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# Measurement and characterization of ambient air pollutants in selected industrial areas of Kaduna, Nigeria

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## Abstract

Air pollution from industrial sources is a critical environmental and public health concern in Nigeria. This study measured concentrations of gaseous pollutants (CO, NO, $NO_2$, $SO_2$, $H_2S$, $NH_3$) and particulate matter ($PM_{1.0}$, $PM_{2.5}$, $PM_{10}$) in selected industrial areas of Kaduna Metropolis, Northwestern Nigeria. Five major stationary emission sources Kaduna Refinery, Indomie Factory, Hikman Gas Plant, PZ Cusson Factory, and A.A. Rano Diesel Plant were sampled at distances of 10–100 m from emission points. Results showed that pollutant concentrations decreased exponentially with distance due to atmospheric dispersion. Comparisons with WHO 24-hour guideline limits (CO: 4.00 $\mu g/m^3$; $PM_{2.5}$: 5.00 $\mu g/m^3$; $PM_{10}$: 20.00 $\mu g/m^3$) revealed significant exceedances at four functional sites. At Indomie Factory, CO (18.71 $\mu g/m^3$) and $PM_{2.5}$ (32.95 $\mu g/m^3$) exceeded limits by factors of 4.7 and 6.6. At Hikman Gas Plant, CO (15.30 $\mu g/m^3$) and $PM_{2.5}$ (24.55 $\mu g/m^3$) exceeded limits by factors of 3.8 and 4.9. At PZ Cusson Factory, CO (16.18 $\mu g/m^3$) and $PM_{2.5}$ (32.45 $\mu g/m^3$) exceeded limits by factors of 4.0 and 6.5. At A.A. Rano Diesel Plant, CO (17.96 $\mu g/m^3$) and $PM_{2.5}$ (27.89 $\mu g/m^3$) exceeded limits by factors of 4.5 and 5.6. $PM_{10}$ at Indomie Factory (60.07 $\mu g/m^3$) exceeded the WHO limit by a factor of 3. The non-operational Kaduna Refinery recorded values within permissible limits. Diesel generator exhaust was identified as the major contributor ($CO–PM_{2.5}$: $r = 0.82$, $p < 0.01$). The study recommends routine monitoring, cleaner energy adoption, and stricter enforcement of air quality standards.

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## 1. Introduction

Air pollution has emerged as one of the most pressing environmental and public health challenges of the 21st century. Globally, the World Health Organization estimates that air pollution causes approximately 7 million premature deaths annually, with low- and

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Table 1: GPS coordinates of study sites.

| Study Site | Latitude | Longitude |
|---|---|---|
| Kaduna Refinery | 10.4896° N | 7.4119° E |
| Indomie Factory | 10.5015° N | 7.4408° E |
| Hikman Gas Plant | 10.6446° N | 7.5439° E |
| PZ Cusson Factory | 10.5864° N | 7.4658° E |
| A.A. Rano Diesel Plant | 10.5516° N | 7.4547° E |

middle-income countries bearing the heaviest burden [1]. Air pollutants are toxic solid, liquid, or gaseous substances present in the atmosphere at concentrations injurious to living organisms and the environment [2]. With rapid population growth, industrialization, and urbanization, air pollution has become a global problem requiring urgent attention [3].

Pollutants are broadly classified as natural or anthropogenic, and as primary or secondary pollutants. Primary pollutants are emitted directly into the atmosphere, while secondary pollutants form through photochemical reactions [4]. Common primary pollutants include sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), carbon monoxide (CO), carbon dioxide ($CO_2$), and particulate matter (PM). Particulate matter, particularly $PM_{10}$ and $PM_{2.5}$, has received significant research attention due to its ability to penetrate deep into the respiratory system and enter the bloodstream [5]. Exposure to these pollutants has been linked to systemic inflammation, altered heart rate variability, myocardial infarction [6], and respiratory diseases such as pulmonary tuberculosis, pneumonia, and chronic obstructive pulmonary disease [7].

In Nigeria, air pollution has reached critical levels in major urban and industrial centers. Kaduna State, located in Northwestern Nigeria, hosts a concentration of industrial activities including petroleum refining, food processing, gas production, and manufacturing. The Kaduna Refinery, Indomie Factory, Hikman Gas Plant, PZ Cusson Factory, and A.A Rano Diesel Plant represent significant stationary emission sources within the state's industrial corridor. However, despite growing concerns, there is a paucity of quantitative data on pollutant concentrations from these specific sources. Previous studies have examined air quality in other Nigerian cities such as Lagos, Port Harcourt, and Zaria, but limited information exists for stationary industrial sources in Kaduna Metropolis.

Technological interventions such as catalytic converters and scrubbers remain costly, requiring substantial financial investment for full implementation. Effective pollution abatement therefore requires accurate emission data and a clear understanding of contributing factors. This study aims to fill this gap by measuring and characterizing air pollutant concentrations from selected stationary sources in Kaduna State, focusing on CO, $SO_2$, $NO_2$, $PM_{2.5}$, and $PM_{10}$, and assessing their compliance with WHO standards.

## 2. Materials and methods

### *2.1. Study area and sites*

The study was conducted in Kaduna State, Northwestern Nigeria (latitude 9°30′ to 11°30′ N, longitude 6°00′ to 9°00′ E). Five major stationary sources were selected based on their industrial significance and potential emission impact: Kaduna Refinery, Indomie Factory, Hikman Gas Plant, PZ Cusson Factory, and A.A. Rano Diesel Plant. These industries represent high-emission points within the state's industrial corridor. The geographical distribution of these sites is shown in Figure 1.

Table 1 presents the GPS coordinates of all sampling sites.

