. Solar radiation also presented negative correlations with pollutants, likely attributable to increased atmospheric mixing and the photochemical breakdown of contaminants. The strong correlations among different pollutants imply a shared source of emissions, specifically from gas flaring activities. This is consistent with the work of Ite and Ibok (2013), who pinpointed petroleum combustion as a common cause of multiple pollutant emissions in the Niger Delta.

4.5 Conclusion

This research illustrates that gas flaring is a major factor in reducing air quality in Alesa Eleme, as pollutant levels diminish with distance but still surpass international limits in many areas. Weather conditions play a crucial role in the distribution of pollutants, and statistical evaluations indicate notable variations in pollutant concentrations across different locations. In general, individuals living near flare sites face dangerous environmental conditions that could pose health risks.

RECOMMENDATIONS

1. Government organizations (such as NESREA) should enhance monitoring and enforcement efforts to ensure adherence to emission regulations.
2. Housing developments should be situated at safer distances (more than 2–5 km) from flare sites to lower exposure risks.
3. Regular health checks for respiratory and cardiovascular issues should be conducted for residents in the impacted communities.
4. Rather than flaring, associated gas should be captured and utilized, in accordance with global climate change mitigation efforts.

REFERENCES

[1]. Ajugwo, A. O. (2013). Negative effects of gas flaring: The Nigerian experience. *Journal of Environment and Pollution, 3*(4), 30–38.

[2]. Amadi, A. N., Olasehinde, P. I., Okoye, N. O., & Okoye, P. A. (2019). Air quality assessment in industrial areas of Rivers State, Nigeria. *Environmental Monitoring and Assessment, 191*(5), 1–14.

[3]. Brasseur, G. P., & Jacob, D. J. (2017). *Modeling of atmospheric chemistry*. Cambridge University Press.

[4]. Ekpoh, I. J., & Obia, A. E. (2010). The role of gas flaring in the rapid corrosion of zinc roofs in the Niger Delta region of Nigeria. *African Journal of Environmental Science and Technology, 4*(4), 251–257.

[5]. Gobo, A. E., Richard, G. A., & Ubong, I. U. (2009). Health impact of gas flares in Nigeria. *International Journal of Environmental Research, 3*(2), 345–351.

[6]. Ite, A. E., & Ibok, U. J. (2013). Gas flaring and venting associated with petroleum exploration and production in the Niger Delta, Nigeria. *American Journal of Environmental Protection, 1*(4), 145–150.

[7]. Jacob, D. J. (1999). *Introduction to atmospheric chemistry*. Princeton University Press.

[8]. Nduka, J. K., & Orisakwe, O. E. (2011). Air pollution and public health in the Niger Delta region. *Environmental Health Perspectives, 119*(7), 105–110.

[9]. Nwankwo, C. N., & Ogagarue, D. O. (2011). Effects of gas flaring on local microclimate in the Niger Delta. *Journal of Environmental Science and Engineering, 5*(6), 743–751.

[10]. Seinfeld, J. H., & Pandis, S. N. (2016). *Atmospheric chemistry and physics: From air pollution to climate change* (3rd ed.). Wiley.

[11]. Turner, D. B. (1994). *Workbook of atmospheric dispersion estimates*. CRC Press.

[12]. World Health Organization (WHO) (2021). *WHO global air quality guidelines*. WHO Press.