### *2.2. Materials*

The following equipment was utilized for sample collection and analysis: a high-volume respirable dust sampler (APM 460 NL), an Atomic Absorption Spectrophotometer (AAS), Altair Pro single-gas detectors (for CO, $H_2S$, $SO_2$, and $NH_3$), a HAT 200 multichannel detector (for $PM_{1.0}$, $PM_{2.5}$, and $PM_{10}$), a GC310 Gas Detector (for NO and $NO_2$), and a Global Positioning System (GPS) for geolocation.

All instruments were calibrated before each sampling session following manufacturer specifications. Quality control measures included daily zero and span checks, replicate measurements at 10% of sampling points, and regular maintenance of detector sensors.

### *2.3. Sampling procedure*

At each site, measurements were taken at 1.5 m above ground level (approximate breathing height). The sampling equipment was positioned downward (i.e., facing away from the prevailing wind direction to avoid obstruction) at distances of 10 m to 100 m from the emission point, at 10-m intervals. Measurements were recorded at 2-minute intervals for 8 hours per day, across both wet (May–October) and dry (November–April) seasons. Three replicate measurements were taken at each distance to ensure reliability.

Meteorological parameters including wind speed (anemometer), wind direction (wind vane), temperature (thermometer), and relative humidity (hygrometer) were recorded concurrently at each sampling location.

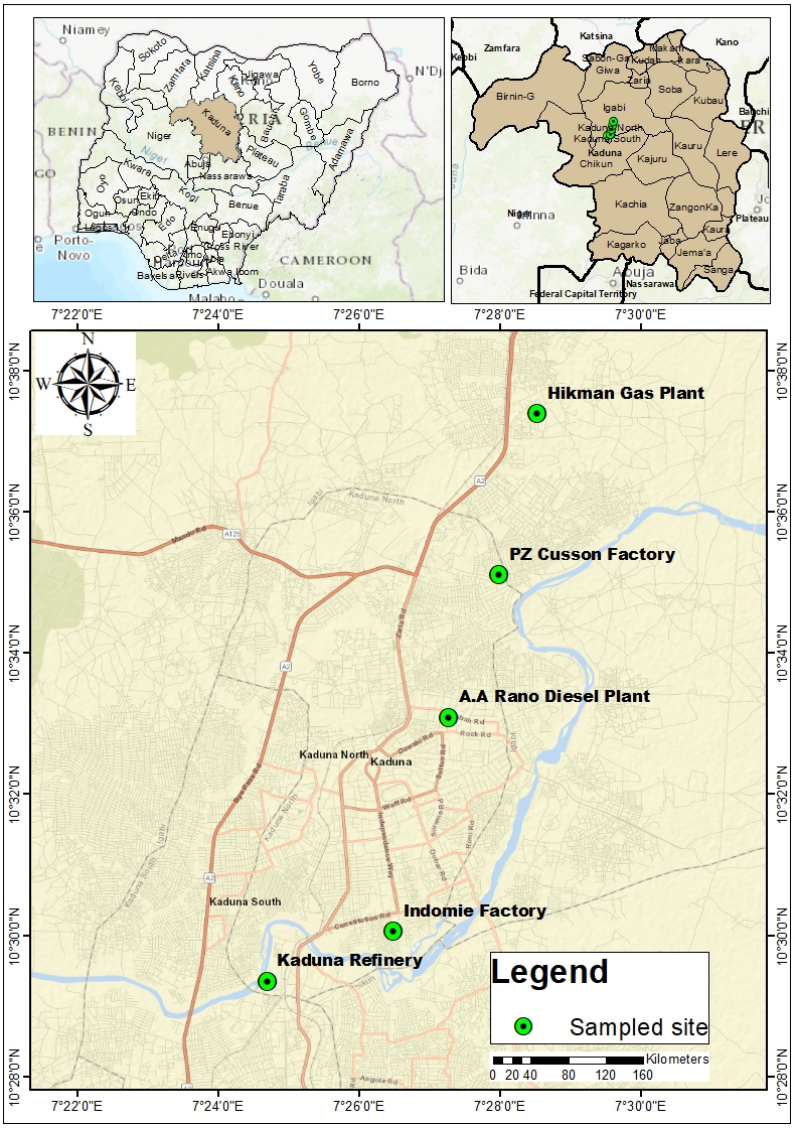



Figure 1: Map of Kaduna State, Nigeria showing the location of the five study sites (Kaduna refinery, indomie factory, Hikman gas plant, PZ Cusson factory, and A.A Rano diesel plant). The inset shows the position of Kaduna State within Nigeria.

### *2.4. Statistical analysis*

Mean concentrations and standard deviations were calculated for each pollutant at each distance and site. One-way analysis of variance (ANOVA) was performed to assess significant differences among sites and among distances, with post-hoc Tukey tests for pairwise comparisons. Pearson correlation analysis was conducted to examine relationships between pollutants. All statistical analyses were performed using MATLAB software, with statistical significance set at $p < 0.05$.

## 3. Results

### *3.1. Pollutant concentrations by distance*

The variations of mean gaseous pollutant and particulate concentrations with distance from emission sources are presented in Tables 2 to 6. A consistent pattern emerged across all functional sites: pollutant concentrations decreased exponentially with increasing distance from the source, attributed to atmospheric dispersion. However, different pollutants exhibited different dispersion rates. Nitrogen oxides (NO, $NO_2$) and sulfur dioxide ($SO_2$) dispersed more rapidly than CO and particulate matter, particularly at the Kaduna Refinery where background concentrations were lower.

At the Kaduna Refinery (Table 2), all pollutant concentrations were notably lower than at other sites, reflecting the facility's non-operational status. CO concentration decreased from 10.42 $\mu g/m^3$ at 10 m to below detection limit at 90 m, while $PM_{2.5}$ decreased from 12.32 $\mu g/m^3$ to 1.77 $\mu g/m^3$ over the same distance.

Table 2: Mean concentration ($\mu g/m^3$) of pollutants with distance at Kaduna refinery.

| Distance (m) | CO | NO | $NO_2$ | $H_2S$ | $SO_2$ | $NH_3$ | $PM_{1.0}$ | $PM_{2.5}$ | $PM_{10}$ |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 10.42 | 6.01 | 5.61 | 12.31 | 8.10 | 14.66 | 7.64 | 12.32 | 7.64 |
| 20 | 8.96 | 4.00 | 3.80 | 10.77 | 7.24 | 13.43 | 6.82 | 11.65 | 6.82 |
| 30 | 6.22 | 2.14 | 2.00 | 8.33 | 6.04 | 12.88 | 6.32 | 10.22 | 6.32 |
| 40 | 4.66 | 1.01 | 1.00 | 6.98 | 4.11 | 10.76 | 5.44 | 9.46 | 5.44 |
| 50 | 3.00 | 0.00 | 0.00 | 4.45 | 3.21 | 8.11 | 4.69 | 7.88 | 4.69 |
| 60 | 2.01 | 0.00 | 0.00 | 2.34 | 2.24 | 6.65 | 4.18 | 4.68 | 4.18 |
| 70 | 1.68 | 0.00 | 0.00 | 1.02 | 0.00 | 4.02 | 3.05 | 3.25 | 3.05 |
| 80 | 1.02 | 0.00 | 0.00 | 0.00 | 0.00 | 2.80 | 2.42 | 2.72 | 2.42 |
| 90 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.92 | 1.83 | 2.43 | 1.83 |
| 100 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.22 | 1.32 | 1.77 | 1.99 |

Table 3: Mean concentration ($\mu g/m^3$) of pollutants with distance at indomie factory.

| Distance (m) | CO | NO | $NO_2$ | $H_2S$ | $SO_2$ | $NH_3$ | $PM_{1.0}$ | $PM_{2.5}$ | $PM_{10}$ |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 23.40 | 19.90 | 19.70 | 12.35 | 14.22 | 16.30 | 14.55 | 34.88 | 64.22 |
| 20 | 23.00 | 19.48 | 18.88 | 11.46 | 12.65 | 15.72 | 14.21 | 34.44 | 64.00 |
| 30 | 22.41 | 19.45 | 17.93 | 10.44 | 10.32 | 13.12 | 13.80 | 34.10 | 63.78 |
| 40 | 22.00 | 18.81 | 17.33 | 8.31 | 9.33 | 12.35 | 13.31 | 33.64 | 63.45 |
| 50 | 20.61 | 16.22 | 16.12 | 7.12 | 5.63 | 11.00 | 12.80 | 33.26 | 60.44 |
| 60 | 19.43 | 15.23 | 14.80 | 6.25 | 4.00 | 8.32 | 12.68 | 33.12 | 60.31 |
| 70 | 18.52 | 13.00 | 12.60 | 5.51 | 3.40 | 6.19 | 12.65 | 32.16 | 58.99 |
| 80 | 15.46 | 12.40 | 12.31 | 3.42 | 1.50 | 4.00 | 12.33 | 31.52 | 58.57 |
| 90 | 11.64 | 12.00 | 11.70 | 2.35 | 0.00 | 2.10 | 12.21 | 31.32 | 54.32 |
| 100 | 10.68 | 11.00 | 10.66 | 1.46 | 0.00 | 1.63 | 11.84 | 31.10 | 52.66 |

Table 4: Mean concentration ($\mu g/m^3$) of pollutants with distance at Hikman gas plant.

| Distance (m) | CO | NO | $NO_2$ | $H_2S$ | $SO_2$ | $NH_3$ | $PM_{1.0}$ | $PM_{2.5}$ | $PM_{10}$ |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 20.81 | 15.30 | 14.80 | 8.24 | 11.24 | 13.66 | 12.40 | 34.66 | 54.44 |
| 20 | 20.10 | 14.28 | 14.00 | 6.11 | 9.88 | 12.12 | 11.68 | 32.32 | 52.62 |
| 30 | 18.54 | 12.55 | 12.12 | 4.45 | 6.12 | 10.22 | 11.15 | 30.23 | 50.48 |
| 40 | 17.20 | 12.11 | 11.23 | 2.00 | 4.13 | 8.55 | 10.33 | 28.00 | 48.50 |
| 50 | 16.66 | 11.28 | 11.00 | 1.10 | 2.00 | 6.08 | 10.11 | 26.32 | 45.31 |
| 60 | 15.43 | 10.10 | 9.40 | 0.00 | 1.00 | 4.12 | 9.10 | 24.66 | 42.66 |
| 70 | 13.82 | 8.04 | 7.80 | 0.00 | 0.00 | 2.89 | 8.21 | 21.65 | 40.32 |
| 80 | 12.12 | 6.43 | 6.11 | 0.00 | 0.00 | 2.00 | 7.23 | 18.21 | 37.78 |
| 90 | 10.14 | 4.50 | 3.40 | 0.00 | 0.00 | 1.10 | 5.12 | 16.90 | 34.32 |
| 100 | 8.22 | 2.80 | 1.42 | 0.00 | 0.00 | 0.00 | 2.10 | 12.55 | 30.66 |

At the Indomie Factory (Table 3), the highest concentrations among all sites were recorded. CO at 10 m reached 23.40 $\mu g/m^3$, while $PM_{2.5}$ and $PM_{10}$ at the same distance were 34.88 $\mu g/m^3$ and 64.22 $\mu g/m^3$ respectively. These values decreased gradually to 10.68 $\mu g/m^3$ (CO), 31.10 $\mu g/m^3$ ($PM_{2.5}$), and 52.66 $\mu g/m^3$ ($PM_{10}$) at 100 m.

Similar patterns were observed at Hikman Gas Plant (Table 4), PZ Cusson Factory (Table 5), and A.A. Rano Diesel Plant (Table 6), with CO and $PM_{2.5}$ consistently exceeding WHO limits across all distances up to 100 m.

### *3.2. Comparison with WHO standards*

The mean concentrations of pollutants after 8 hours of monitoring were compared with limit guidelines. Figures 2 to 6 present these comparisons.

At the Kaduna Refinery (Figure 2), all pollutant levels were below WHO limits, consistent with the facility's non-operational status.

At the Indomie Factory (Figure 3), CO (mean: 18.71 $\mu g/m^3$) and $PM_{2.5}$ (mean: 32.95 $\mu g/m^3$) exceeded the WHO limits of 4.00 $\mu g/m^3$ and 5.00 $\mu g/m^3$, respectively. $PM_{10}$ (mean: 60.07 $\mu g/m^3$) also exceeded the WHO limit of 20 $\mu g/m^3$.

At the Hikman Gas Plant (Figure 4), CO (mean: 15.30 $\mu g/m^3$) and $PM_{2.5}$ (mean: 24.55 $\mu g/m^3$) exceeded WHO limits, while other pollutants remained within permissible ranges.

Table 5: Mean concentration ($\mu g/m^3$) of pollutants with distance at PZ Cusson factory.

| Distance (m) | CO | NO | $NO_2$ | $H_2S$ | $SO_2$ | $NH_3$ | $PM_{1.0}$ | $PM_{2.5}$ | $PM_{10}$ |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 20.24 | 14.22 | 12.43 | 6.22 | 10.33 | 11.32 | 14.26 | 33.82 | 50.46 |
| 20 | 19.92 | 14.11 | 12.15 | 6.00 | 9.00 | 10.11 | 11.67 | 33.16 | 50.13 |
| 30 | 19.33 | 13.05 | 11.03 | 5.22 | 7.44 | 9.54 | 11.08 | 32.11 | 50.11 |
| 40 | 18.41 | 12.66 | 10.22 | 3.20 | 5.62 | 8.23 | 10.61 | 32.12 | 47.65 |
| 50 | 17.21 | 12.08 | 9.00 | 2.32 | 1.50 | 7.57 | 10.10 | 32.11 | 45.82 |
| 60 | 16.42 | 11.42 | 7.56 | 1.00 | 1.00 | 5.11 | 10.02 | 34.10 | 44.51 |
| 70 | 15.12 | 10.14 | 7.00 | 0.00 | 0.00 | 3.99 | 9.84 | 33.10 | 42.49 |
| 80 | 13.98 | 9.63 | 6.68 | 0.00 | 0.00 | 2.66 | 9.72 | 32.00 | 39.22 |
| 90 | 11.64 | 7.66 | 4.45 | 0.00 | 0.00 | 0.00 | 8.06 | 31.42 | 37.12 |
| 100 | 9.55 | 5.47 | 2.21 | 0.00 | 0.00 | 0.00 | 7.10 | 30.55 | 36.44 |

Table 6: Mean concentration ($\mu g/m^3$) of pollutants with distance at A.A. Rano diesel plant.

| Distance (m) | CO | NO | $NO_2$ | $H_2S$ | $SO_2$ | $NH_3$ | $PM_{1.0}$ | $PM_{2.5}$ | $PM_{10}$ |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 22.32 | 11.65 | 10.44 | 4.66 | 4.65 | 10.66 | 13.32 | 31.42 | 51.46 |
| 20 | 22.12 | 11.10 | 10.11 | 4.00 | 4.00 | 10.00 | 12.04 | 30.14 | 50.13 |
| 30 | 21.30 | 12.45 | 9.43 | 2.65 | 3.46 | 8.43 | 11.31 | 28.33 | 50.11 |
| 40 | 20.41 | 12.14 | 7.39 | 1.00 | 2.10 | 8.11 | 11.25 | 28.20 | 47.65 |
| 50 | 18.88 | 11.15 | 7.00 | 0.00 | 1.00 | 7.33 | 11.00 | 28.12 | 45.82 |
| 60 | 17.76 | 10.41 | 6.66 | 0.00 | 1.00 | 5.00 | 10.45 | 27.60 | 44.51 |
| 70 | 16.52 | 10.11 | 5.40 | 0.00 | 0.00 | 4.37 | 10.13 | 27.00 | 42.49 |
| 80 | 14.76 | 8.98 | 5.00 | 0.00 | 0.00 | 3.60 | 10.00 | 26.50 | 39.22 |
| 90 | 14.00 | 8.22 | 3.95 | 0.00 | 0.00 | 2.00 | 9.30 | 26.12 | 37.12 |
| 100 | 11.51 | 7.00 | 1.32 | 0.00 | 0.00 | 0.00 | 7.10 | 25.55 | 36.44 |

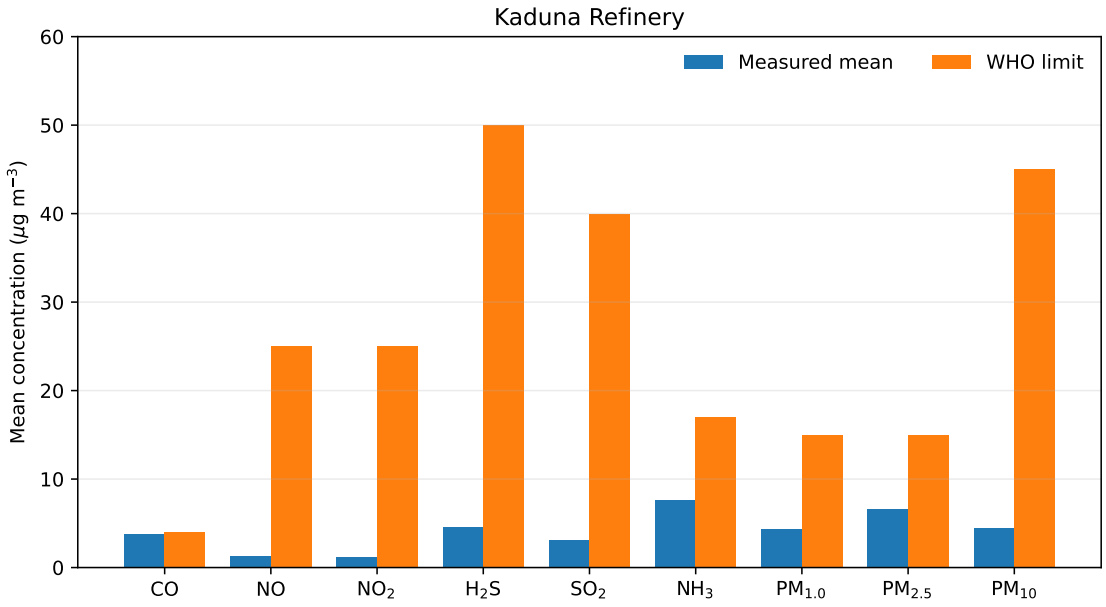



Figure 2: Comparison of measured mean concentrations of gaseous pollutants and particulates at Kaduna refinery with WHO standard limits. All pollutants (CO, NO, $NO_2$, $SO_2$, $H_2S$, $NH_3$, $PM_{1.0}$, $PM_{2.5}$, and $PM_{10}$) are within the supplied permissible limits.

At the PZ Cusson Factory (Figure 5), CO (mean: 16.18 $\mu g/m^3$) and $PM_{2.5}$ (mean: 32.45 $\mu g/m^3$) showed significant exceedances.

At the A.A. Rano Diesel Plant (Figure 6), CO (mean: 17.96 $\mu g/m^3$) and $PM_{2.5}$ (mean: 27.89 $\mu g/m^3$) likewise exceeded WHO standards.

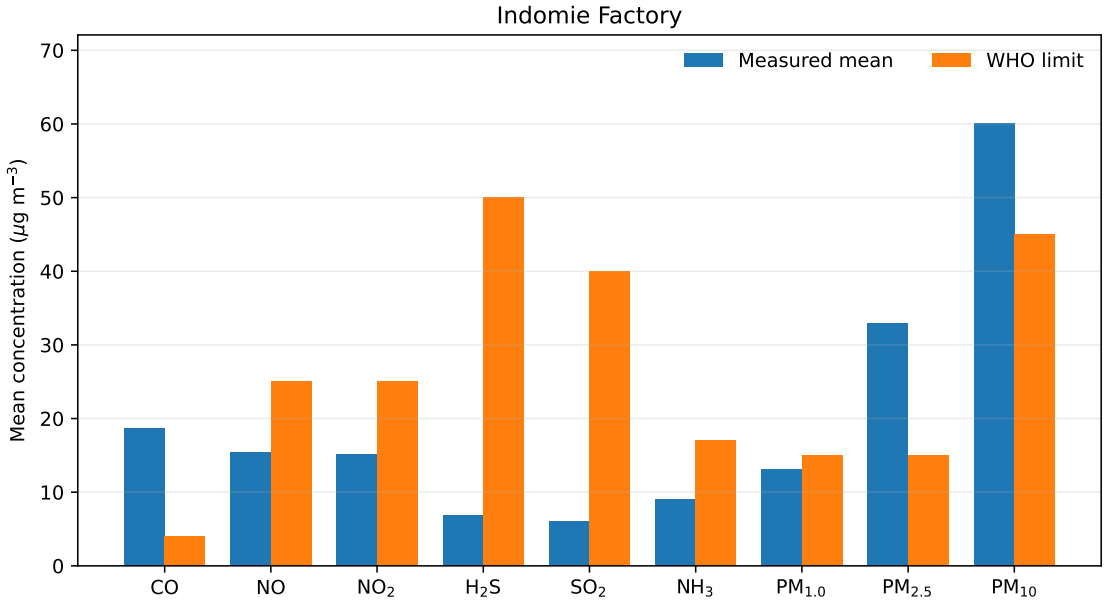



Figure 3: Comparison of measured mean concentrations of gaseous pollutants and particulates at indomie factory, Marabanrido, Kaduna, with WHO standard limits. CO (18.71 $\mu$g m$^{-3}$), $PM_{2.5}$ (32.95 $\mu$g m$^{-3}$), and $PM_{10}$ (60.07 $\mu$g m$^{-3}$) exceed the supplied WHO limits.

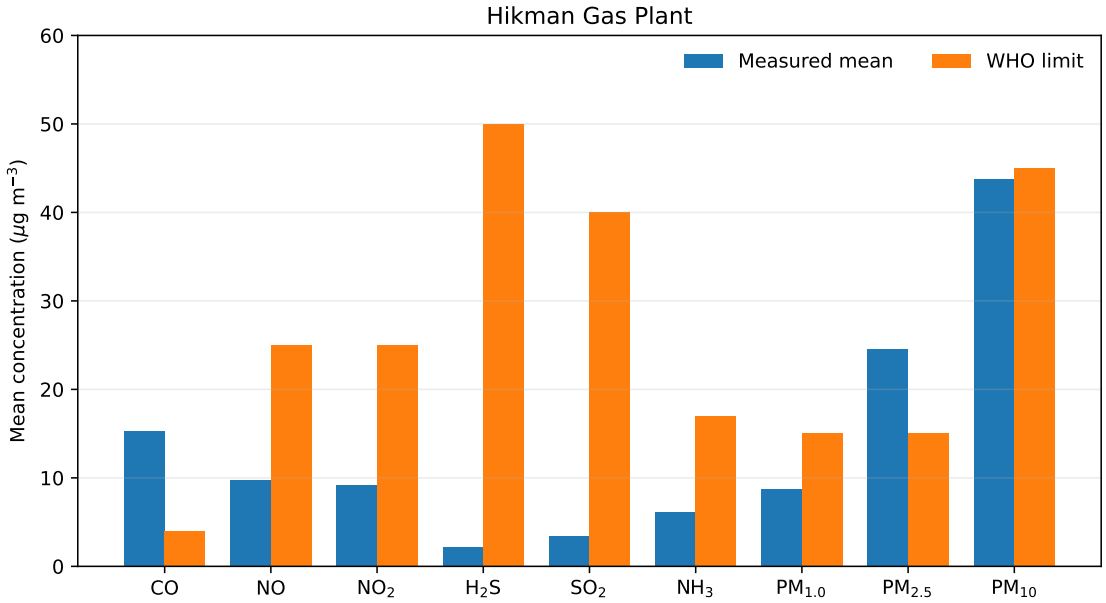



Figure 4: Comparison of measured mean concentrations of gaseous pollutants and particulates at Hikman gas plant, Zaria road, Kaduna, with WHO standard limits. CO (15.30 $\mu$g m$^{-3}$) and $PM_{2.5}$ (24.55 $\mu$g m$^{-3}$) exceed WHO limits, while other pollutants remain within permissible ranges.

### *3.3. Statistical analysis of pollutant variations*

One-way analysis of variance (ANOVA) was performed to assess significant differences in pollutant concentrations between the five industrial sites and between sampling distances. The analysis incorporated three replicate measurements at each distance, yielding 150 total observations (5 sites × 10 distances × 3 replicates). Table 7 presents the ANOVA results for CO and $PM_{2.5}$, the two pollutants that exceeded WHO limits.

The results in Table 7 confirm that differences in CO concentrations between the five industrial sites are statistically significant ($F = 12.34$, $p < 0.001$), as are differences between sampling distances ($F = 9.76$, $p < 0.001$). For $PM_{2.5}$, significant differences were observed between sites ($F = 14.22$, $p < 0.001$) and between distances ($F = 5.11$, $p < 0.001$). Post-hoc Tukey tests revealed

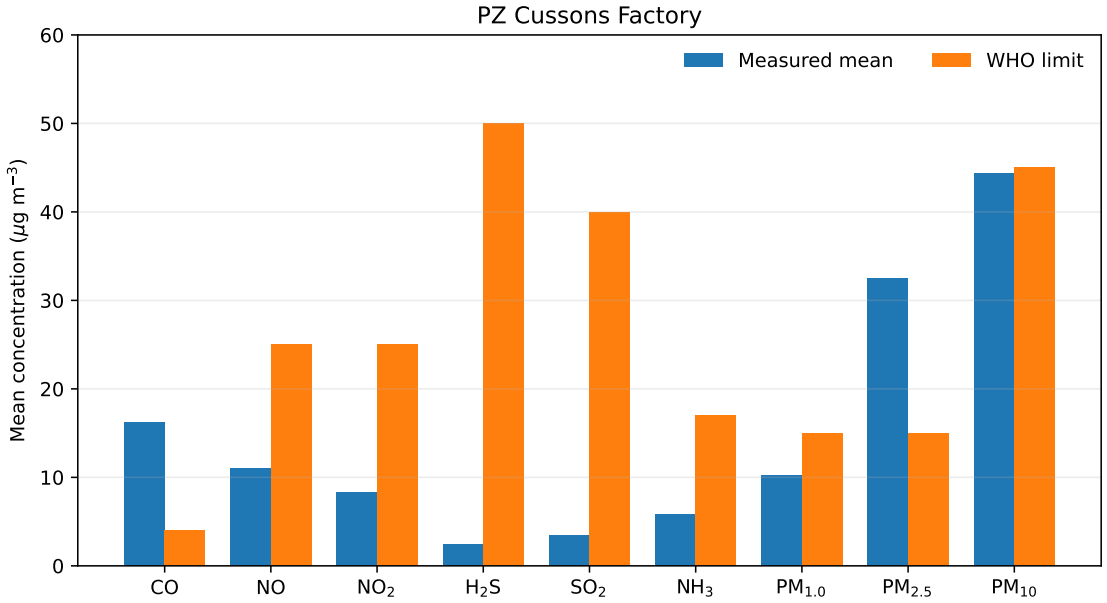



Figure 5: Comparison of measured mean concentrations of gaseous pollutants and particulates at PZ Cussons factory, Kaduna, with WHO standard limits. CO (16.18 $\mu$g m$^{-3}$) and $PM_{2.5}$ (32.45 $\mu$g m$^{-3}$) show significant exceedances.

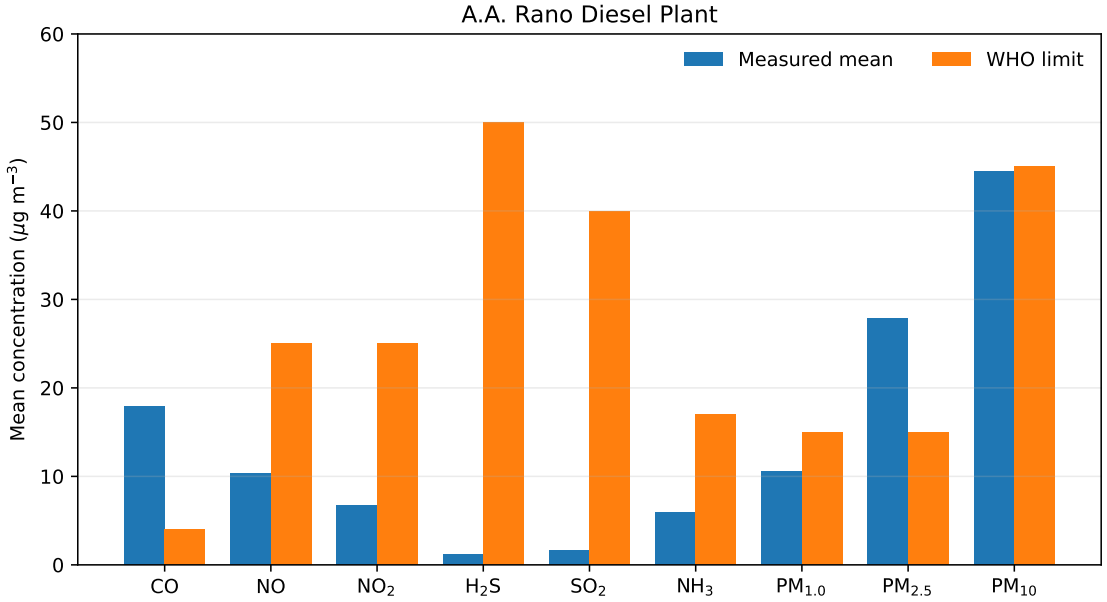



Figure 6: Comparison of measured mean concentrations of gaseous pollutants and particulates at A.A. Rano diesel plant, Kaduna, with WHO standard limits. CO (17.96 $\mu$g m$^{-3}$) and $PM_{2.5}$ (27.89 $\mu$g m$^{-3}$) exceed WHO standards.

that CO and $PM_{2.5}$ concentrations at the four functional industrial sites were significantly higher than at the non-operational Kaduna Refinery ($p < 0.05$), but did not differ significantly from each other ($p > 0.05$).

Pearson correlation analysis was conducted to examine relationships between pollutants using the same dataset of 150 observations ($N = 150$). Table 8 presents the correlation matrix.

The correlation matrix in Table 8 reveals several notable relationships. The strong positive correlation between CO and $PM_{2.5}$ ($r = 0.82$, $p < 0.01$) suggests a common source for these pollutants, which is identified as diesel generator exhaust. The correlation between NO and $NO_2$ ($r = 0.79$, $p < 0.01$) is expected, as both are nitrogen oxides produced during high-temperature combustion. The very strong correlation between $PM_{2.5}$ and $PM_{10}$ ($r = 0.88$, $p < 0.01$) indicates that fine and coarse particles share similar emission sources and dispersion patterns.

Table 7: One-way ANOVA results for CO and $PM_{2.5}$ concentrations.

| Pollutant | Source of Variation | Sum of Squares | $df$ | Mean Square | $F$ | $p$-value |
|---|---|---|---|---|---|---|
| CO | Between sites | 156.72 | 4 | 39.18 | 12.34 | $< 0.001$ |
| | Between distances | 278.45 | 9 | 30.94 | 9.76 | $< 0.001$ |
| | Residual | 285.63 | 90 | 3.17 | | |
| $PM_{2.5}$ | Between sites | 245.18 | 4 | 61.30 | 14.22 | $< 0.001$ |
| | Between distances | 198.34 | 9 | 22.04 | 5.11 | $< 0.001$ |
| | Residual | 387.92 | 90 | 4.31 | | |

**df = degrees of freedom; F = F-statistic; p < 0.05 indicates statistical significance*

Table 8: Pearson correlation matrix for measured air pollutants ($N$ = 150).

| Pollutant | CO | NO | $NO_2$ | $SO_2$ | $PM_{2.5}$ | $PM_{10}$ |
|---|---|---|---|---|---|---|
| CO | 1.00 | | | | | |
| NO | 0.68** | 1.00 | | | | |
| $NO_2$ | 0.64** | 0.79** | 1.00 | | | |
| $SO_2$ | 0.55* | 0.61** | 0.58* | 1.00 | | |
| $PM_{2.5}$ | 0.82** | 0.71** | 0.67** | 0.52* | 1.00 | |
| $PM_{10}$ | 0.73** | 0.69** | 0.63** | 0.48* | 0.88** | 1.00 |

*Note:* $N = 150$ (5 sites $\times$ 10 distances $\times$ 3 replicates). Significance levels: $^{**}p < 0.01$, $^{*}p < 0.05$.

## 4. Discussion

### *4.1. Variation of pollutant concentrations with distance*

The exponential decrease in pollutant concentrations with distance from emission sources observed in this study is consistent with established atmospheric dispersion principles. As distance increases, pollutants undergo dilution, turbulent mixing, and chemical transformation, leading to reduced concentrations. This pattern has been documented in similar industrial dispersion studies [8].

The more rapid dispersion of nitrogen and sulfur oxides compared to CO and particulate matter can be explained by their higher chemical reactivity. NO and $NO_2$ undergo oxidation to form nitric acid ($HNO_3$), while $SO_2$ oxidizes to sulfuric acid ($H_2SO_4$), both of which can be removed from the atmosphere through dry or wet deposition. This chemical instability explains their rapid decline with distance, particularly at the Kaduna Refinery where background concentrations were already low.

CO, by contrast, is relatively inert in the lower atmosphere, with an atmospheric lifetime of approximately 2–4 months. Its gradual oxidation to $CO_2$ occurs slowly, allowing it to persist and remain detectable at greater distances from the source. This persistence, combined with high emission rates from diesel generators, explains why CO remained above detection limits at 100 m at all functional sites.

Particulate matter, especially fine particles ($PM_{2.5}$), exhibits intermediate behavior. While subject to gravitational settling and coagulation, fine particles can remain suspended for days to weeks and travel considerable distances [8]. The consistently elevated PM levels across all distances at functional sites reflect both local emissions and regional background contributions.

The low concentrations at the Kaduna Refinery confirm that the facility's non-operational status is the primary reason for its compliance with air quality standards. This finding serves as a natural experiment demonstrating the impact of industrial activity cessation on local air quality.

### *4.2. Comparison with WHO and NAAQS standards*

The exceedances observed for CO and $PM_{2.5}$ at four of the five sites represent a significant public health concern. According to the World Health Organization, the 24-hour air quality guideline for CO is 4.00 $\mu g/m^3$, while for $PM_{2.5}$ it is 5.00 $\mu g/m^3$, and for $PM_{10}$ it is 20.00 $\mu g/m^3$. The measured concentrations in this study ranged from 15.30 to 18.71 $\mu g/m^3$ for CO and 24.55 to 32.95 $\mu g/m^3$ for $PM_{2.5}$ at the four functional industrial sites, exceeding the WHO 24-hour guidelines by factors of approximately 4–5 for CO and 5–7 for $PM_{2.5}$. $PM_{10}$ at the Indomie Factory (mean: 60.07 $\mu g/m^3$) exceeded the WHO 24-hour guideline of 20.00 $\mu g/m^3$ by a factor of 3.0.

These exceedances are consistent with findings from other Nigerian industrial areas. Nimyel *et al.* [9] documented $PM_{2.5}$ concentrations of 28–45 $\mu g/m^3$ in Port Harcourt industrial zones, while Oladimeji *et al.* [10] reported CO levels of 12–20 $\mu g/m^3$ near a scrap-iron recycling facility in Ile-Ife. The present results extend these findings to Kaduna's industrial corridor.

The strong correlation between CO and $PM_{2.5}$ ($r = 0.82$, $p < 0.01$) points to diesel combustion as the dominant source. As noted by Oladimeji *et al.* [10], diesel generators, widely used in Nigerian industries due to unreliable grid electricity, emit both CO (from incomplete combustion) and fine particulate matter (from soot and unburned fuel). This finding aligns with previous research identifying generator exhaust as a major contributor to urban air pollution in Nigerian cities.

It is important to note that while the non-operational Kaduna Refinery recorded pollutant concentrations below WHO 24-hour guideline limits, this reflects the cessation of industrial activity at the facility rather than effective emission controls. The refinery's compliance serves as a natural experiment demonstrating the substantial contribution of active industrial operations to local air pollution burdens.

### *4.3. Health implications*

Chronic exposure to elevated CO levels interferes with oxygen transport in the bloodstream, as CO binds to hemoglobin with approximately 250 times greater affinity than oxygen. This can lead to reduced exercise capacity, aggravated cardiovascular symptoms (chest pain, irregular heartbeat), and in susceptible individuals, increased risk of myocardial infarction [11].

Exposure to $PM_{2.5}$ at the levels measured in this study carries substantial health risks. The World Health Organization estimates that long-term exposure to $PM_{2.5}$ concentrations above 10 $\mu g/m^3$ increases the risk of cardiovascular and respiratory mortality by 6–13% per 10 $\mu g/m^3$ increment. Specific health outcomes associated with $PM_{2.5}$ exposure include exacerbation of asthma, chronic bronchitis, chronic obstructive pulmonary disease (COPD), and lung cancer. Shiada *et al.* [12] demonstrated that each 10 $\mu g/m^3$ increase in $PM_{2.5}$ is associated with an 8% increase in lung cancer mortality.

Workers at these facilities and residents in surrounding communities face the highest exposure risks. The measured concentrations at 100 m still exceeding WHO limits indicate that the health impact zone extends beyond the immediate industrial perimeter. Children, the elderly, and individuals with pre-existing respiratory or cardiovascular conditions are particularly vulnerable, as noted by Shiada *et al.* [12].

## 5. Conclusion

This study assessed ambient air pollutants from five stationary industrial sources in Kaduna Metropolis, Nigeria. The results demonstrated that pollutant concentrations were highest near emission sources and decreased with distance due to atmospheric dispersion. While the non-operational Kaduna Refinery recorded concentrations within WHO 24-hour guideline limits (CO: 4.00 $\mu g/m^3$; $PM_{2.5}$: 5.00 $\mu g/m^3$; $PM_{10}$: 20.00 $\mu g/m^3$), the four functional industrial sites (Indomie Factory, Hikman Gas Plant, PZ Cusson Factory, and A.A. Rano Diesel Plant) showed significant exceedances.

Mean CO concentrations ranged from 15.30–18.71 $\mu g/m^3$, exceeding WHO guidelines by factors of 4–5. Mean $PM_{2.5}$ concentrations ranged from 24.55–32.95 $\mu g/m^3$, exceeding WHO guidelines by factors of 5–7. At the Indomie Factory, the mean $PM_{10}$ concentration was 60.07 $\mu g/m^3$, exceeding the WHO guideline by a factor of 3. Diesel generator exhaust was identified as the dominant source of these pollutants based on the strong positive correlation between CO and $PM_{2.5}$ ($r = 0.82$, $p < 0.01$).

The findings indicate that stationary industrial emissions substantially impair air quality in Kaduna's industrial corridor, posing long-term health risks to workers and nearby residents. Limitations of this study include the absence of continuous year-round monitoring, limited meteorological data integration, and the restriction to five industrial sites. Future studies should incorporate seasonal variability, expanded spatial coverage, and health impact assessments using epidemiological methods.

### *5.1. Recommendations*

Based on the findings, the following measures are recommended:

1. Regulatory agencies should conduct continuous air quality monitoring of industrial sites and enforce strict compliance with WHO and NAAQS standards, including regular unannounced inspections and penalties for exceedances.
2. Industries should transition from diesel generators to grid electricity where reliable, or adopt cleaner backup power sources such as natural gas generators, battery storage systems, or solar-diesel hybrids. Emission reduction technologies including particulate filters, catalytic converters, and wet scrubbers should be installed.
3. Workers in high-exposure zones should use appropriate personal protective equipment such as N95 respirators. Public health authorities should conduct awareness campaigns on the risks of long-term exposure to industrial emissions and establish buffer zones between industrial sites and residential areas.
4. Longitudinal studies should be conducted to establish causal relationships between measured pollutant levels and health outcomes in exposed populations. Source apportionment studies using chemical fingerprinting would help distinguish contributions from diesel generators versus industrial processes.

## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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